University of Technology

Mechanical Engineering Department

Inspection and Diagnosis in Power Plant

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2018-2019

Course Outline

Course Name:	**Inspection and Diagnosis in Power Plant**	**الفحص والتشخيص في محطات القدرة**	**اسم المقرر:**
Course Code:	**ME1494**	**همك/ 1494**	**رمز المقرر:**
Units:	**4**	**4**	**الوحدات:**

Hours per Week			الساعات الأسبوعية		
Theoretical	**Experimental**	**Tutorial**	**مناقشة**	**عملي**	**نظري**
3	2	-	-	2	3

Assessment criteria		معايير التقييم	
Final exam	**60%**	**%60**	**الامتحان النهائي**
Midterm exam	**15%**	**%15**	**امتحان نصف فصلي**
Quizzes	**10%**	**%10**	**امتحانات مفاجئة**
Lab	**10%**	**%10**	**درجة المختبر**
Continuous assessment	**5%**	**%5**	**تقييم مستمر**

Week	Contents	المحتويات	الاسبوع
1	**Introduction** • Difinition of Inspection, Monitoring and Diagnosis • Aims of Inspection, Monitoring and Diagnosis Activities. • The Required Skills of Inpection Engineer. • Applicable Codes and Standards for Inspection.	**المقدمة** • تعريف الفحص الهندسي , المراقبة والتشخيص • الهدف من فعاليات الفحص والمراقبة والتشخيص • المهارات المطلوبة من مهندس الفحص والتشخيص. • الأنظمة والمعايير المستخدمة في الفحوصات الهندسية	1
2	**Classification of Inspection Activities** • Inspection Activities During Design and Manufacturing • Inspection Activities During Unit Erection and Construction • On- Stream Inspection Activities • Inspection and Maintenance Activities During Programmed or Annual Units shutdown • Inspection and Maintenance Activities During Unit Emergency Shutdown	**تصنيف فعاليات الفحص** • فعاليات الفحص اثناء التصميم والتصنيع • فعاليات الفحص اثناء التنصيب والتشييد • فعاليات الفحص اثناء التشغيل • فعاليات الفحص والصيانة اثناء التوقفات المبرمجة الدورية • فعاليات الفحص والصيانة اثناء التوقفات الطارئة والاضطرارية	2
Inspection Methods		**طرق الفحص**	
3	**Non Destructive Examinations** • Visual Inspection - With Naked Eye - Using Tools (Bore Scope, Camera, magnifying glass) • Liquid Penetrant Inspection	**الفحوصات الغير اتلافية** • الفحوصات النظرية - بالعين المجردة	3

	• Magnetic Particle Inspection	- باستخدام الادوات (الناظور، كاميرات، عدسات مكبرة) • فحص السوائل النافذة • فحص الدقائق الممغنطة	
4	• Ultrasonic Technique - Thickness Measurements - Hardness Test. - Flaw Detection • Eddy Current Inspection - For Tubes Bundles of Heat Exchangers - For Welding Joints and Base Material	• التقنيات فوق الصوتية - قياس السمك - فحص الصلادة - كشف العيوب • الفحص بالتيارات الحثية - لحزمة انابيب المبادلات الحرارية - لوصلات الحام و المادة الاساس	**4**
5	**Radiographic Examination** - X-Ray Technique - Gama Detection **Infrared Inspection** • Hydrostatic Test for Pressure Vessel - Positive Pressure - Negative or Vacum Pressure	**الفحص الاشعاعي** - تقنية اشعة اكس - الفحص بالكاما **الموجات تحت الحمراء** • اختبار الضغط الاستاتيكي - الضغط الموجب - الضغط التخلخلي	**5**
6	**Vibration Analysis** • Principles of Vibration Analysis • Unbalance • Eccentric Rotor • Bent Shaft • Misalignment • Resonance • Rolling Element Bearings • Gearing Defects • Belt Defects • Flow-related Vibrations	**تحليل الاهتزازات** • مبادئ تحليل الاهتزازات • عدم الاتزان • انحناء المحور الدوار • عدم المحاذة • الرنين • الركائز التدحرجية • اعطال التروس • اعطال الاحزمة • الاهتزازات المتولدة نتيجة التدفق	**6**
7	**Destructive Examination** • Chemical Composition Aanlysis for Metals • Tensile Test • Bending Test • Impact Test • Fatigue Test	**الفحوصات الاتلافية** • التحليل مركبات للمعادن • اختبار الشد • اختبار الانحناء • اختبار الصدمة • اختبار الكلال	**7**

	• Creep Test • Hardness Test **Inspection Tools and Measurement**	• اختبار الزحف • اختبار الصلادة **ادوات الفحص والقياس**	
8	**Conditions Causing Deterioration or Failures** • Correction • Erosion • Effect of HighTemperture • Improper Selection of Materials and Equipment • Welding • Lubricant Oil	**الظروف المسببة للضرر والفشل** • التأكل • التعرية • تأثير درجات الحرارة العالية • الاختيار الغير صحيح للمواد والمعدات • اللحام • زيوت التشحيم	**8**
9 & 10	**Data Processing and Anlysis** • Signal Classification • Signal Conditioning • Time-domain Signal Analysis (Standard deviation, Entrop, Kurtosis and so on) • Frequency-domain Signal Analysis • Time-Frequency Signal Anlysis	**معالجة وتحليل البيانات** • تصنيف الإشارات • تحليل الإشارات باستخدام المجال الزمني • تحليل الإشارات باستخدام المجال الترددي • تحليل الإشارات باستخدام المجال الترددي-الزمني	**9 & 10**
11 & 12	**Data Acquisition (DAQ) Systems** • Sampling and Aliasing • Quantizing Theory • Analog-to-Digital Conversion • Digital-to-Analog Conversion • Virtual Instrumentation and Data Acquisition • Data Acquisition using Labview Programming • Wireless DAQ Systems • Wireless Sensor Network Topologies • Available Wireless technology • Introduction to SCADA System	**أنظمة جمع البيانات** • اخذ العينات والتعرج • نظرية التكميم • التحويل من التناظري الى الرقمي • التحويل من الرقمي الى التناظري • الأجهزة الافتراضية وجمع البيانات • جمع البيانات باستخدام برنامج اللابفيو • أنظمة جمع البانات اللاسلكية • انوع ألانظمة اللاسلكية • تكنلوجيا الأنظمة اللاسلكية المتوفرة • مقدمة الى نظام التحكم الاشرافي	**11 & 12**
Equipment Subjected to Inspection Activities		**المعدات الواجب فحصها**	
13	**Mechanical Equipments** • Heat Exchangers and Condensers	**المعدات الميكانيكية** • المبادلات الحرارية والمكثفات	**13**

