

Module 2

**COMMON
MECHANICAL–BASED
FAILURE MODES**

OBJECTIVES:

After completing this module you will be able to:

- | | | |
|------------------|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Page 3</i> ⇔ | 2.1 | Explain why the turbine shaft develops a greater sag at rest than during operation. |
| <i>Page 3</i> ⇔ | 2.2 | State the consequences of not regularly rolling out the sag. |
| <i>Page 4</i> ⇔ | 2.3 | Explain the difference between ductile and brittle fracture. |
| <i>Page 4</i> ⇔ | 2.4 | State why ductile fracture is the preferred failure mode. |
| <i>Page 6</i> ⇔ | 2.5 | Explain why a material exhibiting a ductile/brittle transition temperature has operating limitations with respect to temperature. |
| <i>Page 7</i> ⇔ | 2.6 | Give:
a) two examples of operating procedures to compensate for selection of a material with a ductile/brittle transition temperature,
b) one example where very low levels of mechanical shock will cause fracture in notch sensitive materials. |
| <i>Page 8</i> ⇔ | | |
| <i>Page 10</i> ⇔ | 2.7 | Explain why a pressure boundary must be inspected following an incident that exceeds design or maximum allowable working pressure. |
| <i>Page 10</i> ⇔ | 2.8 | State, for fatigue failure in metals:
a) the type of fracture,
b) two conditions necessary to initiate the fatigue process,
c) the relationship between magnitude of loading (either thermal or mechanical) and component operating life. |
| <i>Page 11</i> ⇔ | | |
| <i>Page 13</i> ⇔ | 2.9 | Explain the phenomenon of creep in metals. |
| <i>Page 15</i> ⇔ | 2.10 | State three factors which increase creep rate. |

Page 16 ⇔**Page 17** ⇔**Page 17** ⇔

2.11 Describe the type of wear or surface failure occurring in:

- a) cavitation in pumps and valves,
- b) wiping or smearing of bearings,
- c) fretting of tubing and couplings.

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INSTRUCTIONAL TEXT

INTRODUCTION

In Module 1, we developed some basic definitions for such fundamental material properties as strength, ductility, and toughness. We also discovered how these properties, and the deformation process, were affected by various imperfections in the crystalline structure. In this second module we will use our understanding of material properties and the deformation process to learn about a few of the common types of mechanical or stress-induced failures encountered in the workplace.

Why do we require a good understanding of failure processes? Whether we like it or not, various components in service suffer failure (either breakage or change of shape) and cannot perform their designated function. The failed component requires replacement, and, if we do not want a repetition of the failure, we must understand what caused it. Then, we can select an improved material or design for the component, or modify the operating conditions.

SAG: THE ANELASTIC BEHAVIOUR OF TURBINE SHAFTS

In Module 1, failure was described either as fracture or rupture of the material into two or more pieces, or as plastic deformation or yielding of the material. There is actually a third category of failure; **excessive elastic deformation**. Although there is no permanent deformation, large amounts of elastic deformation are clearly undesirable where close tolerances between moving parts are a consideration.

Excessive elastic deformation is controlled not by the strength of the material, but by the **Modulus of Elasticity**. This modulus, also known as Young's Modulus, relates stress and strain in the region of elastic or reversible deformation and is a measure of stiffness.

NOTES & REFERENCES

Some materials such as steels exhibit time dependent or anelastic deformation because atoms relocate themselves within the total structure under the influence of stress. This means that the total elastic strain is composed of two components:

- a) a time-independent strain occurring immediately on application of stress, and
- b) an additional anelastic strain, dependent on the length of time the stress is applied.

The total strain is approached exponentially. On removal of the stress, the time-independent strain is recovered immediately but the anelastic strain relaxes exponentially.

Obj. 2.1 ⇔

The turbine shaft is basically a massive but slender component supported at discrete points by bearings. The force of gravity causes the shaft to assume a sag. Since the shaft is an alloy steel, there will be a sag introduced immediately the shaft becomes non-uniformly supported. This sag will increase with time as the steel assumes anelastic behaviour. To reduce the amount of anelastic deformation in the shaft, it is not allowed to remain in one position such that gravity is always acting in the same plane, but is rotated on the turning gear to roll out the sag or remove the anelastic component of the total elastic strain. In fact, even during construction before the shaft is placed in position within the casing, it should be turned over regularly to reduce the anelastic strain.

Obj. 2.2 ⇔

The major problems which may arise due to excessive elastic deformation in the turbine shaft are unbalance*, rapid wear of bearings and possible rubbing or interference between fixed and moving parts. All of these may lead to excessive vibration during run-up. In addition, the sag causes the centre of mass of the shaft to be offset from the centre of rotation. At the operating speeds of our turbines, even an offset of 0.025 mm ($1/1000$ inch) can result in significant out of balance forces and vibration during operation. The final result of sag, if left for extended periods, may be the beginning of creep, a permanent deformation discussed later in this module.

