Task 2:

i) **Fatigue**

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.

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

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.

Often, the stresses required to produce fracture in fatigue arc 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-!L'1e". In fact. at BNGS-A where the steam generator consists of four boiler legs connected to a common steam drum, the "1''' 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.

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 ancl 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.

Line chart

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Figure 1: S-N Diagram for Phosphor Bronze slip in Reverse Bonding.

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 int1nite. However, very few components are ever designed for operation at stress levels which would ensure an intimate life.

Chart, line chart

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Figure 2: 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 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.

**Creep**

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 waHs 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 hirge in time and may even result in fracture. This time dependent strain under constant load is known as creep.

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 5500 C. In fact, creep of components in our nuclear stations has presented no serious difficulties to date except for the pressure tubes. As this problem will be dispussed in more detail in a latermodule, itis sufficient to say that operating conditions have produced significantly more pressu.11: ~.lbe creep thall 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 defonnarlon can be overcome.

Let us consider a typical creep curve illustrated in Figure. Creep strain (or deformation) is plott.ed against time for a constant load and temperature..?OC. t'1 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 were included, the curve would not start at the origin but at a value on the strain axis corresponding to the instantaneous strain.

Diagram

Description automatically generated

Figure 3: Schematic Creep Curve showing the 3 stages of creep

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 an elasticity 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 itis the predominant mode of creep experienced under 'nonnal operating conditions.

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 defonnation. 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 defonnation 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·.

**Brittle and Ductile failure:**

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:

a) the initiation or brink of a crack, and

b) growth of the crack to critical size

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 defonnationbeforc 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 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.

Brittle fracture is not possible unless the cracks initiated in the material can propagate at very high velocities, usually in the order of 2000 III/sec. This obviously produces a sudden failure without warning, known as a catastrophic failure. In addition, the actual magnitude ofthe 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 ofthe associated plastic deformation, gives early warning signs of impending trouble as well as a more reliable estimate of the fracture stress.

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 sharp change from ductile to brittle behaviour at a "transition temperature".

Diagram, schematic

Description automatically generated

Figure 4: Ductility vs temperature (Tensile Tests -Schematic)

Diagram

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Figure 5: 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.

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 two ways of plotting the data, both. The energy absorbed by talte specil11en on i~pact may be plotted against temperature, or the percentage of cr

ystalline or brittle fracture apparent on the fracture surface may be plotted against temperature. H the material is notch sensitive; it will show a narrow range of temperature over which its behaviour under load changes markedly.

Diagram

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Figure 6: Impact Test Results – Two Plots

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 detennined differently. The ductility transition temperature isthat temperature at which the material absorbs a set amount of energy on fracture (forsteels this energy is frequently 15 ft-Ib). 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

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

Diagram

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Figure 7: Energy vs 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 arc 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 must control operating conditions which basically implies the component should be above its transition temperature before loading occurs.

n many components the transition temperature is close to room temperature or somewhat above. ego for turbine and generator shafts 90-1200 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 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 ductilelbrittle 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 isolation values example feeders. A refrigerant is applied to the appropriate section of pipe and the fluid (usually D2O) it's frozen solid in this area. Maintenance work can be there performed on the isolated and trained section.

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 be not located closer than a specified number of pipe diameters\* from a Weld since wells may already be an area of brittleness.

of major concerns the severe embrittlement of steel piping the area of ice plug. The refrigerant will bring the temperature of 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 here to accelerate thawing is prohibited

**Corrosion Failure:**

Failure analysis involves metallurgical investigations of components, equipment, metals, alloys, coatings, linings, and structures due to corrosion, environmental degradation and abuse, misapplication of the particular metal and mechanical failure. Studies of failure analysis are particularly strong in the chemical processing, refining, oil & gas and pulp & paper industries. Failure mechanisms evaluated usually include:

* general corrosion
* localized corrosion
* intergranular corrosion
* weld corrosion
* stress corrosion cracking
* fatigue & corrosion fatigue
* fretting & wear
* erosion
* overload
* brittle fracture
* hydrogen embrittlement
* hydrogen sulfide cracking
* microbiological corrosion
* oxidation, sulfidation & carburization

Corrosion is the deterioration of materials by chemical interaction with the environment. unstable due to higher energy comes to lower state.

classification of corrosion

1. wet corrosion
2. Dry corrosion

Diagram, text, letter

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Figure 8: Galvanic attack of aluminium guard rail bolted to a steel point.

Diagram

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Figure 9: Galvanic Insulation of a bolt

8 forms of corrosion

* Uniform
* Fitting
* Crevice corrosion or concentration cell
* galvanic or Two-metal
* stress corrosion cracking
* intergranular
* Dealloying
* erosion corrosion

Uniform corrosion is characterised by corrosive attack proceeding evenly over the entire surface area of large fraction of the to

A picture containing water, outdoor, stone, rock

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Figure 10: Uniform Corosion

Pitting corrosion is a form of extremely localised corrosion that leads to the creation of small holes in the metal. The driving power of pitting corrosion is there depassivation of a small area, which becomes anodic while an unknown but potentially vast area becomes cathodic, leading to a very localised galvanic corrosion. The corrosion penetrates the mass of the metal which limited diffusion of ions the mechanism of pitting corrosion is probably the same as crevice corrosion.

Graphical user interface, application

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Figure 11: pitting corrosion

Crevice corrosion or concentration self

concentration cell corrosion occurs pin 2 or more areas of metal surface or in contact with different concentration of the same solution. there are 3 general types of concentration cell corrosion

metal ion concentration cells

oxygen concentration cells

active passive cells

Galvanic corrosion

possibility went to dissimilar metals are electrically connected with an electrolyte. results from a difference in oxidation potentials of metallic ions between 2 or more metals. the greater the difference in oxidation potential the greater the galvanic corrosion. the less noble metal will corrode and the more noble metal will not corrode. perhaps the best known of all corrosion types is galvanic corrosion which occurs at contact point of 2 metals or alloys with different electrode potentials

**Stress corrosion cracking**

Stress-corrosion occurs when a material exists in a relatively inert environment but corrodes due to an applied stress. The stress may be externally applied or residual. This form of corrosion is particularly dangerous because it may not occur under a particular set of conditions until there is an applied stress.