	• Storage Tanks • Boilers (Water and Fired Tubes Boilers) • Rotary Equipment (Turbine, Pumps and Fans) • Pipe Lines and its Fittings	• الخزانات • المراجل البخارية • المعدات الدوارة • الانابيب وملحقاتها	
14 & 15	**Electical Generators** • Stator Frame and Casing Inspection • Stator Core Inspection • Stator Winding Inspection • Phase Connector • Coolers, Exchangers and Leak Inspection • Rotor Inspection • Auxiliaries Inspection • Stator Core and Winding Electrical Test • Rotor Mechanical and Electrical Testing • Seals, Bearing and Thermal Sensitivity Testing	**المولدات الكهربائية** • فحص هيكل الجزء الثابت و الغلاف • فحص قلب الثابت • فحص ملفات الثابت • طور الموصل • فحص المبرد، المغير و التسريب • فحص الجزء الدوار • فحص الاجزاء المساعدة • أختبار قلب الثابت و الملفات الكهربائية • الاختبارات الميكانيكية والكهربائية للجزء الدوار • اختبار مانع التسريب، كراسي التحميل و حساس الحرارة	**14 & 15**

References

1. Power Plant Equipment Operation and Maintenance Guide, by: Philip Kiameh, McGraw Hill, 2011.
2. Practical Acoustic Emission Testing, by: The Japanese Society for Non-Destructive Inspection, Springer, 2006.
3. Machinery Component Maintenance and Repair, by: Heinz. P. Bloch and Fred K. Ceitrer, Gulf Publishing Company, Houston,Texas, 2005.

Lecture One

1.1 Need for inspection

Testing is an essential part of any engineering activity. Inspection and testing must take place at many stages in the complex process of producing engineering materials. Much valuable information is obtained from these tests including data on the tensile, compressive, shear and impact properties of the material, but such tests are of a **destructive nature**. In addition, the material properties, as determined in a standard test to destruction, do not necessarily give a clear guide to the performance characteristics of a complex-shaped component which forms part of some larger engineering assembly.

Defects of many types and sizes may be introduced to a material or a component during manufacture and the exact nature and size of any defects will influence the subsequent performance of the component. Other defects, such as fatigue cracks or corrosion cracks, may be generated within a material during service. The origins of defects in materials and components are shown in Figure 1.1. It is therefore necessary to have reliable means for detecting the presence of defects at the manufacturing stage and also for detecting and monitoring the rate of growth of defects during the service life of a component or assembly. Generally, the types of test used can be broadly classified into two categories

a) tests to establish the properties of the material (destructive testing), and

b) tests to determine the integrity of the material or component (non-destructive testing).

1.2 Defects and Flaws

- All parts have “flaws” of some magnitude but the parts are not necessarily defective.

- A defective component is one that will not perform as required for the necessary time.
- A "defect" is a deviation from what is allowable.

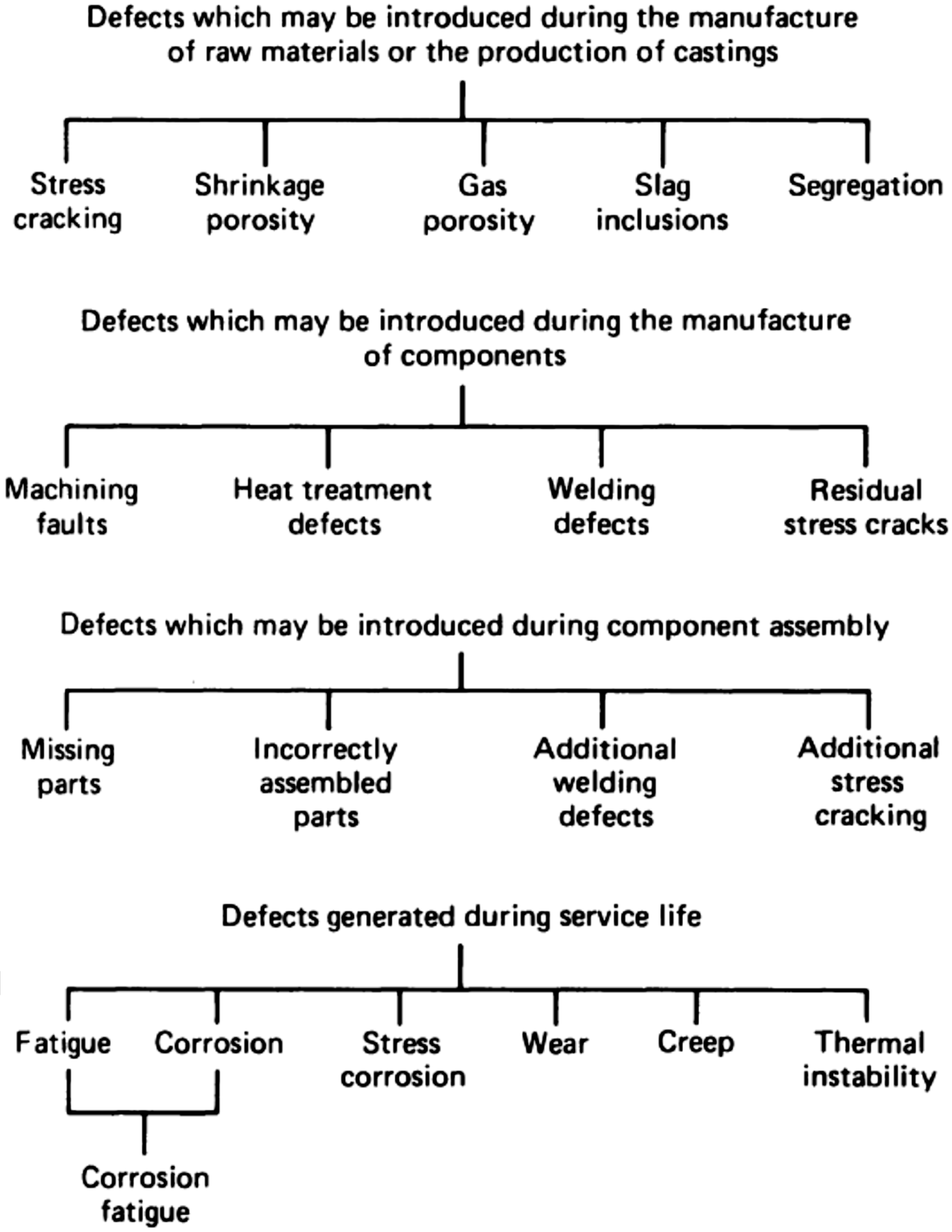


Figure 1.1: Origins of some defects found in materials and components

1.3 Failures, Faults and Errors

Failure is the termination of the ability of an item to perform a required function. A system failure occurs due to the failure of one or more of its components. Failures can be classified as follows:

Primary failure*:* A primary failure of a component occurs when the component fails due to natural causes (for example, aging). An action (for example, repair or replacement by a working unit) is needed to make the component operational.