A COMPARISON OF DUCTILE AND BRITTLE FRACTURE

Fracture, as we have already seen, is the rupture or separation of a solid body into two or more pieces by the action of applied stress. The basic process consists of two steps:

* Further information on turbine unbalance can be found in the 234-14 Turbine & Auxiliaries course.

NOTES & REFERENCES

- a) the initiation or birth of a crack, and
- b) growth of the crack to critical size.

Obj. 2.3 ⇔

The ease or speed with which these steps occur enables us to categorize fractures as brittle or ductile. A brittle fracture is characterized by rapid crack growth with no gross or visible plastic deformation and little deformation on a microscopic scale. On the other hand, ductile fracture is characterized by much slower crack growth with appreciable plastic deformation before and during growth. Generally there is considerable visible evidence of deformation at the fracture surfaces.

Ductile fracture is primarily a flow process; the material is slowly torn apart with a large expenditure of energy. The crack grows through the grains, and the fracture appearance is grey and fibrous. The plastic deformation may produce a necked region (refer to Module 1) and often internal rupture begins at defects in the crystal structure before the actual fracture is seen.

Brittle fracture, because it involves little or no flow (ie, deformation) of material, is essentially the separation of two surfaces by tensile or pulling forces. The cracks grow along crystal boundaries and give the fracture surface a bright crystalline or granular appearance. Highly ductile metals, such as copper, which have a crystal structure that deforms or flows easily, do not exhibit brittle fracture. On the other hand, less ductile metals such as steel do show brittle fracture under certain conditions.

Obj. 2.4 ⇔

Brittle fracture is not possible unless the cracks initiated in the material can propagate at very high velocities, usually in the order of 2000 m/sec. This obviously produces a sudden failure without warning, known as a catastrophic failure. In addition, the actual magnitude of the fracture stress is highly variable and cannot be predicted accurately. For these reasons, *brittle fracture is a dangerous situation and must be avoided at all costs*. Ductile fracture, progresses much more slowly and, because of the associated plastic deformation, gives early warning signs of impending trouble as well as a more reliable estimate of the fracture stress.

The Susceptibility of Certain Ductile Materials to Brittle Fracture

A material which has a ductile/brittle transition temperature is known as **notch sensitive**. This means that fracture of this material is particularly sensitive to the nature and distribution of stress, temperature, and changes in the rate of deformation. Certain metals such as carbon steel, and other materials such as plastics, are highly notch sensitive. They experience a fairly sharp change from ductile to brittle behaviour at a "transition temperature". Figure 2.1 illustrates this phenomenon.

NOTES & REFERENCES

Figure 2.1(a) shows that, within a narrow temperature range, certain metals and plastic show a marked decrease in elongation which is indicative of brittle behaviour. Figure 2.1(b) shows the same for steels of varying carbon content, but is plotting energy absorbed in fracture rather than elongation.

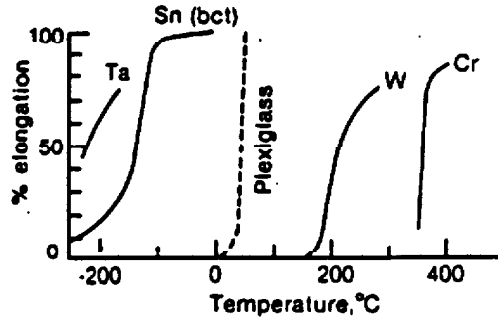


Figure 2.1 (a): Ductility versus Temperature (Tensile Tests – Schematic)

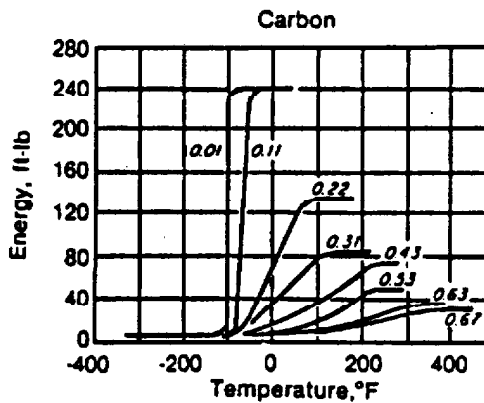


Figure 2.1 (b): Effects of Carbon Content on the Energy-Transition-Temperature Curves for Steel

Obviously, when selecting a material which may behave in a brittle manner under load, we must be aware of this “transition temperature” and select appropriate operating conditions to ensure ductile behaviour.

A test known as the impact test allows us to measure notch sensitivity and determine the “transition temperature”. Notched specimens at different temperatures are fractured under the impact of a heavy pendulum, and the energy absorbed on impact is recorded. The notch basically simulates the micro-flaws or cracks present in real materials. Notches or cracks make materials more sensitive to brittle fracture because, when present, they concentrate the applied stress at their narrow base or tip.