One of the most common failure mechanisms in stainless steels is chloride induced stress corrosion cracking (SCC). In particular, the conventional austenitic grades are susceptible to this failure mode. Duplex stainless steels offer much greater resistance to this form of cracking with all grades being superior to 316L and the superduplex grades apparently immune1 in 3%NaCl up to 250CC. Nevertheless, duplex alloys do suffer from SCC given concentrated chloride solutions. And, at least for austenitic alloys, this will also be dependent on the cation present, i.e. Mg > Ca > Na in order of increasing aggressivity. In addition, high applied stress to tensile strength ratios, with elevated temperatures and high oxygen contents enhance susceptibility, combined with the presence of a crevice/deposit.

[Stress corrosion](https://www.sciencedirect.com/topics/materials-science/stress-corrosion-cracking) cracking (SCC) is interpreted to take place due to specific combinations of susceptible materials in suitable corrosion environments under adequate stress, specifically under constant stress, Figure 1. The equivalent mechanism for crack growth under [cyclic stresses](https://www.sciencedirect.com/topics/engineering/cyclic-stress) is called [corrosion fatigue](https://www.sciencedirect.com/topics/engineering/corrosion-fatigue) (CF), and crack growth here depends upon the stress ratio. In particular, when the stress ratio is high, CF becomes close to SCC; this type of loading is called ripple loading, which often simulates very well the loading situation during plant operations. Strain-induced corrosion cracking (SICC) is used especially in Germany as a term for the situation, where cracking takes place under increasing load, which may not necessarily increase monotonically, but also some cyclic variations may be present as typically in start-up and shut-down situations of plants. Therefore, the last mechanism can be considered to be a special case of corrosion fatigue, when only a very small number of cycles are present. This loading can be simulated by the slow strain rate test (SSRT) technique, where a specimen is tensile tested with a very slow strain rate in the environment. All these mechanisms can be described by a general term, namely, environment-assisted cracking (EAC).

Text

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Figure 12: stress corrosion cracking of stainless steel

ii) Refactory Ceramics

Refractories are a special class of structural ceramics and can be defined as typical non-metallic inorganic materials that constitute a unique combination of properties such as high refractoriness under high load. Classification based on the chemical nature is of prime importance since the rightful selection of a refractory for any application typically depends on the chemistry of the high temperature process environments. The failure of a refractory often occurs in metallurgical process environments due to a combined wear attack involving the most common types of mechanical, chemical, and thermal wear processes; however, the predominant wear mechanism varies with the nature of the process chemistry in distinct service atmospheres. Properties reflect the characteristic features of a refractory and unambiguously show its durability under diverse and extreme high temperature metallurgical process environments. The mechanism of refractory wear by thermal shock is illustrated for one of the most thermal shock–prone areas: the bottom portion of a basic oxygen steelmaking furnace.

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**Polymers:**

Environmental Stress Cracking (ESC) is one of the most common causes of unexpected brittle failure of thermoplastic (especially amorphous) polymers known at present. When Tg is approached, more fluid can permeate into the polymer chains. ESC and polymer resistance to ESC (ESCR) have been studied for several decades.

Mechanical Polymer Failure

Mechanical modes of polymer failure are extremely varied and may occur at stress levels below the ultimate tensile strength (UTS) of the product. Creep rupture, also known as long-term stress, is a measure of time-dependent deformation under constant load. This can result in gradual deformation by sustained albeit low loads. Fatigue, or cyclic loading, promotes a similar type of gradual failure via slow crack growth.

Other mechanical modes of polymer failure include brittle and ductile fracture, rapid fracture due to impacts, and wear due to surface abrasion.

Thermal Polymer Failure

Temperature changes can have a dramatic influence on polymer failure, by accelerating chemical or mechanical modes, or by thermally-inducing degradation. Cyclic heating and cooling can cause thermal fatigue in polymeric materials which contribute to macroscopic crack growth and structural distortion. Irreversible dimensional instability can be caused by single instances of high peak temperatures, which may be characterized by depolymerization, shrinking, swelling, or more.

Other, more severe, forms of thermal polymer failure include combustion and direct flame impingement.

Chemical Polymer Failure

Chemical attack, more so than many other modes of polymer failure, is largely determined by the material’s application area. Interactions between polymeric materials and a limitless range of chemicals can cause some form of degradation or strain. Polymers intended for use outdoors will have to withstand oxidation and exposure to ultraviolet light. Hydrolysis can also cause failure when molecules from water, acids, or alkalis rupture the chemical bonds of polymeric materials.

Other modes of chemical polymer failure include stress corrosion cracking (SCC), but this mechanism is incredibly broad, owing to the impossibly large number of combinations of chemical interactions between corrosives and polymers. This is common in applications where polymers come in contact with cleaning agents.

Polymer Failure Analysis with Jordi Labs

Jordi Labs is one of the US’s foremost polymer failure analysis laboratories, with an experienced team of Ph.D. chemists who are well-versed in the various modes of [polymer failure](https://jordilabs.com/lab-testing/problems-we-solve/polymer-failure/) that can affect your products. Alongside the above, we can also screen for more complex modes of failure, such as ultraviolet degradation (optical) and molded-in stress (polymer processing defects).

**Metals**

The failure modes discussed are hydrogen embrittlement, stress-corrosion cracking, corrosion fatigue, metal-induced embrittlement, galvanic corrosion, selective corrosion (dealloying), and intergranular corrosion.

[FOREIGN OBJECT DAMAGE (FOD)](https://www.lsptechnologies.com/foreign-object-damage/)

FOD is a term frequently used in the aircraft industry to describe damage occurring on components as a result of non-regular operating conditions. For instance, aircraft operating on a runway have the potential to ingest rocks and debris into the engine intake systems. Upon ingestion, the debris may damage the engine blades leading to dents, nicks, and partial fractures. These FOD induced defects can lead to poor performance, but more concerning, is unanticipated failure via fatigue cracking from stress concentrations. Processing via laser peening induces such deep residual stresses that FOD concerns can be reduced to negligible concern.