Secondary failure*:* A secondary failure is the failure of a component due to one or more of the following causes*:* (i) the (primary) failure of some other component(s) in the system, (ii) environmental factors, and/or (iii) actions of the user.

Command failure*:* A command failure occurs when a component is in the non-working state because of improper control signals or noise.

Fault is the state of an item characterized by its inability to perform its required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. A fault is, hence, a state resulting from a failure.

Error is not a failure because it is within the acceptable limits of deviation from the desired performance (target value), as shown in Figure 1.2. An error is sometimes referred to as an *incipient* failure

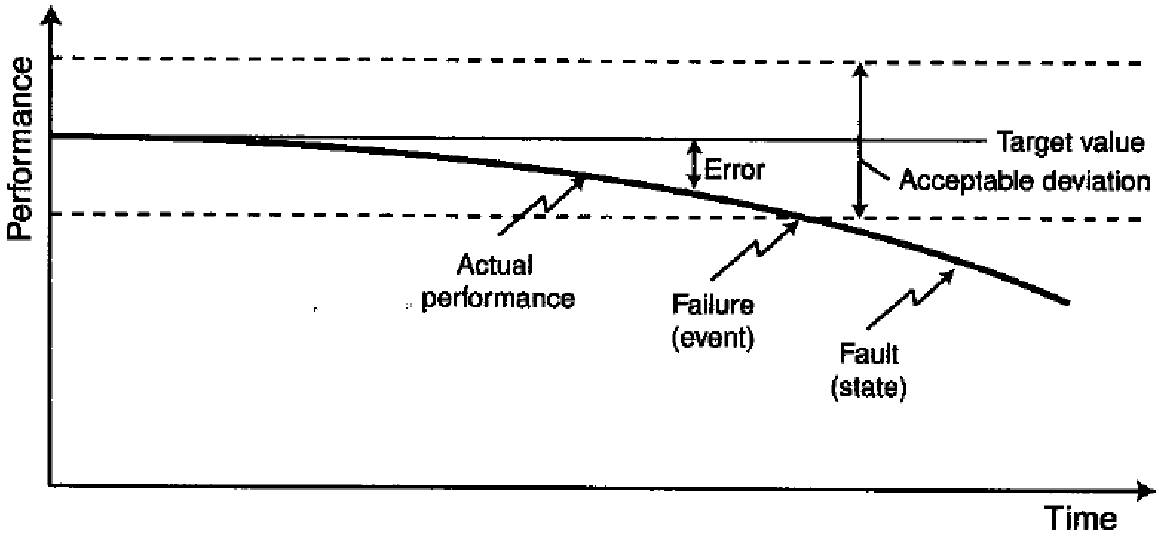


Figure 1.2: the difference between failure, fault and error

1.4 Classification of Maintenance Actions

Figure 1.3 shows an effective way of grouping the various maintenance actions into a multi - level hierarchy. At the first level we have (i) preventive and (ii) corrective maintenance. Each of these can be subdivided, as indicated in the figure, and we discuss them further in the next three sections.

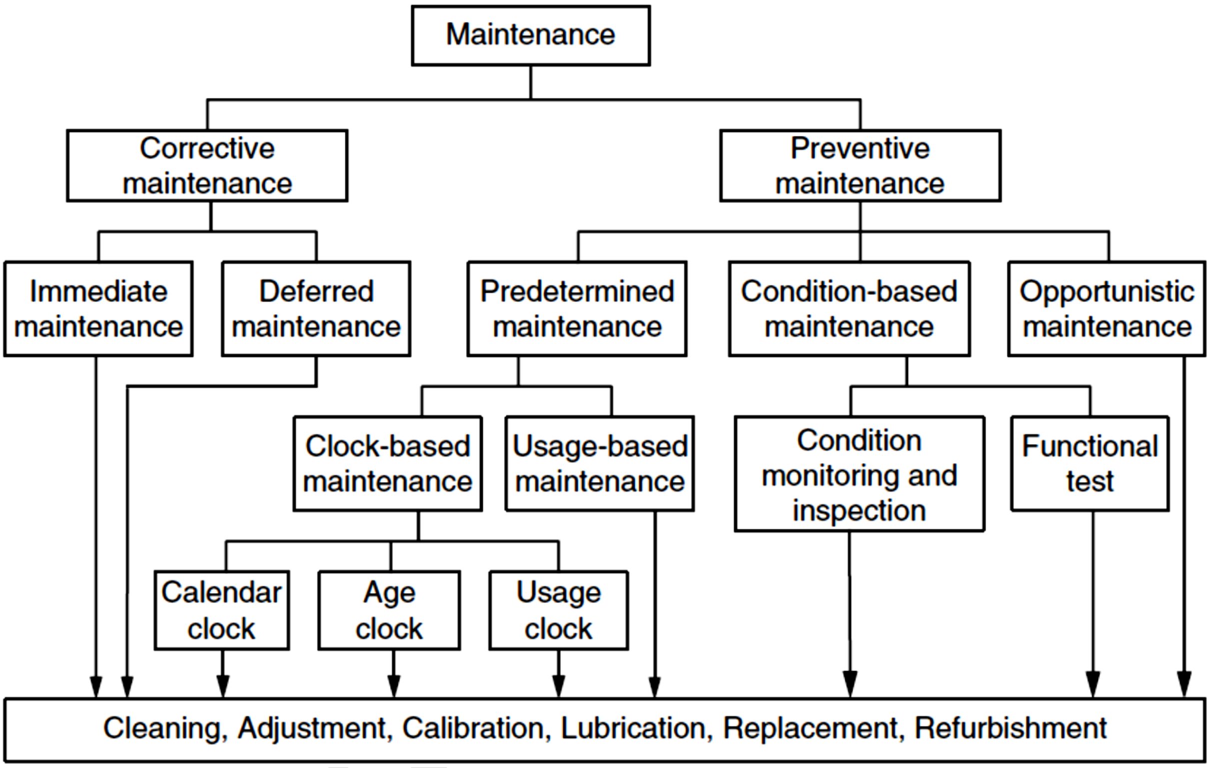


Figure 1.3: Classification of maintenance actions.