NOTES & REFERENCES

In fact, the stress concentration factor, ie, stress at notch tip/nominal applied stress, may easily be 100–1000. The stress concentration increases as the radius at the tip of the notch decreases.

Now let us examine the results of an impact test. There are actually two ways of plotting the data, both illustrated in Figure 2.2. The energy absorbed by the specimen on impact may be plotted against temperature, or the percentage of crystalline or brittle fracture apparent on the fracture surface may be plotted against temperature. If the material is notch sensitive, it will show a narrow range of temperature over which its behaviour under load changes markedly, as seen in Figure 2.2.

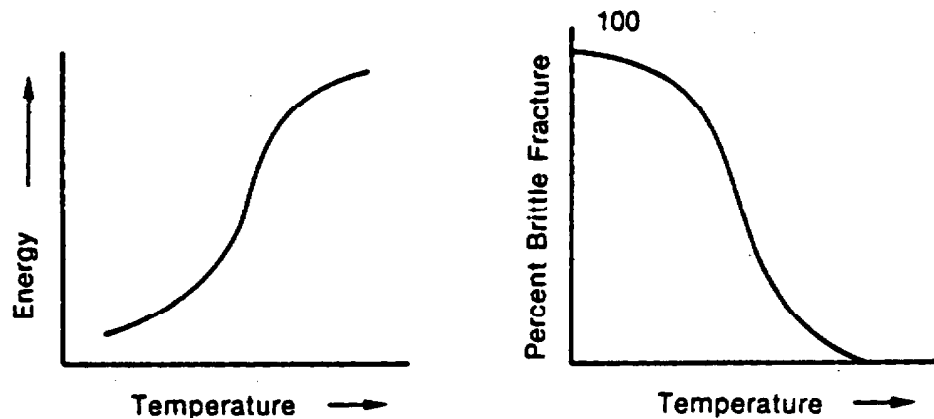


Figure 2.2: Impact Test Results – Two Plots

Obj. 2.5 ⇔

We can actually identify two transition temperatures, a ductility transition temperature usually called the ductile/brittle or nil ductility transition temperature, and a fracture appearance transition temperature. They do not coincide as they are determined differently. The ductility transition temperature is that temperature at which the material absorbs a set amount of energy on fracture (for steels this energy is frequently 15 ft–lb). The fracture appearance transition temperature is that temperature at which there is a set amount of ductile fracture, usually 50%.

Below the ductility transition temperature crack initiation is easy and crack growth is rapid. This is characteristic of brittle fracture. Above the fracture appearance temperature crack growth is difficult and fracture ductile. Between these two transition temperatures, crack initiation is difficult but, if cracks are present, they grow readily. This information is summarized visually in Figure 2.3.

- We have already concluded that brittle fracture is dangerous and to be avoided. Therefore, materials which exhibit a ductile/brittle transition temperature, must be operated above that temperature to ensure ductile behaviour of components in service, ie, avoid brittle fracture.

NOTES & REFERENCES

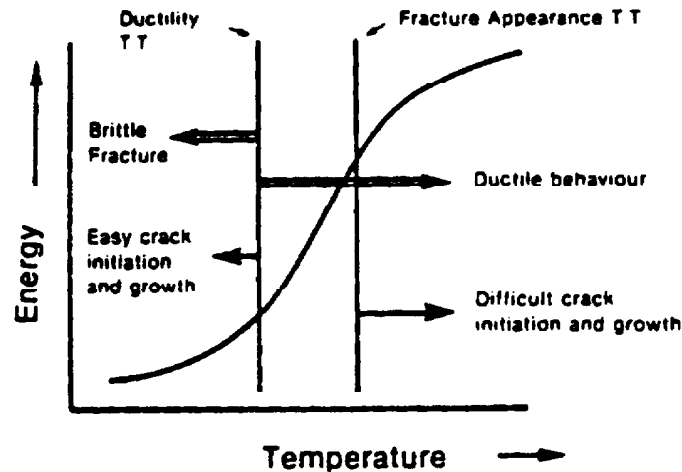


Figure 2.3: Energy versus Temperature Curve for Notch Sensitive Material

Many factors influence the ductile/brittle transition temperature. For example, in steels increasing carbon content or silicon contents beyond 0.25% cause the transition temperature to rise. On the other hand, nickel and manganese lower the transition temperature. Cold work raises the transition temperature whereas small grain size decreases it. And, of major importance to us, neutron irradiation *raises* the transition temperature.

Steels are the most common metal used for components in our nuclear stations. Normally we cannot alter composition, grain size, or amount of cold work to give a more acceptable transition temperature. We have to control operating conditions which basically implies the component should be above its transition temperature before loading occurs.