SENSITIZATION

Certain alloys commonly in use, especially 5xxx series aluminum, can develop sensitization, making them more vulnerable to stress corrosion and cracking. High temperatures can promote an electrochemical reaction in which alloy particles – e.g. magnesium or iron – migrate to the boundaries between grains of aluminum or stainless steel. This promotes separation of individual grains of metal, causing intergranular corrosion and cracking. Exposure to saltwater can further promote corrosion of sensitized metals.  Laser peening does not treat sensitization itself, but it can impart compressive residual stresses in order to mitigate the resulting corrosion and cracking, even after some metals have experienced sensitization.

STRESS CORROSION CRACKING

Stress corrosion cracking (SCC) is a failure that occurs when three factors interact: a tensile stress, a susceptible material, and a corrosive environment. Similar to fatigue, these cracks frequently initiate at the surface at stress levels significantly below material capabilities. Because laser peening induces compressive residual stress at the surface of a part, the potential for SCC is drastically reduced and even eliminated.

CORROSION AND CORROSION FATIGUE

By inducing compressive residual stresses on the surface of metal components, the electrochemical potentials necessary for corrosion to occur are increased and current density decreases. By modifying the surface of components with laser peening, the risk of operating in a corrosive environment can be mitigated and even eliminated for many materials.

[METAL FATIGUE FAILURE](https://www.lsptechnologies.com/how-to-improve-fatigue-life-of-metal/)

Metal [fatigue failure](https://www.lsptechnologies.com/what-is-fatigue-failure/) is when the surface of a metal experiences cyclic loading and begins to crack or fracture, causing the part to weaken. Laser peening specializes in achieving beneficial compressive residual stresses at a depth that is unmatched by conventional metal surface treatments. This is important because fatigue strength improvements are directly related to the magnitude of depth where compressive residual stresses appear.

EROSION

Erosion can occur on components due to a flowing media. This can be a result of wind, water, and compounds carried by these different media types.  Hardening of the surface by laser peening helps to prevent material removal via erosion. This can be a significant cost savings for propellers, blades, and other components subjected to erosion concerns.

CAVITATION

Damage occurring on components operating at high speeds in fluid is often a result of cavitation. The cavitation occurs as high pressures between the fluid and component and results in the formation and collapse of a small air cavity; basically, a bubble. Modifying the surface of the component with laser peening increases the material strength locally at the surface and can aid in the resistance of the material to damage from the bubble collapse.

HYDROGEN EMBRITTLEMENT

Hydrogen embrittlement is a particularly concerning method of failure due to the random and unpredictable nature it presents. During certain processes and in certain environments, hydrogen atoms will migrate into a material structure. These hydrogen atoms can stay in the materials crystal structure or migrate to areas where they are able to combine and form. The hydrogen atoms, or molecules, can severely weaken the material leading to unexpected cracking and lower material strengths. Laser peened surfaces present a large compressive residual stress field that reduces the permeability of the component surface to hydrogen.

GALLING

Although not often a failure mode in itself, galling can cause significant problems in machinery and lead to other failure mechanisms. Galling occurs when adhesive forces on two metal surfaces work to tear fragments of the mating surfaces apart. Galling is frequently seen on stainless steel and titanium alloys, but can also be found on other base alloy systems including nickel and aluminum. Laser peening the surface of mating components helps increase the material resistance to galling by cold working the surface and inducing compressive residual stresses.

FRETTING

As metal surfaces slide against one another they frequently generate abrasive compounds. With continued relative motion, these abrasive compounds score the surface and give rise to even more wear, called fretting. As the fretting continues it can lead to corrosion, further wear, or fatigue cracking from fretting damage. By cold working the surface of metal components with laser peening, the residual stresses reduce the fretting mechanism of wear.

MICROSTRUCTURAL POROSITY

Additive manufacturing (AM) creates metallic parts by laying down fused layers of powdered metal alloys and fusing them together with a laser or electron beam, as in powder bed fusion (PBF). But PBF, like other additive manufacturing processes, results in microstructural voids or bubbles in the metal. This porosity has the potential to create mechanical weaknesses in the AM part, and materials scientists have found[laser peening can compensate for porosity](https://www.lsptechnologies.com/resources/additive-manufacturing-parts-obtain-10-15x-life-exension-from-laser-peening/) with compressive residual stresses.

Composites

The term composites now cover a wide range of existing and emerging engineering materials. Different types of composites exhibit a wide variety of failure mechanisms. However, a common feature of these diverse materials is their inhomogeneous and frequently markedly anisotropic nature, resulting in fracture behaviour unlike that of conventional metallic alloys. As a result, current fracture mechanics-based analyses and test procedures are often found to be unsuitable for describing the behaviour of composites. Some of the important features of the fracture processes which occur in composites are described in this article. Understanding damage accumulation pro- cesses is an exciting challenge to materials scientists and engineers.

Polymer matrix composites, particularly in the form of laminates, have become established as engineering materials in many failures’ critical applications, for example in aerospace, in transport generally and in chemical plant. New areas of application, eg offshore, are being actively sought, and recent material developments include high temperature and thermoplastic matrices. Despite all these advances, the definition of failure in a fibre reinforced composite, and the monitoring and prediction of component life, remain major problems.

The difficulties arise because, in most situations, fibre reinforced materials do not fail by the initiation and propagation of a single dominant crack. During service, damage accumulates throughout the material until it reaches some 'critical' level, which might be determined by an unacceptable drop in modulus, or by complete separation in certain load-controlled situations. Even when complete separation into two or more parts occurs, the failure process is complex.