1.5 Preventive Maintenance (PM) Action

Preventive maintenance (PM) actions are carried out according to prescribed criteria of time, usage, or condition and are intended to reduce the probability of failure or the functional degradation of an item.

The aims of PM actions are to:

1- Prevent failure.
2- Detect the onset of failure: Whilst we may not be able to prevent a failure, frequently we do know how to detect the onset of failure. Our knowledge of how to do this is increasing every day, through condition monitoring technology.

3- Find hidden failures: Check to see if a failure has occurred before equipment is called into service.

PM actions can be grouped into **predetermined, condition-based maintenance**, and **opportunistic maintenance**, as shown in Figure 1.3.

1.5.1 Predetermined Maintenance Actions

A predetermined PM action has the following characteristics:

1- The action is carried out at discrete time instants determined by some predetermined rule.
2- The action timing involves either a clock or a measure of the usage.

Predetermined PM actions can be further divided into two subcategories: (i) **clock-based** and (ii) **usage-based**, as indicated in Figure 1.3.

- **<u>Clock-Based Maintenance Actions</u>**

This category has three further subcategories, as shown in Figure 1.3, which are:

1- ***Calendar clock****:* This is the familiar clock with a fixed starting time – start of a new year.
2- ***Age clock****:* Here, one uses the familiar clock which is set to zero when an item is put to use.
3- ***Usage clock:*** Here, one uses the age clock which stops when the item is not in use. An example of this is the usage clock which clocks the number of hours flown for an aircraft engine.

- **<u>Usage-Based Maintenance Actions</u>**

PM actions are based on usage of the item. Usage can be measured in different ways such as output (number of copies made by a photocopier, number of take-offs and landings for landing gear, number of tons produced, etc.).

1.5.2 Condition-Based Maintenance (CBM) Actions

In this type of maintenance action, the most important factor is the ability to identify **a measurable parameter** that provides a correlation between the measurement and the level of degradation. The selected parameter can provide either direct or indirect measurement of degradation. An example of indirect measurement is the monitoring of bearing degradation based on analysis of particle debris in the lubricating oil.

The parameter may be monitored continuously or at discrete points in time, **online** or **offline**, and in the case of monitoring at discrete points in time, the monitoring frequency needs to be determined.

Figure 1.4 illustrates the concept of CBM. The periodic monitoring of degradation occurs at time instants t_1, t_2, …. These are PM actions to assess the state. The inspection at time t_a (the first time after the alarm threshold is crossed) is the starting point of a CBM window. Note that t_p represents a possible time for CBM action and t_f is a failure time if CBM action has not been taken by that time. Beyond t_f a CM is required which is usually much **more expensive** than the preventive action to improve the state through some appropriate action.

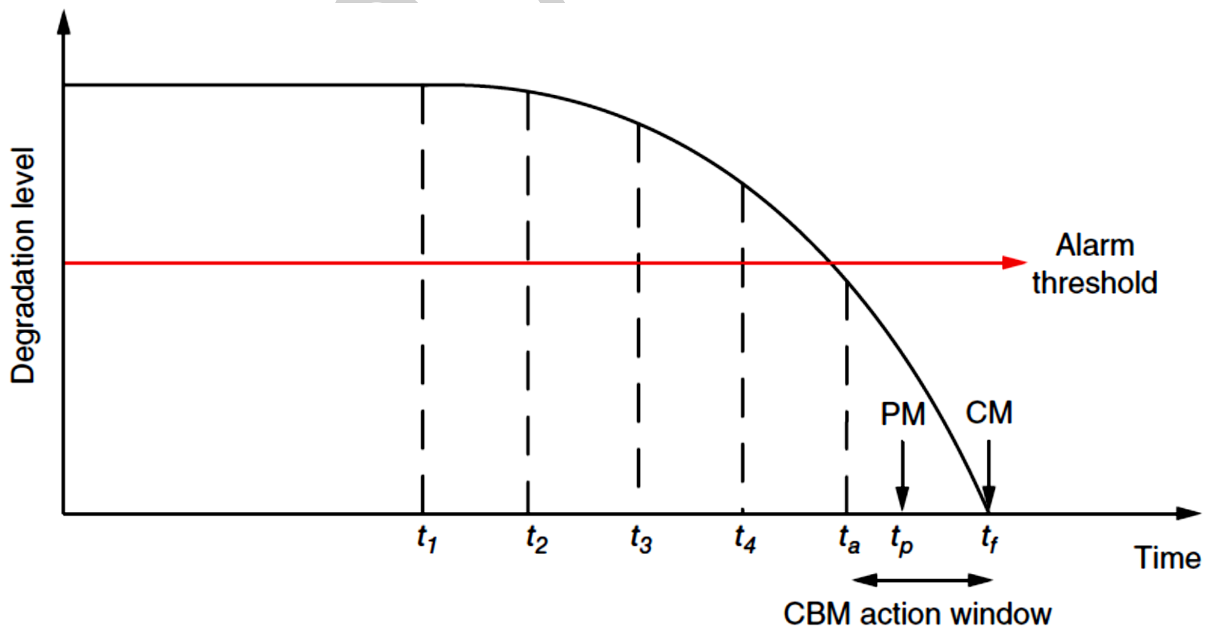


Figure 1.4: Concept of condition-based maintenance.

As shown in Figure 1.3, CBM actions can be further divided into the following two categories:

1- Functional tests.
2- Condition monitoring and inspection.

In both cases the data are analysed to assess the condition or state of the item. In the former case, the focus is on deciding whether to **take immediate action** (such as to repair or not) while the latter case involves **extrapolating the degradation into the future** (through trend analysis) and predicting when action might be needed. This allows some time for proper planning of maintenance activities and the necessary resources needed.