Obj. 2.6 a) ⇔

In many components the transition temperature is close to room temperature or somewhat above, eg, for turbine and generator shafts 90–120° C. Both the turbine and generator must undergo some pre-warming prior to loading. Initially, the turbine is rotated slowly on the turning gear while gland steam is admitted. This helps to warm the rotor and even out thermal stresses. The generator is pre-warmed either by conditioning heaters or by the magnetic heating effect of the excitation current.

Another area where the operator will have concern for materials which have a ductile/brittle transition temperature is isolation by ice plugs. Using ice plugs is an accepted procedure for isolating piping in many reactor systems where there are no isolating valves, eg. feeders. A refrigerant is applied to the appropriate section of pipe and the fluid (usually D₂O) is frozen solid in this area. Maintenance work can then be performed on the isolated and drained section.

NOTES & REFERENCES

There are many considerations which must be looked at when forming ice plugs. They must not be applied to short runs* of rigidly constrained piping where pipe shrinkage may cause problems. The end of the freeze jacket must not be located closer than a specified number of pipe diameters* from a weld, since welds may already be an area of brittleness.

Obj. 2.6 b) ⇔

Of major concern is the severe embrittlement of steel piping in the area of the ice plug. The refrigerant will bring the temperature of the piping well below the ductile/brittle transition temperature thus *ensuring* brittle behaviour under load. For this reason, mechanical shocks to the isolated system must be avoided. The application of heat to accelerate thawing is prohibited.

SUMMARY OF THE KEY CONCEPTS

- A turbine shaft, supported at discrete points while at rest, is subject to a time-independent (elastic) strain and a time-dependent (anelastic) strain which lead to sag. When the turbine is in operation, the force of gravity no longer acts in a single plane and sag is greatly reduced.
- If the sag is not rolled out of the shaft on a regular basis, fixed and moving parts may rub together and/or significant vibration may occur when the turbine is put into service.
- Brittle fracture is characterized by rapid crack growth with no gross or visible plastic deformation. There is little deformation even on a microscopic scale.
- Ductile fracture is characterized by much slower crack growth with appreciable plastic deformation before and during crack growth.
- Ductile fracture is the preferred failure mode since it gives early warning signs of impending trouble and allows reasonably accurate assessments of the magnitude of the fracture stress.
- A material which exhibits a ductile/brittle transition temperature has operating limitations with respect to temperature to ensure it operates in a temperature region where it will fail in a ductile mode.
- To compensate for the fact that materials used in the turbines and generators at our nuclear stations exhibit near room temperature ductile/brittle transition temperatures, these devices are preheated prior to service operation.
- Due to the effect of a ductile/brittle transition temperature, steel piping with ice plugs applied for isolation purposes must not be subjected to any sudden or shock loading, as brittle fracture will result.

* Allowable ice plug locations will be specified in your station documentation.

OPERATION OF PRESSURE VESSELS

Explain why a pressure boundary must be inspected following an incident that exceeds design or maximum allowable working pressure.

This may seem a trivial objective in that our natural response to an overpressure incident would be to examine the vessel for any signs of failure, such as deformation or cracks. However, if we see no visible evidence of failure, our next response is that there is no problem. This may not be true because, as we have already seen with brittle fracture, there may be no visible warning signs of the impending failure. The inspection following an overpressure excursion is generally very rigorous and conducted by an authority other than the vessel operator. To better understand the importance of the inspection, it is necessary to consider, briefly, certain aspects of the design and operation of pressure vessels.

The majority of pressure vessels used in our nuclear stations are designed to the specifications contained in Section VIII of the ASME Code. There are two divisions in this section; one containing the general requirements for construction of unfired pressure vessels and another containing alternate rules for construction of unfired pressure vessels requiring detailed stress analysis. Operation of the completed pressure vessels must comply with the Ontario Boiler and Pressure Vessel Act which is enforced through the Ministry of Consumer and Commercial Relations. The inspectorate of this Ministry effectively licenses the operation of pressure vessels.

The Boiler and Pressure Vessel Act prohibits the operation of boilers, pressure vessels, or plant at a working pressure higher than their design pressure or higher than the maximum allowable working pressure shown on the Certificate of Approval (or Inspection) issued for the vessel. To avoid confusion over what may appear a double standard, let us define design and maximum allowable working pressure*. **Design pressure** is the maximum difference in pressure (for the most severe condition of coincident pressure and temperature) between the inside and outside of the vessel expected in normal operation. It is recommended that a suitable margin be provided above the normal operating pressure of the vessel to allow for possible pressure surges in the vessel (up to the setting of the pressure relieving devices). Design pressure is normally used to determine the thickness of parts of the vessel.

On the other hand, the **maximum allowable working pressure** is the maximum pressure permissible at the top of the vessel in its normal operating position at the operating temperature specified for that pressure. This value is chosen such that protection is provided for the portion of the vessel that is under the highest stress situation (which may not be at the top of the vessel).