The reasons for the non-localised accumulation of damage throughout the material are the statistical dependence of the strength of the brittle reinforcing fibres (eg glass and carbon) and the different properties of the matrix, reinforcement, and interfacial regions,

Unidirectional composites In a unidirectionally reinforced material, eg a pultruded rod, the types of damage which occur involve fibre fracture, inter- facial debonding and matrix cracking. The stiff, brittle fibres are 'Griffith' materials. Fibre fracture initiates from surface defects, and the fibre strength distributions can be modelled using Weibull statistics. The longer the fibre, the lower the strength because the more likely it is to contain a defect of a particular size. The distribution of defects means that within a group of fibres the weakest points in neighbouring fibres are unlikely to be adjacent to each other. When fibre fracture occurs within a composite, the damage can spread in several ways. Where an extraordinarily strong fibre/ matrix bond is combined with a brittle matrix, the effect of stress concentration at the crack tip can cause the crack to propagate across the whole section. This is an unusual situation in polymer composites, and one which must be avoided in ceramic matrix systems where the main function of the reinforcement is to provide toughening. Alternatively, the matrix around the crack can yield (thus blunting the crack and reducing the stress concentration) and/or shear failure can occur in the interfacial region, allowing the unloaded fibre to start to shrink back into the matrix. Which of the three mechanisms occurs will depend on the relative values of the stresses σ1, σ2 and τ developed at the crack tip, and on the fibre breaking strength, matrix shear strength and interfacial shear and tensile strengths. In polymer matrix systems interfacial shear failure usually occurs, to an extent determined by the interfacial strength and the energy released when the fibre fails.

Diagram

Description automatically generated

Figure 13: Fibre failure propagation: a brittle cracking of matrix (high interfacial strength), b shear yielding of matrix, c interfacial failure, d propagation of fracture involving a and c.

iii) Turbine Blades – creep

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.

Engine degradation

Gas turbines (GTs) can be found in many applications in such critical industries as aviation, power generation, oil and gas production and process plant as well as smaller related industries and even domestically. The power generation applications include offshore platforms and marine use where minimizing weight is a major consideration and the GTs used are usually aero-derivative engines. With land-based industries GTs can be used for either direct drive or mechanical drive application. Normally operation for GTs in aviation is about 2000h before inspection of turbine components, and often more than 5000h before overhaul. GTs for power applications can operate for considerably longer periods before inspection and maintenance due to the difference in safety factors between aviation and industrial/marine applications. Depending on the manner of operation and the working environment, GT components are subjected to different temperature and stress levels, and these differences cause different GT components to fail in different ways: e.g. creep, oxidation, corrosion, or fatigue. During service, industrial, marine, or aero, engine failures can exist individually or in combination, and vary with application. Although life techniques for hot section components have been studied for the last three decades, understanding failure mechanisms with related driving factors to estimate the lifting of hot section component requires further attention. Failure of a GT engine component is defined as any change in the size, shape and/or mechanical properties of the component that makes it unable to continue to satisfactorily perform its design functions. Failure mode is defined as a physical or chemical process which singly or in combination produces component failure.

GT engine performance degradation is one of the most important concerns for manufacturers and operators. There are different types of component degradation mechanisms such as fouling, erosion and corrosion. The physical degradation of components and the consequences for the engine performance and life will vary. For example, sand particles deposited on the compressor blades can cause compressor fouling and erosion, though erosion is probably more of a problem for aero engine application, since the state-of-the-art filtration system used for industrial and marine application will invariably eliminate large particles. Fouling will change blade and annulus dimensions causing reduction in mass flow, blade erosion will change blade geometry, boundary layer and aerodynamic profile and, through metal loss, will result in a drop in the compressor efficiency.

GT degradation results in lower component efficiencies and reduction of available power which usually requires higher fuel flows and increased Turbine Inlet Temperature (TET) to maintain the required thrust or power. However, due to the limitations of the materials used and air-cooling technologies available the TET cannot exceed a certain point. Increasing the TET with given operating conditions and working environment will quickly detract from the life of the hot section components.

Common failures in gas turbines

During service in a corrosive environment under high stress and high temperature, turbine components such as NGV, blade and discs suffer from cumulative damage. This gradually degrades their mechanical properties and may cause component failure. Indeed, new failure modes are being discovered with the increasing demand for modern engines to operate at higher temperature and stresses, combined with the use of new materials and new cooling technology systems.

Most of the turbine hot section components An Evaluation of Operation and Creep Life of Stationary Gas Turbine Engine 13 are classified as critical components because the consequences of failure could be catastrophic to machine and personnel.

Naturally, those GT engine parts operating under the most extreme conditions of temperature and stress show the most failures, see Table 2-1. Understanding these failure mechanisms and their driving factors are especially important in evaluating the life of hot section components.

Different GT engine applications and their different influences on damage mechanisms. Land based GT engines for most of their time are operated at known conditions and therefore can operate for long periods of constant load (speed) coupled with a high operating temperature. For this reason, land-based engines are more susceptible to creep than fatigue or oxidation. On the other hand, helicopter engines with frequent start-up and shut-down cycles, and change of flight profiles, makes fatigue more dominant. Marine engines work in an environment where the air ingested into the engine contains higher concentrations of salt and during combustion sulphur from the fuel reacts with the sodium chloride to form sodium sulphate which will then be deposited on the hot section components resulting in accelerated corrosion attack.

Table

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Car Crankshaft – Fatigues

Typical approaches of Fatigue Analysis

There are several approaches to predict the fatigue life of the components subjected to cyclic loads. The three wellknown approaches used to predict fatigue life are the stress life (S-N), the strain life (E-N), and the linear elastic fracture mechanics (LEFM). The S-N method depends on nominal stress life using counting the cycle of the rain flow. This approach can be useful for measuring fatigue life. However, the drawback of this approach is that it does not consider the effect of plasticity and that it provides low precision for the components subjected to the low cycle fatigue (Metkar et al., 2011). The strain life approach considers the effect of the plasticity and gives a more effective than the S-N method, especially in low cycle fatigue. The mechanics of a linear elastic fracture assumes that a crack already exists and recognizes it by considering the stress intensity factor and predicts the crack growth. The stress life approach is the most employed due to its ease of implementation and variety of data available.