Predetermined PM actions are unable to avoid many item failures because they do not take into account the condition of the item. The only way of reducing the probability of failure is through early replacements. This results in the discarding of useful remaining life. With CBM the discarding of useful life is reduced and hence CBM is more desirable than predetermined PM. However, this is achieved at the additional expense of technologies (sensors for collecting data, data analysis, model building, etc.). Therefore, for expensive objects, CBM is the preferred option whereas for cheap objects, predetermined PM is more appropriate.

1.5.3 Opportunistic Maintenance Actions

Opportunistic maintenance actions are carried out at convenient moments which are unpredictable and they can be categorized broadly into the following two groups:

1- Internal to the object: Failure of a component providing an opportunity to carry out PM actions on some of the non-failed components.
2- External to the object: The object being in the idle state due to external factors (such as stopping the production due to running out of inputs) provides an opportunity to carry out PM actions.

1.6 Corrective Maintenance Actions

Corrective maintenance actions are actions carried out after fault recognition and are intended to put a failed item into a working state to perform its normal function. CM is unplanned and happens without notice. Based on the timing of CM actions, they may be classified into two categories: (i) immediate (emergency) CM and (ii) deferred CM, as shown in Figure 1.3.

- **Immediate CM** is corrective maintenance which needs to be carried out immediately after fault detection.
- **Deferred CM** is corrective maintenance which is not immediately carried out after fault detection but is delayed in accordance with given maintenance rules

1.7 Applicable Codes and Standards for Inspection

Standards are published documents that establish specifications and procedures designed to ensure the reliability of the materials, products, methods, and/or services that people use every day. There are standards for practically everything that can be measured or evaluated. Standards always represent an effort by some organized group of people. Any such organization, be it public or private, becomes the standardizing agency. Various levels of these agencies exist, ranging from a single business to local government to national groups to international organizations. The professional and industrial organizations that leads the development of standards relative to the field of NDT include:

1- The ASTM International, which is an abbreviation for the American Society for Testing and Materials.
2- The Society of Automotive Engineers (SAE).
3- The American Iron and Steel Institution (AISI).
4- The American Welding Society (AWS).
5- The ASME International, which is an abbreviation for American Society of mechanical engineers.

1.8 The Technical Skills of the Inspector

In order to feel confident in inspection situations it is necessary to have a technical understanding of a wide variety of engineering plant. Figure 1.3 is an attempt to summarize the skill-set of the in-service plant inspector. Look how it is constructed - the topics nearest the centre of the circle are those core activities of greatest importance to the in-service inspector, while those further from the centre are used in less depth, or less often. Now look at the radial sections of the diagram -it is divided into three technical sections and two non-technical sections.

The technical sections cover the topics of how plant is **manufactured**, **operated**, and then the **mechanisms by which it fails**. The remaining two sectors involve the two non-technical aspects: the tactics of inspection and understanding commercial realities. The tactics of inspection are a set of actions that make the task of in-service inspection more effective and help it to run more smoothly. In contrast, the skills relating to the commercial aspects are mainly passive – it is the understanding that is important, rather than any actions which necessarily result from this understanding.