* *Definitions are from ASME code – Section VIII – Division 1.*

NOTES & REFERENCES

The maximum is the basis for the pressure setting on relief devices and is the pressure specified on the Certificate of Approval.

The Act also requires operators to notify the inspector of vessels found in an unsafe condition and the nature and extent of repairs to be performed. The repairs will be authorized by the inspector and on completion the vessel will be inspected and a new Certificate of Inspection issued.

Obj. 2.7 ⇔

It should now be clear that there is a legal requirement to inspect pressure vessels (or pressure boundaries) following an over pressure incident. What are the material considerations behind this requirement? Simply, over pressure may cause localized plastic deformation of the pressure vessel. This will raise the yield stress and limit further deformation. Although the material of the vessel is effectively stronger, it is less ductile and less resilient in its behaviour under load. The material in the areas subject to deformation becomes more susceptible to brittle fracture.

FATIGUE: FAILURE UNDER DYNAMIC LOAD CONDITIONS

Materials subjected to fluctuating or repeated loads tend to behave somewhat differently, in certain respects, than under static loads. This behaviour is known as fatigue and is characterized by failure at relatively low loads, increased brittleness of the material, and an uncertainty of service life before failure. All these characteristics arise essentially because of the non-uniform nature of real materials. This non-uniformity may result from visible imperfections such as cracks or inclusions of foreign matter or may be sub-microscopic. The effect of these imperfections under repeated loading is strongly emphasized and there are many similarities here to brittle fracture.

Obj. 2.8 a) ⇔

Fatigue due to cyclic loading is characteristic of ductile materials but the *final fracture is rapid* and therefore classified as brittle.

Obj. 2.8 b) ⇔

Fatigue failures comprise a large percentage of all failures encountered in engineering, primarily because the conditions producing fatigue are frequently difficult to recognize. The basic requirements for fatigue are:

- (a) a fluctuating applied stress with sufficiently high amplitude in the fluctuation,
- (b) sufficiently large number of cycles of fluctuation.

These factors are inter-related and there is no simple formula for predicting what stress will cause fracture or when it will occur.

NOTES & REFERENCES

Often, the stresses required to produce fracture in fatigue are well within the elastic region as measured in static tension, ie, the material or component will be working within specified design loads. These stresses commonly alternate between tension and compression, such as experienced by a loaded rotating shaft, but, may also alternate between high and low values of the same type of stress, such as experienced by a spring. They can be induced either mechanically or thermally. For example, the steam generator experiences both thermally and mechanically induced stress as it is heated and pressurized when brought "on-line". In fact, at BNGS-A where the steam generator consists of four boiler legs connected to a common steam drum, the "T" junction weld between the boiler and steam drum is causing considerable concern as an area for fatigue failure of the unit.

The actual mechanism of fatigue is quite complicated. The overall deterioration consists primarily in the formation of cracks, which may start at visible imperfections and discontinuities such as surface damage or holes, or originate from areas of localized deformation. Initially the cracks start as sub-microscopic but develop through the cycles of loading to microscopic and eventually visible size. The cracks concentrate stress but crack growth is slow in ductile materials. Finally, the cracks reach a critical size, such that the stress concentration exceeds the fracture strength and catastrophic failure occurs.

Obj. 2.8 c) ⇔

The basic method for presenting fatigue data is the S-N curve, illustrated in Figure 2.4. It plots applied stress (S) against component life or number of cycles to failure (N).

As the stress decreases from some high value, component life increases slowly at first and then quite rapidly. Because fatigue like brittle fracture has such a variable nature, the data used to plot the curve will be treated statistically. The solid or Median curve represents 50% survival of test specimens at the indicated stress level. The dashed curve represents 95% survival.

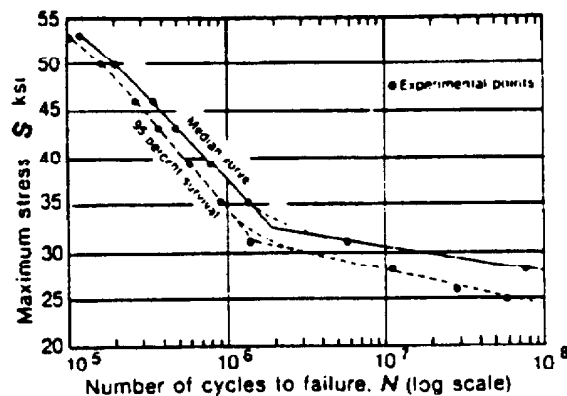


Figure 2.4: S-N Diagram for Phosphor Bronze Strip in Reverse Bending

NOTES & REFERENCES

Iron and steel exhibit what is called a **fatigue or endurance limit**. Their S-N curve appears as in Figure 2.5. For all practical purposes the fatigue curve becomes horizontal and fatigue life at lower stress levels is assumed to be infinite. However, very few components are ever designed for operation at stress levels which would ensure an infinite life.