Crankshaft is the vital part of an engine crankshaft was reciprocating motion of piston and to rational motion crankshaft have more complex geometry experiences large number of load cycles during its service life therefore balancing fatigue performance and durability or key consideration in crankshaft design during service life crankshaft operates at high poses resulting from gases combustion and inertia force these forces acting on the crankshaft causes 2 types of fluctuating loadings torsional load and bending load pins crankshaft requires high torsional and bending fatigue strength and better balancing characteristics to serve safely during its service life designers of modern internal combustion engines are facing the challenge of reducing the environmental pollution to meet stages pollution control regulation all over the world end row mental pollution can be reduced through improving engine efficiency in addition the designers are also required to reduce the weight and overall dimension of the engine to make them more and more compact to increase the power and RTM development of lightweight compact high pressure and high rpm engine depends and demands a crankshaft with better dynamic balancing characteristics with high fat IK strength this result into lower end vh levels rate reductions in bearing and engine block loads along with improved engine performance

there are closed die forging and casting crankshaft for an automobile engine and die forging is mainly used for engine that need the high strength or rigidity however in recent years the poses to act and crankshaft becomes higher because high performance required for engines when all balance weights are uniformly small the main bearings or damaged by increase of bearing load and engine vibrations hens crankshaft counter weight configurations plays significant role in Gran shaft balancing bearing and engine block life crankshaft balancing is the term used to describe changes made in counterweights to compensate for weights of the moving components including the crankshaft and the components attached to it the counterweights are cast or forged in place when crankshaft is formed and the balancing is required to remove some amount of material from the counterweights until the amount of unbalance is within acceptable limits

unbalance is defined as the unequal distribution of mass with rotor about its rotating center align the amount of unbalanced rotating body is normally expressed as the product of the residual unbalance mass and its distance from the central line therefore a general unit of expressing unbalance in grams the output of the balance force and centrifugal force these forces pull the crank towards the bearing as it rotates this cause he premature bearing we are loss of power and damaging vibrations the international standard organization defries unbalanced as that condition which exists in rotor go and vibrating force or motion is imported to which bearing as a result of centrifugal force the rotating center align being defined as the axis about which the rotor would rotate if not constrained by its bearing the geometric center align is being the physical center align of the motor when the 2 center align or coincident then the rotor will be in a state of balance when they are upper the rotor will be unbalanced during the balancing process when the unbalance has been identified and quantified the correction can be done by either adding or removing the material from rotating elements the ultimate aim being to reduce the uneven mass distribution so that this centrifugal forces and hence the vibration reduced in the supporting structure or at an acceptable level

the amount of forces create by unbalanced it depends on speed of rotation and the amount of unbalanced force generated by the unbalance can be calculated by the formula

F = mrw2

where F is the centrifugal force, M is mass r is distance of center of gravity from axis of rotation and w is angular speed

Diagram

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Figure 15: Rotor Shaft

Crankshaft balancing is the important part of today’s engine development activity. In this study balancing analysis was carried out by using in-house developed balancing software and its initial unbalance mass and position was predicted. After forging and machining the crankshaft, the actual balancing was carried out using balancing machine. The results had shown that, the actual position of unbalance was deviated from predicted due to machining stock distribution in non-favorable direction during forging process. The actual unbalance position was in such a direction that, there was complex counterweight profile available for removal of material. Due to this, the balancing of such crankshafts was difficult. To correct this, counterweight profile was optimized in such a way that, position of initial unbalance lies at the center of counterweights. With this optimized design the crankshafts were produced and the results shown good correlation between the predicted and actual position of unbalance. With this unbalance position the balancing was achieved with maximum 6 numbers of holes which is within target limit.

3D CAD model of the 6 cylinder crankshaft was created in Unigraphics NX7. Balancing analysis was carried out by using Dual plane method. One plane is passing through center of main journal 1 and normal to the axis of crankshaft called as tail side unbalance plane. And normal to the axis of crankshafts called as flange side unbalance plane. These tail side and flange side planes are called as unbalance measurement planes as shown in Figure 14.

Amount of initial unbalance measured on flange side and tail side is shown in Figure 3 and Table 1. To remove the initial unbalance on flange and tail side, depending on unbalance angle, the holes are drilled on respective counterweights. Total 6 numbers of holes are drilled to reduce the unbalance up to the acceptance limit

A picture containing chart

Description automatically generated

Figure 14: Unbalance measurement plane

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Tail side | | Flange side | |
| unbalance | angle | unbalance | angle |
| Initial Design | 60 | 135 | 75 | 140 |

After forging and machining the crankshaft, balancing was carried out using balancing machine. Due to uneven stock distribution during forging process, it was observed that, tail side initial unbalance mass was up to 60 g and angle was not at center of end counterweight.

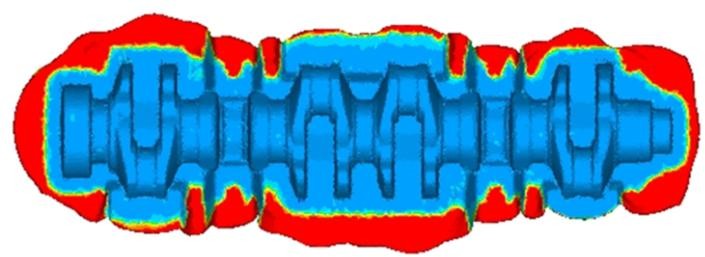
After balancing, one of the important stage in the product development is the fatigue testing to ensure the required bending fatigue strength of crankshaft. Fatigue strength is the mean stress level at which component have 50% probability of failure and 50% pass. The test was carried out according to staircase method by inducing expected stress level at pin fillet. First specimen was tested at a stress level close to expected endurance limit of crankshaft until it either fails or runs out at the expected life (in this case it is 5m cycles). If the specimen fails at that stress level, the same is reduced by a preselected step and the new specimen is tested at new stress level. If the specimen passes the required life at a particular stress level, the same is increased by a preselected step and the second specimen is tested at this new stress level. In this way 10 specimens were tested. Using statistical approach fatigue strength is evaluated.

According to the acceptance criteria and as per the design requirement, crankshaft has to resists 5 x 106 cycles without failure so it was tested for the said number of cycles. But during the fatigue testing, crack initiation occurred before this load cycle limit. It was observed that, premature crack was observed in the abnormal location i.e. pin bevel after 1 million cycles

However critical locations on the crankshaft geometry are all located on the fillet areas because of high stress gradients in these locations which result in high stress concentration factors (7). Hence the expected failure region in bending fatigue test in most cases in pin fillet and in some cases in journal fillet.