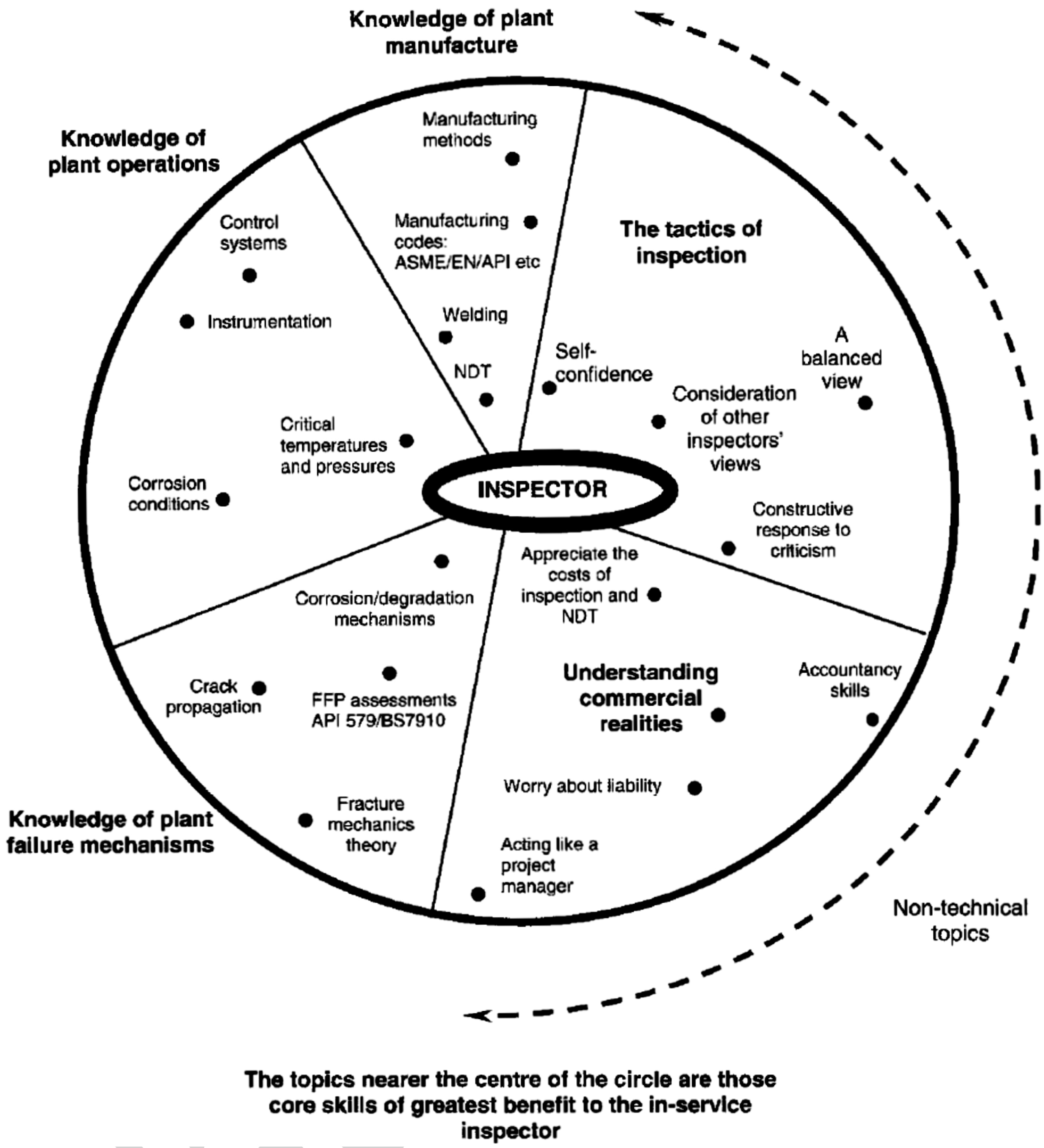


Figure 1.5: Skills of the in-service inspector

Lecture Two

Conditions Causing Deterioration or Failures

2.1 Failure Mechanisms

Failure mechanisms are physical, chemical, or other processes which lead to failure. Failure mechanisms depend on the type of component (electrical, mechanical, pneumatic, etc.), material (wood, metal, composite, plastic, glass, etc.), manufacturing processes (annealing, casting, machining, etc.) and the operating environment – load (electrical, mechanical, thermal, etc.), chemical properties (pH level of gas or fluid in a pipe network), and so on. There are different classifications of failure mechanisms, as discussed in Section 2.2.

2.2 Classification of Failure Mechanisms

Failure mechanisms can be grouped into two broad categories: **(i)** overstress mechanisms and **(ii)** wear-out mechanisms. In the former case, an item fails only if the stress to which the item is subjected exceeds the strength of the item. If the stress is below the strength, the stress has no permanent effect on the item. In the latter case, however, the stress causes damage that usually accumulates irreversibly. The accumulated damage does not disappear when the stress is removed.

There are many different failure mechanisms in each of the above two groups and some them are discussed as follows.

2.2.1 Overstress Failure Mechanisms

In this section, a qualitative characterization of the various mechanisms that may lead to overstress failures are discussed.

- **Large Elastic Deformation**

Elastic deformation typically occurs in slender items. Failure is due to excessive deformation under overstress. Being elastic, the deformations are reversible and therefore do not cause any permanent change in the material. These types of failures occur in structures such as long antennas and solar panels, where large deformations can trigger unstable vibration modes and thereby affect the performance. The overstress is due to external factors and failure occurs when the stress exceeds some safe limit.

- **Yield**

A component that is stressed past its yield strength results in an irreversible plastic strain. This strain causes a permanent deformation due to a permanent change in the material. This phenomenon most often occurs in components made of metals which are **ductile**. Plastic deformation is an instantaneous deformation occurring due to a slip motion (called *dislocation*) of planar crystal defects in response to an applied stress.

- **Creep and Rupture**

The strength of different metals varies significantly with temperature. In the low temperature region, all materials deform **elastically**, then plastically, and are **independent** of time. However, at higher temperatures deformation occurs under constant load conditions. This **time-dependent** characteristic of metals under high temperature is called creep rupture. Figure 2.1 illustrates the various stages of creep. The first region is the elastic strain, followed by the plastic strain region. Then, a constant-rate plastic strain region is followed by a region of increasing strain rate to fracture. Creep varies with the **material, stress, temperature**, and **environment**. Low creep (less than 1 percent) is desirable for a gas turbine blade.

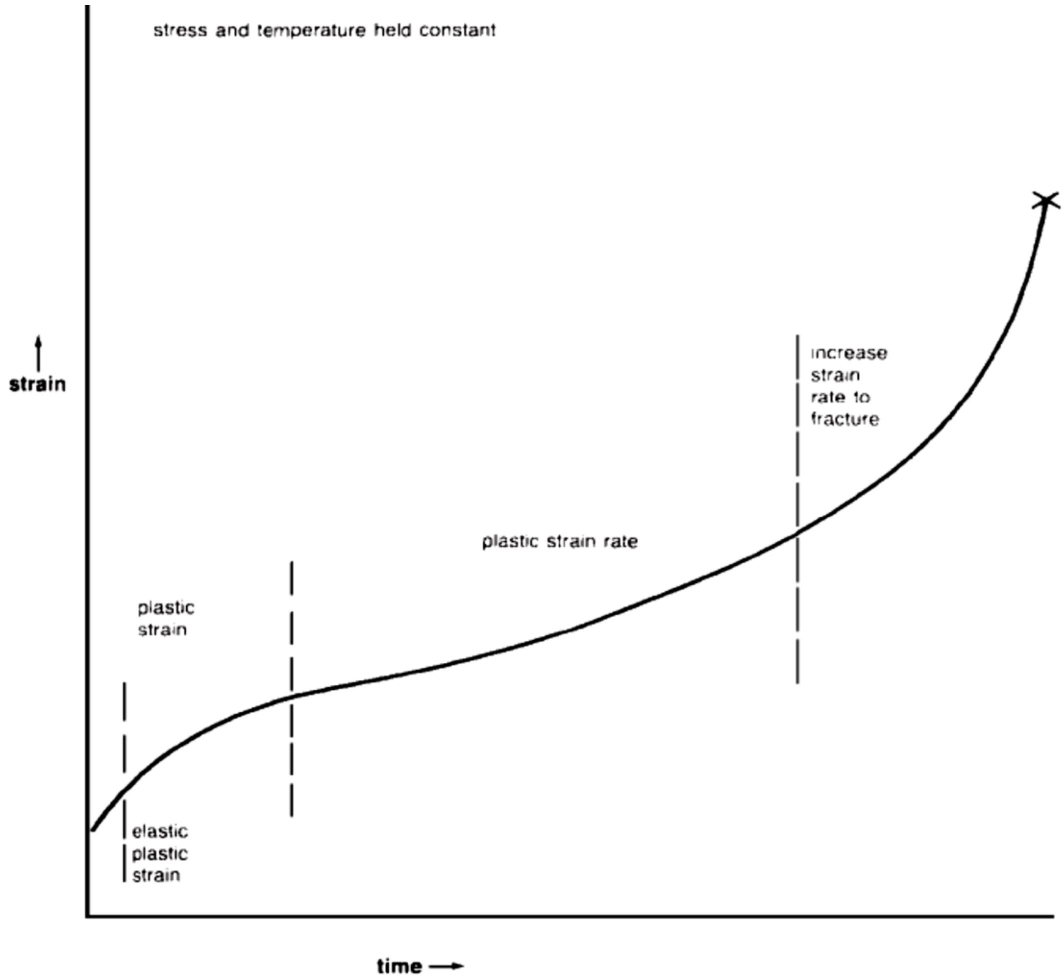


Figure 2.1: time-dependent strain curve under constant load

- **Buckling**

Buckling is a phenomenon that occurs in slender structures under **compressive overstress**. Deformation in the direction of the compressive load can suddenly change at a critical point, resulting in an instantaneous and catastrophic deformation in a direction perpendicular to the loading direction. The load at which buckling occurs is called the ***critical load*** and the new deformation mode is termed ***post buckling***. Buckling is a structural rather than a material failure mechanism. Post buckling deformation often involves large deformation and/or finite rotation of the structure.