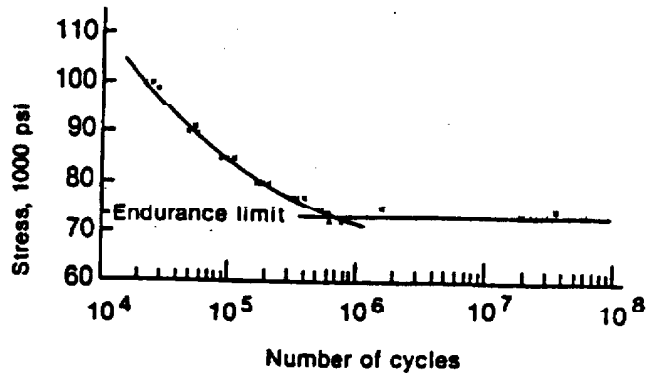


Figure 2.5: S-N Curve (4340 Steel, Hot-Worked Bar Stock)

Now consider a few factors which affect the fatigue life of machine components. As we have already seen, anything which leads to stress concentration, and the development of cracks, will reduce fatigue life. Therefore, increasing the degree of surface finish, ie, polishing as compared to grinding, improves fatigue life. Increasing the strength and hardness of the surface layers of metal components will also improve fatigue life. Shot-peening and surface rolling accomplish this by introducing surface stresses through limited plastic deformation of surface layers. The presence of discontinuities such as holes, keyways, fillets, etc, must be considered carefully in component design in order to reduce their effect as stress raisers (points that concentrate stress).

Attack by a corrosive agent occurring simultaneously with fatigue loading will reduce fatigue life significantly, because chemical attack accelerates crack growth. Generally, increased operating temperatures reduce fatigue life. This is caused primarily by the reduction in yield strength with temperature. Component size also influences fatigue performance. For the same material, fatigue strength (as well as fatigue life) for large components will be lower than for small components.

SUMMARY OF THE KEY CONCEPTS

- A pressure boundary must be inspected following an incident in which its design or maximum allowable working pressure is exceeded to ensure any localized plastic deformation is detected. If not, a hazardous brittle failure may result when the pressure rises above the allowable limits again.
- Fatigue failure is classified as brittle because the final fracture is rapid and usually occurs without warning.
- Two conditions must be present for fatigue to occur. They are:
 - a) a fluctuating applied stress with sufficiently high amplitude in the fluctuation,
 - b) the stress must be applied for a sufficient duration.
- From a plot of applied stress versus operating life (an S–N curve), it can be seen that as the applied stress decreases, the component operating life increases. Initially, the increase in component operating life is small but it becomes very large at lower stress levels.

CREEP: PERMANENT DEFORMATION UNDER CONSTANT LOAD

Obj. 2.9 ⇔

In Module 1, we looked at a simple picture of failure which considered only static load situations. In this module we have seen that factors other than just exceeding the yield or ultimate stress of the bulk material influence failure. Materials under impact or cyclic loading experience highly localized yielding and embrittlement (enhanced by the presence of various imperfections) and fracture occurs readily at stresses below the ultimate stress and very often below the yield stress. Creep is another failure mode whereby components experience deformation which would not be expected from our experience of material performance under the static loading of a tensile test.

In many applications materials are required to sustain steady loads for long periods. One example discussed earlier in this module was the turbine shaft supporting its own weight, but, there are many others such as the walls of vessels or piping operating under pressure, blading on the turbine rotor, cables in pre-stressed concrete beams and even overhead power lines. For the turbine shaft, we saw that a portion of the total elastic deformation (sag) was time dependent and, if left unattended, could become permanent.

Time dependent deformation may be experienced by any material under steady loading and, even though it may be almost imperceptible in the short term, it can become very large in time and may even result in fracture. This time dependent strain under constant load is known as creep.

NOTES & REFERENCES

Creep is often thought of as an elevated temperature problem but this is only true if elevated temperature is defined relative to the material's melting point (in degrees Kelvin). For example, lead and plastics exhibit significant creep at room temperature whereas many low alloy steels such as those used for turbine rotors and casings experience little creep below 550° C. In fact, creep of components in our nuclear stations has presented no serious difficulties to date with the exception of the pressure tubes. As this problem will be discussed in more detail in a later module, it is sufficient to say that operating conditions have produced significantly more pressure tube creep than expected and the design allowance to accommodate creep will be expended after only 10–15 years of operation. Basically, creep is possible only because barriers to deformation can be overcome.

Let us consider a typical creep curve illustrated in Figure 2.6. Creep strain (or deformation) is plotted against time for a constant load and temperature. In this example, only the strain resulting from creep is shown. On initial loading, there will be an instantaneous strain as the material accommodates the applied stress. If this strain was included, the curve would not start at the origin but at a value on the strain axis corresponding to the instantaneous strain.