## Re-Engineered Design – Forge ability Validation

With modified counterweight profile, it is necessary to ensure forging feasibility of crankshaft. Metal flow simulation was carried out by using high end software Forge 2007. Forging die models were generated by using Unigraphics 3D modeling software. Die models were meshed in Hypermesh. Die and billet mesh models imported in Forge software. Process parameters such as friction, temperature, lubricant were defined as per actual working conditions. Press parameters such as R/L ratio (R is crank radius and L is pitman arm length), maximum available energy were defined. The analysis completed with high speed supercomputing cluster. Crankshaft forging simulation was carried out in successive steps i.e. reduce roll, blocker and finisher. Reduce roll was optimized as per metal requirements of die cavities. Output deformed shape of each operation used as input for subsequent operation. During analysis, metal fill up was analyzed



## Bending Deflection and Bearing Load Evaluation

Fig. 15 Re-engineered crankshaft design metal flow analysis

When a crankshaft rotates with given rpm, generated centrifugal force causes bending deflection in crankshaft. Counterweight profile has significant effect on bending deflection and bearing load of crankshaft. This analysis was carried out by using ANSYS. In FEA for evaluation of bending deflection, bearings were mounted on first and last journal and crankshaft rotated with 2500 RPM. Due to centrifugal forces, bending deflection occurs in crankshaft. Bending deflection for modified design

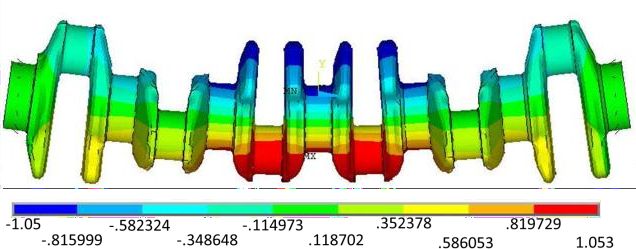


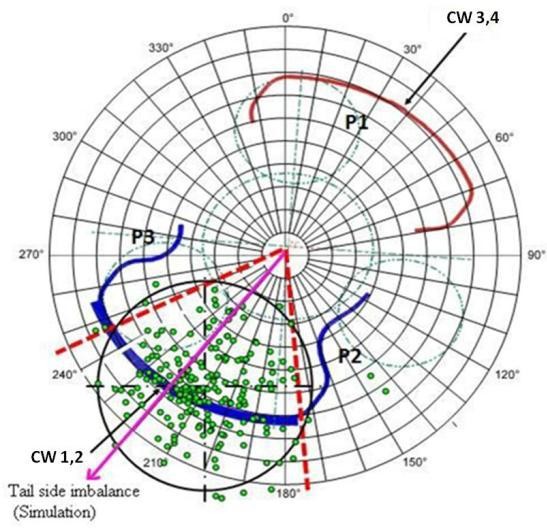
Fig. 16 Crankshaft Bending Deflection (mm)

Fig. 17 Re-engineered design - Tail side unbalance (Actual)

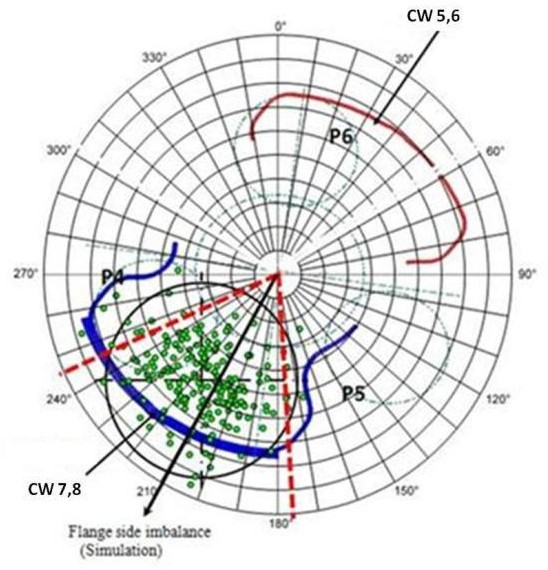


Fig. 16 Re-engineered design - Flange side unbalance (Actual)

**Boat hull – Uniform Corrosion**

Corrosion of a ship hull that began after continuous failure of the impressed current cathodic protection system. The purpose of this article is not to question or criticise the design, installation, maintenance, or operation of the cathodic protection system, but only to show through the inspection carried out that the main aspects of the corrosive process that occurred when it was anchored for more than six months. In order to leave the ship in normal operating conditions, repairs were conducted that consisted of cleaning with pressurised water blasting, welding repair of corroded plates, paint application, and installation of zinc anodes in cathodic protection replacement.

The study of corrosion and anti-corrosion protection technique development began in the 19th century and continues to this day. However, corrosion and corrosion protection are known to be associated with a range of disciplines extending from chemistry to human behaviour. Corrosion is defined as the deterioration of material by chemical or electrochemical actions of a corrosive medium. Due to this, corrosion is a permanent challenge to man, because when more science creates and develops and the technology applies and advances, the more she finds spaces and ways of doing this. Generally speaking, we can say that a corrosive attack carries considerable costs, which may, in certain cases, include environmental pollution, compromise the operational safety of the equipment, and promote catastrophic accidents and the loss of human life.

The interaction between biological activity and steel performance is very important in seawater. Depending on the contact time, the macro fouling, such as barnacles and mussels, can be either protective or result in accelerated corrosion depending on the area of steel exposed and the extent of the amount of biological fouling. The corrosion of carbon steel in seawater can occur under various forms: localised, generalised, plates, pitting, and considering the properties of seawater are common, the occurrence of corrosion by differential aeration, crevice corrosion, and corrosion under deposits.

Anticorrosive protection of ships and maritime facilities is generally accomplished through cathodic protection by application of coatings that resist the aggressive action of seawater. Currently, the cathodic protection of ships is made of cathodic protection with galvanic anodes (aluminium or zinc) or impressed current cathodic protection. Cathodic protection of small boats is simple, but medium and large ships are more complex and require very specific plans.