- **Brittle Fracture**

In brittle materials (such as glass and ceramics), high stress concentration can occur at local microscopic flaws under overstress. This excessive stress can cause a failure by sudden catastrophic propagation of the dominant micro-flaw. The failure is not only related to the **applied stress** on the component but also depends on the **flaw size**. Failure resulting from brittle fracture is also referred to as ***cracking***. **Cleavage fracture** is the most common brittle type of fracture and it occurs by direct separation along crystallographic planes and is due to tensile breaking of molecular bonds.

- **Ductile Fracture**

Ductility is the amount of elongation that a metal experiences when subjected to stress. In ductile fracture, the failure is due to sudden propagation of a pre-existing crack in the material under external stress. It differs from brittle fracture in the sense that there is largescale yielding at the tip of the crack which preceded the crack propagation.

The alloys used for turbine blades normally have low ductility at operating temperatures. Thus, surface notches initiated by erosion or corrosion could easily lead to cracks that propagate rapidly.

2.2.2 Wear-Out Failure Mechanisms

In this section, a qualitative characterization of the different failure mechanisms leading to wear-out failures are given.

- **Fatigue Crack Initiation and Propagation**

When a component is subjected to a cyclic stress, failure usually occurs at stresses significantly **below** the ultimate tensile strength and is due to the accumulation of damage. Such failures are a result of incremental damage that occurs during each load cycle and accumulates with the number of cycles. Failures of this type are termed ***fatigue failures***. *Fatigue causes more failures than any other mechanism*.

Fatigue failure is comprised of two stages: **crack initiation** and **crack propagation**. A crack typically develops at a point of discontinuity (such as a bolt hole or a defect in the material grain structure) because of local stress concentration. Once initiated, a crack can propagate stably under cyclic stress until it becomes unstable and leads to overstress failure. Fatigue is the leading cause of wear-out failures in engineering hardware. Typical examples are fatigue cracking in rotating shafts, reciprocating components, and large structures such as buildings and bridges.

- **Thermal Fatigue**

Thermal fatigue is a secondary failure mechanism in turbine blades. Temperature differentials that occur during start-up and shutdown produce **thermal stress**. Thermal fatigue is the cycling of these stresses. It is low-cycle and similar to the failure caused by creep-rupture. Highly ductile materials tend to have higher resistance to thermal fatigue and to crack initiation and propagation. The life of the blades is directly affected by the number of **starts per hour of operation**.

- **Corrosion**

The two mechanisms that cause deterioration of the turbine blade material are erosion and corrosion. **Erosion** is caused by the impingement of hard particles on the turbine blade and removal of material from the blade surface. These particles may have passed through the gas turbine filter. **Corrosion** is the process of chemical or electrochemical degradation of materials. The three common forms of corrosion are **uniform**, **galvanic**, and **pitting** corrosion.

In **uniform corrosion**, the reactions occurring at the metal-electrolyte interface are uniform over the surface of the item. Continuation of the process depends on the nature of the corrosion product and the environment. If the corrosion product is washed off or otherwise removed, fresh metal is exposed for further corrosion.

Galvanic corrosion occurs when two different metals are in contact. In this case, one acts as a cathode (where a reduction reaction occurs) and the other as an anode (where corrosion occurs as a result of oxidation).

Pitting corrosion occurs at localized areas and results in the formation of pits.

- **Wear**

Wear is the erosion of material resulting from the sliding motion of two surfaces under the action of a contact force. The engineering science that deals with the study of such contacts is called ***tribology***. Erosion can be due to physical and chemical interactions between the two surfaces. However, there are five wear mechanisms:

Adhesive wear*:* The molecular attractions existing between two relatively moving surfaces create adhesion between the touching asperities. If the adhesive strength is greater than the internal cohesive strength of the material, there is a tendency to create a wear particle after several cycles of contact.

Abrasive wear: When a hard material is sliding against a soft material.

Surface-fatigue wear.

Corrosive (chemical) wear: Sliding surfaces may wear by chemically reacting with the partner surface or the environment or both.

Thermal wear.

Wear erosion may be **uniform** (for example, wearing - away of piston rings in an internal combustion engine) or **non-uniform** (for example, pitting in gear teeth and cam surfaces).

Lecture Three

Distractive Testing

3.1 Stress and Strain

When a force is applied to a material, a stress will be developed within the material and this will generate a strain, which is a dimensional change. Strain may be elastic, meaning that the material will return to its original dimensions when the stress is removed, or it may be plastic or permanent, so that when the level of stress reduces to zero the material will not revert to its original dimensions. When the strain is purely elastic, most materials conform to **Hooke's law** which states that the strain is directly proportional to the stress causing it.

Stress = strain * a constant

or

Stress/strain = a constant

The constant is known as an elastic constant. There is more than one elastic constant, depending on the type of stress involved. A direct tensile force *F* acting on a body of length *L* will cause the body to extend by some amount *x*. The direct stress within the material caused by the force *F* is the force exerted per unit area. Stress has the units of (N/m^2).

Strain is the dimensional change caused by stress and direct strain is the ratio of the change in length *x* to the original length *L* (Figure 3.1). Strain, being a ratio, has no units. A shear force acting on a body causes a twisting effect (Figure 3.1 (c)).