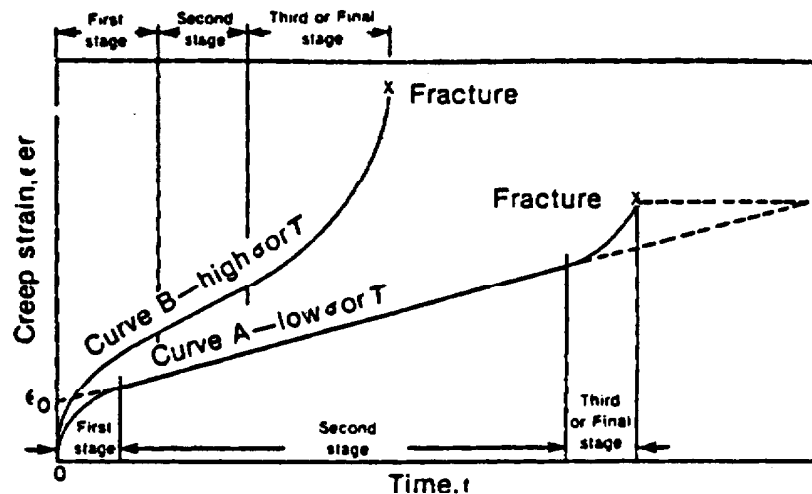


Figure 2.6: Schematic Creep Curves Showing the Three Stages of Creep

NOTES & REFERENCES

There are three stages of creep. The first stage of creep (primary or transient creep) shows the creep rate, ie, the slope of the curve, starting at a comparatively high value but decreasing rapidly to a constant value. The phenomenon of anelasticity or time dependent elastic deformation discussed earlier is a part of transient creep. The second stage of creep (steady state or viscous creep) shows constant creep rate. The final stage of creep (tertiary creep) shows an increase in creep rate before fracture. All three stages of creep do not necessarily appear, it depends on temperature and stress. The region of most interest to engineers and designers is steady state creep (the second stage) because it is the predominant mode of creep experienced under normal operating conditions.

Obj. 2.10 ⇔

Before completing the discussion on creep let us consider some important factors which affect creep rate. From the foregoing notes, it will be apparent that both stress and temperature influence creep rate; both increased stress and higher temperature increase creep rate. Radiation, a major factor in our nuclear stations, also influences creep rate.

Neutron irradiation damages crystalline lattices and creates defects which, at temperatures approximating room temperature, hinder deformation. We would therefore expect creep rate to decrease and the material to become somewhat stronger. This happens and will be discussed more fully in the module on radiation damage. However, as temperature increases, softening (increased ductility) begins to influence deformation and make it easier. Therefore, high neutron fluxes in combination with elevated operating temperatures will increase creep rate. This is essentially the situation with pressure tube creep*.

A DESCRIPTION OF THREE TYPES OF SURFACE FAILURE

In concluding our study of mechanical failure processes, we should take a brief look at surface failure. **Surface failure** is essentially the process of wear, and represents a loss of material from the surface layers of various components. This loss may be caused by chemical attack such as corrosion or by mechanical based mechanisms such as erosion or abrasion. Wear processes are very common with operating plant and equipment. We will consider three types of wear: abrasion, adhesion and fretting. There are other types of wear, but only these three commonly result in component failure in our nuclear stations.

In order to understand wear, we must first realize that surfaces on a microscopic scale are not perfectly smooth. They are essentially undulating with a number of high spots, or “hills”, and low spots.

* The problem of pressure tube creep is discussed in Module 5 of this course.

NOTES & REFERENCES

Load is basically carried by the microscopic “hills” and not by the entire surface. This means that although the surface as a whole may not experience stress beyond its design limits, the microscopic hills may experience severe stress transients.

Abrasion is simply described as the gouging (microscopically) of a softer surface by the “hills” of a harder moving surface, or by hard particles trapped between the moving surfaces. These particles may be foreign (ie, brought into the system from an external source) or may be “hills” which have been broken from one of the surfaces. The filter in a recirculating lubrication system is, of course, used to remove debris from the lubricant and, therefore, prevent abrasive wear. Regular cleaning and maintenance of these filtration units on lubrication systems is essential for efficient operation.

Obj. 2.11 a) ⇔

Abrasive wear also occurs in fluid transportation when the fluid consists of a slurry, ie, a solid suspended in a liquid, or a liquid–vapour mixture. The suspended solid or the collapse of entrained vapour bubbles can have an eroding effect on the pumps, valves and pipework carrying the fluid.

Cavitation is an erosive process frequently encountered in valves and pumps in our stations. (The high pressure service water pumps at PNGS–A have been a particular problem.) The actual mechanism is discussed more fully in Fluid Mechanics and/or Mechanical Equipment and it is sufficient to say here that metal surfaces are deformed and embrittled in the early stages. In the final stages, the brittle metal surfaces can no longer resist or support fluid forces and fail resulting in pits and loss of surface material.