The principles of this technology come from the past. It is believed that the first ship to use the cathodic protection was during the Sammarang Sea voyage to Nova Scotia in 1824–1825

Systems using galvanic (sacrificial anodes) for current cathodic protection are provided by the potential difference that exists between the galvanic anode (aluminium, magnesium, or zinc) and the carbon steel structure. In cathodic protection of a metallic structure, the flow of the electric current is provided by the potential difference between the metal surface to be protected and the anode, which has a more negative potential, according to the following electrochemical reactions:

Anodic: Zn – 2 e- → Zn2+

Cathodic: H2O + ½ O2 + 2 e- → 2 OH- (aerated seawater)

In the case of cathodic protection of the stern (back zone, where the propeller, which is usually made from bronze, is located) with zinc anodes requires a higher number of anodes than the bow to prevent galvanic corrosion

Problems associated with corrosion due to seawater have been studied for many years, but despite the published information about the behaviour of materials in seawater, failures still occur. The corrosion rates of carbon steel range from 0.20 to 2.0 mm/year depending on several factors, such as oxygen, pH, contaminants, macro-, and micro-organisms. Some of these factors are interrelated and depend on physical, chemical, and biological variables, such as depth, temperature, nearby rivers, contamination by industrial effluents, and the availability of nutrients



Figure 16 – Aspects of galvanic anodes disposal in the stern and the bow

In impressed current cathodic protection, buried metal structures receive the protection current from an external source or current rectifier installed on the surface, and using a set disperser current in the electrolyte, which consists of an inert anode. The inert or nearly inert anodes can be made of graphite, iron-silicon alloys, platinum clad titanium, or 2% silver-lead. The source of the electrical current from by the rectifier converts AC power into a DC current and injects this into the medium by means of inert anodes, whose selection depends on several factors, such as cost, useful life, conductivity, and resistivity of the corrosive medium.

Figure 17 shows the system of protection using inert anodes for the protection of the ship hull (carbon steel). Currently, the use of impressed current cathodic protection are favoured for protecting the hulls of medium and large ships based on three important factors: the development of direct current rectifiers that are more compact and efficient, continuous monitoring of the potential for corrosion protection, and automation of current injection based on the critical condition of seawater. It is important to manage the corrosive process because, when the ship is at sea, aggression increases as a function of salinity and the speed of the ship, while when anchored, the hull is exposed to fresh water or effluents, which may modify the conductivity of the medium

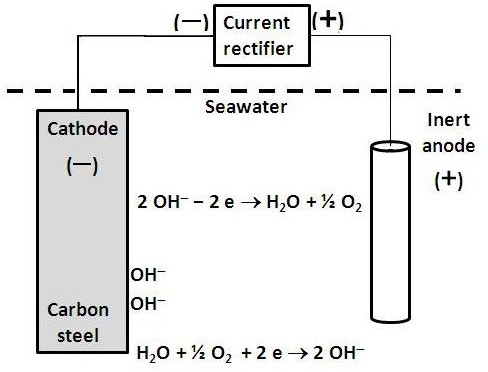


Figure 17 – Carbon steel protected by impressed current cathodic in aerated seawater

Figure 18 shows the system of protection by inert anodes for the ship hull (carbon steel) protection using a control unit based on a reference electrode.

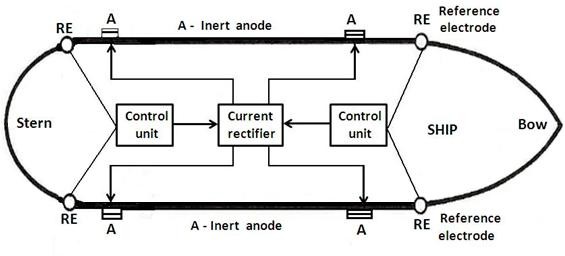


Figure 18 – Ship protection scheme with impressed current cathodic

The most commonly used anodes for ship protection projects are platinised titanium and lead-antimony-silver alloys. The reference electrodes (RE) are, normally, made of zinc and are meant to determine the potential of the hull. When connected, the control unit automatically provides information for the rectifier to inject by inert anodes the amount of current required to anti-corrosion protection of the hull ship

The inspection of the ship revealed that 80% of the hull was compromised by corrosion on several levels, from the surface corrosion until the perforation of the carbon steel plate. Repair of ship's hull consisted of the pressurised water blasting, welding, and repair of the damaged carbon steel plates. Considering the existing past problems with the impressed current cathodic protection system that failed and compromised the hull has been chosen by galvanic zinc anodes system. Blasting with pressurised water and installation of zinc anodes are presented in Figures 7 and 8. The total cost to repair the ship was valued at $ 85,000.



Figure 19 – Blasting with pressurised water and installation of zinc anodes



Figure 20 – Blasting with pressurised water and installation of zinc anodes

iv)

Low-carbon/medium nitrogen 316 stainless steel called 316FR is a principal candidate for the high-temperature structural materials of a demonstration fast reactor plant. Because creep-fatigue damage is a dominant failure mechanism of the high-temperature materials subjected to thermal cycles, it is important to establish a reliable creep-fatigue life prediction method for this steel. Long-term creep tests and strain-controlled creep-fatigue tests have been conducted at various conditions for two different heats of the steel. In the constant load creep tests, both materials showed similar creep rupture strength but different ductility. The material with lower ductility exhibited shorter life under creep-fatigue loading conditions and correlation of creep-fatigue life with rupture ductility, rather than rupture strength, was made clear. Two kinds of creep-fatigue life prediction methods, i.e. time fraction rule and ductility exhaustion method were applied to predict the creep-fatigue life. Accurate description of stress relaxation behaviour was achieved by an addition of 'viscous' strain to conventional creep strain and only the latter of which was assumed to contribute to creep damage in the application of ductility exhaustion method. The current version of the ductility exhaustion method was found to have particularly good accuracy in creep-fatigue life prediction, while the time fraction rule overpredicted creep-fatigue life as large as a factor of 30. To make a reliable estimation of the creep damage in actual components, use of ductility exhaustion method is strongly recommended.