On the other hand, **adhesion** is the welding or bonding of metals on a microscopic scale and the subsequent ripping away of material as the surfaces move relative to one another. Bonding of the metal surfaces occurs at the high spots or “hills” due to pressure welding. Pressure welding is essentially the formation of a metallic bond through gross deformation of surface layers. This, of course, requires very high stresses, but these can be generated at high spots on very rough surfaces where the actual load bearing area is relatively small. Adhesive wear is basically dependent on material hardness and surface smoothness; hard materials and materials with a high degree of surface finish resist adhesive wear best.

One of the most important procedures for combating adhesive wear is lubrication, which helps to prevent contact and bonding by maintaining a continuous oil film between the surfaces. However, this generally proves inadequate in the early life of machines, because new surfaces often have hills that initially rise above the oil film. With careful loading and controlled adhesive wear during machine “run in”, surface roughness will be reduced and with maintenance of adequate lubrication, further adhesive wear should not be a problem.

NOTES & REFERENCES

Obj. 2.11 b) ⇔

The most common occurrence of adhesive wear is the wiping or smearing of bearings where the lubricating oil film breaks down and the surfaces bond over large areas. The bearing metal, normally a Babbitt, is very soft with a low melting point, and therefore deforms and welds readily. The breakdown of the lubricating film often results from shaft/ bearing misalignment which creates areas where the lubricating film will be insufficient to prevent metal to metal contact. Extreme adhesive wear, where the bonding or welding of the surfaces is so severe as to prevent further movement, is known as seizure. Fortunately, this has not been a major problem in our stations.

Obj. 2.11 c) ⇔

The last type of surface failure, fretting, often occurs in combination with corrosion. It is responsible for a growing number of material failures in the station. Fretting occurs when two surfaces in constant contact experience a small periodic motion relative to each other. It differs from the other wear processes described, in that the velocity of motion between the surfaces is small and the surfaces are never out of contact. Corrosion products such as oxides tend to accumulate between the surfaces and, because these are quite abrasive, assist the wear process.

Fretting is most common in piping systems and heat exchangers where piping or tubing experiences high flow rates, and is rigidly supported to restrict movement developed by fluid forces. It is often difficult to reduce the movement between piping and the support to zero, and small vibrations develop which lead to fretting. There is a general concern in the stations that fretting may become a problem with feeders and it is already sighted as a cause of tube degradation in a number of heat exchangers. One other area where fretting can cause severe wear is in press-fit hubs and couplings.

SUMMARY OF THE KEY CONCEPTS

- Creep is a time dependent strain experienced by a component under steady loading. Creep rate is initially high, but decreases rapidly to a constant value.
- Creep rate can be affected by stress, temperature and neutron irradiation. An increase in applied stress or temperature will increase creep rate. High neutron fluxes, in combination with elevated temperatures, also increase creep rate.
- Cavitation in pumps and valves involves a form of erosion (abrasive wear) in which collapsing vapour bubbles behave like hard particles and remove material from the surfaces of the pump or valve body.
- Fretting occurs when two surfaces in constant contact experience a small relative motion or vibration. This is common in piping systems where rigidly fixed pipes undergo vibration due to high flow rates.

NOTES & REFERENCES

- The adhesive wear process occurs when the “hills” on a surface are highly stressed and pressure weld or bond to a mating surface. The motion between the surfaces causes the “hills” to be torn apart and a loss of material results. This type of failure occurs in the wiping of bearings.

Page 19 ⇔

You can now do assignment questions 1 – 16.

ASSIGNMENT

1. Explain why the turbine shaft experience a greater sag at rest than during operation.
2. State the consequences of not regularly rolling out the sag.
3. Explain the difference between ductile and brittle fracture.
4. Explain why ductile fracture is the preferred fracture mode.
5. Explain why a material with a ductile/brittle transition temperature has operating limitations with respect to temperature.
6. Describe two examples of operating procedures which compensate for selection of a material with a ductile/brittle transition temperature.
7. Describe one example where very low levels of mechanical shock will cause fracture of a notch sensitive material.
8. Explain why a pressure boundary must be inspected following an incident that exceeds design or maximum allowable working pressure.
9. State the type of fracture that occurs during fatigue failure in metals.
10. State the two conditions necessary to initiate the fatigue process.
11. Explain the relationship between applied stress and component operating life.
12. Describe the process of creep in metals.
13. State three factors which increase creep rate.
14. State and describe the type of wear that occurs during cavitation of pumps and valves.
15. State and describe the type of wear that occurs during wiping of bearings.
16. State and describe the type of wear that occurs during fretting of tubing.

Before you move on to the next module, review the objectives and make sure that you can meet their requirements.

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