For dealing with the situation that creep-fatigue life properties of materials do not exist, a development of the simple method to predict creep-fatigue life properties is necessary. A method to predict the creep-fatigue life properties of Cr-Mo steels is proposed based on D. Diercks equation which correlates the creep-fatigue lifes of SUS 304 steels under various temperatures, strain ranges, strain rates and hold times. The accuracy of the proposed method was compared with that of the existing methods. The following results were obtained. Fatigue strength and creep rupture strength of Cr-Mo steel are different from those of SUS 304 steel. Therefore in order to apply Diercks equation to creep-fatigue prediction for Cr-Mo steel, the difference of fatigue strength was found to be corrected by fatigue life ratio of both steels and the difference of creep rupture strength was found to be corrected by the equivalent temperature corresponding to equal strength of both steels. Creep-fatigue life can be predicted by the modified Diercks equation within a factor of 2 which is nearly as precise as the accuracy of strain range partitioning method. Required test and analysis procedure of this method are not so complicated as strain range partitioning method.

To validate the applicability of the proposed multi-axial creep-fatigue life prediction procedure, a series of fatigue and creep-fatigue tests were carried out at 650 °C for uniaxial uniform and notched specimens made from nickel-based GH4169 superalloy. After that, metallographic observations were performed through the electron backscatter diffraction (EBSD) technique to characterize crack initiation sites of the notched specimens undergoing various loading conditions. Firstly, rough machining cylindrical bars were extracted from the as-received disk using the electrical discharge machining wire Page-8- cutting (wire EDM). Then, a standard heat treatment (HT) was carried out to ensure the optimized distributions of Ni3Al type γ' and Ni3Nb type γ" strengthening phases. The detail of the standard HT is listed as follows: solid solution at 960 °C for 60 min, air cooling (AC) to room temperature (RT), aging at 720 °C for 480 min, furnace cooling to 620 °C for 120 min, aging again at 620 °C for another 480 min, and then AC to RT. Finally, the uniaxial uniform and notched specimens were machined from the above-mentioned heat-treated specimens (HTS), the detailed dimensions of which are, respectively. The uniaxial uniform specimens were fine machined from the HTS, in which the gauge length was polished using DiaPro Dac diamond suspension. For each notched specimen, a single edge notch with a radius of 8 mm was located at the center of the gauge portion by the additional wire EDM method after fine machining. The critical position of notch surface was polished up to a mirror surface to avoid the local stress concentration at the notch root.

Fatigue and creep-fatigue tests

Strain-controlled fatigue and creep-fatigue tests were carried out at 650 °C using a MTS model 809 A/T testing system. The input parameters for the uniaxial and notched specimens regarding the strain-controlled tests. Strain-controlled triangular loading waveforms were employed for pure fatigue tests, while tension-hold-only trapezoidal loading waveforms were employed for creep fatigue tests. Specimens U-1 to U-4 denote the uniaxial uniform specimens. which are used to determine the material parameters for the NUVCM. Detailed experimental procedures and loading conditions for the uniaxial uniform specimens have been reported in our previous work . Specimens N-1 to N12 represent the notched specimens The aims of this group are to prove the feasibility of the proposed numerical procedure in multi-axial creep-fatigue life prediction and to discuss the crack initiation mechanisms. Testing temperature, T , strain ratio, Rε , and strain rate, ε , were respectively set to be 650 °C, -1 and 0.4 %/s, which were the same as those for the uniaxial uniform specimens. Note that specimens N-1 to N-12 were subjected to global strain-controlled loading waveforms with a total strain range, t Δε , ranging from 0.6% to 1.0% Crack initiation life of all the specimens two ceramic rods of a high temperature extensometer were symmetrically attached to the gauge-length area of the specimen. The gap between the two ceramic rods was calibrated to be 25 mm before clamping both sides of each specimen. Hold times at the peak tensile strain period, h t , for each t Δε were selected to be 0s, 60s, 600s and 3600s. To study the crack initiation mechanisms of the notched specimens undergoing differing loading conditions, post-test examinations on creep-fatigue tests were conducted using the EBSD technique. After determining the crack initiation life of each notched specimen, the longitudinal cross section near the notch root was prepared by the wire EDM. With a combination of scanning electron microscopy (SEM) and high quality EBSD Kikuchi patterns, the crack initiation sites were captured by a CamScan Apollo 300 SEM equipped with a Hikari EBSD detector. The key factor for ensuring a high-resolution EBSD map is to remove residual stress as far as possible. To this end, a careful treatment was conducted as follows: SiC Foil #220 paper at 25 N force for 1 min with water-based diamond suspension, MD-Largo polishing disc at 25 N force for 4 min with DiaPro Allegro/Largo diamond suspension, MD-Dac polishing disc at 20 N force for 3 min with DiaPro Dac diamond suspension, and finally MD-Chem polishing disc at 15 N force for 15 min with oxide polishing suspension (OPS). After the sample preparation, Kikuchi patterns were collected by the Hikari detector and EBSD data were processed by the Oxford Instruments HKL Channel 5 and the Tango software

The main equations of the unified constitutive model developedDiagram

Description automatically generated

where the total strain t ε is separated into the elastic component e ε and inelastic component in ε , and the creep and plastic deformation are treated together as a uniform inelastic variable. Meanwhile, the linear elasticity obeys the Hooke’s law in which E and ν denote Young’s modulus and Poisson’s ratio, respectively. σ and trσ are the stress tensor and the trace of stress tensor, and I is the unit tensor of second-rank. In addition, in ε and p are the rate of inelastic strain and accumulated inelastic strain, respectively. s and α are the deviators of stress tensor and back stress tensor, respectively. F is the von-Mises yield function, K and n are the material parameters representing the viscous characteristics of the investigated material. Q0 is the initial yield stress, and R is isotropic deformation resistance reflecting the change of the yield surface size. (:) represents the inner product between second-rank tensors, and is the MaCauley bracket, which means that x = 0 when x Both have their advantages and limitations. For traditional power-law equation, the main advantage is that when the value of n is high enough, it can also describe rate-independent cyclic behavior. Moreover, the procedure to derive the consistency tangent modulus will be quite simple if the power-law equation is adopted, indicating good applicability