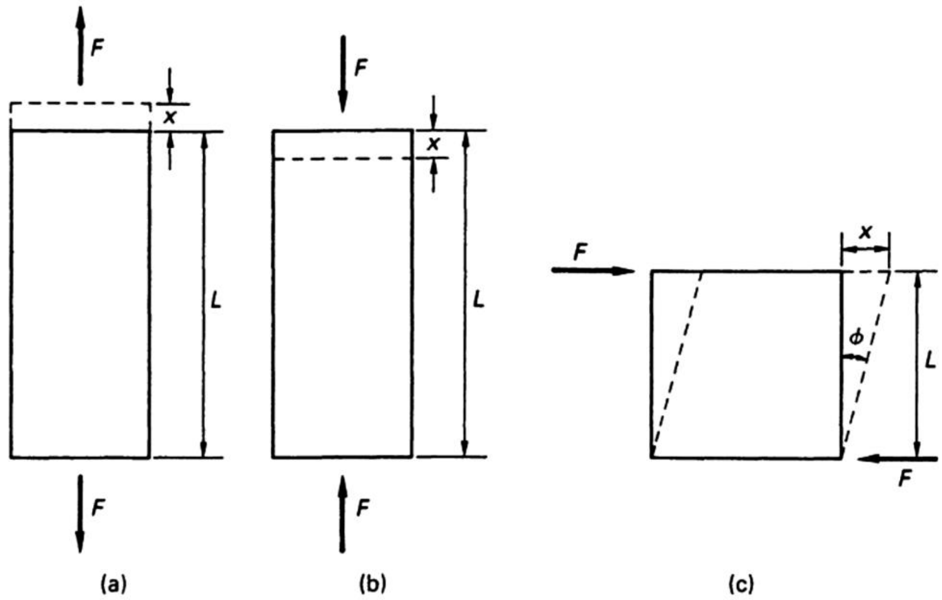


Figure 3.1: Elastic stress and strain: (a) tensile force *F* acting on body of length *L and* cross-sectional area *A*. Tensile stress ***σ= F/A***. Tensile strain **ϵ= *x/L;*** (b) compressive force *F* acting on body. Compressive stress **τ= *F/A***. Compressive strain **ϵ = *-x/L;*** (c) shear force *F* acting on body of cross-sectional area *A*. Shear stress **τ= *F/A***. Shear strain **γ = *x/L* = tan ϕ**.

A direct tensile or compressive stress will cause a direct strain and

Direct stress/direct strain = *E*

where *E* is **the *modulus of elasticity*** or ***Young's modulus***. Shear stress will produce a shear strain and the ratio

Shear stress/shear strain = G

where G is the ***modulus of rigidity*** or ***shear modulus***. The elastic constants are fundamental properties of a material.

3.2 Fatigue

Probably the greatest proportion of failures of components or structures in service can be ascribed to failure by fatigue. This is a type of failure caused by the action of varying stresses below the short-term static tensile or torsional strength of the material. Examination of a fatigue fracture surface shows two distinct parts. There is a smooth portion and the crystalline fracture zone (Figure 3.2). Usually a series of curved lines can be seen on the smooth section of the fracture surface. These indicate that crack propagation has taken the form of step growth from the point of initiation.

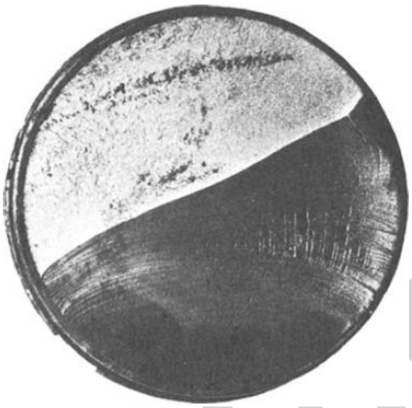


Figure 3.2: Fracture surface of large diameter shaft which has failed by fatigue

This part of the surface has been worn smooth by the relative motion between the two surfaces of the crack during very many loading cycles. Finally, when the fatigue crack, or cracks, have grown to such an extent that the area of unbroken section is no longer sufficient to sustain the load, fracture propagates rapidly across the remainder. This final portion of the fracture surface generally has the crystalline appearance typical of a brittle failure. When metal samples are tested to determine the fatigue characteristics, the test conditions often involve the application of an alternating stress cycle with a mean stress of zero. The results of such tests are plotted in the form of an S - log N curve, where S is the **maximum stress in the cycle** and N is the **number of stress cycles to failure** (Figure 3.3). Most steels show an S -log N curve of type (i) in the figure with a definite fatigue limit. This fatigue limit for steels occurs at about one-half of the value of static tensile strength after some 106 or 107 cycles. This means that if the maximum stress in any cycle does not exceed the fatigue limit then failure by fatigue should never occur. Non-ferrous metals do not show a definite fatigue limit and give S - log N curves similar to that shown in Figure 3.3 (ii).

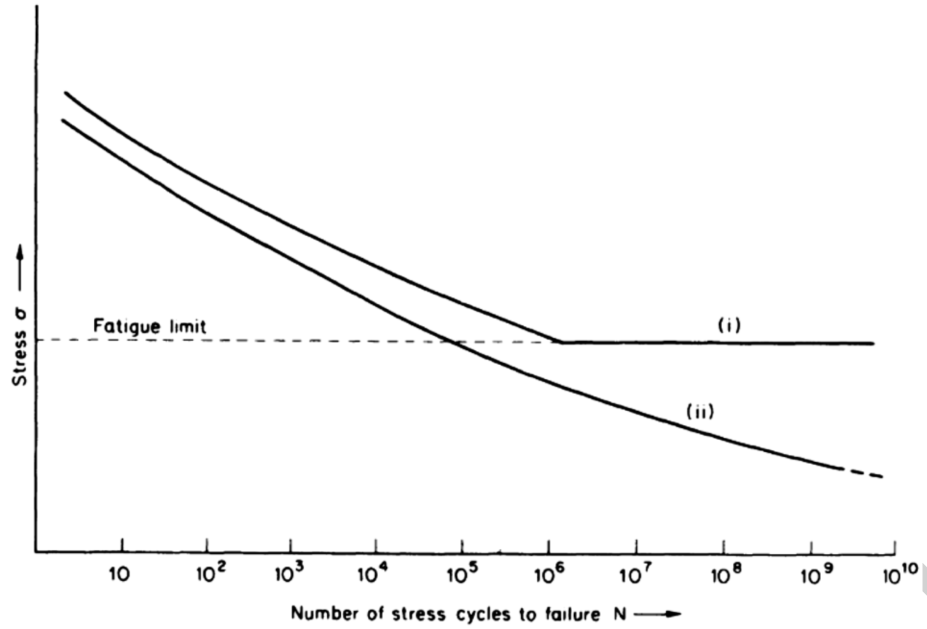


Figure 3.3: S - log *N* curves for (i) metal showing fatigue limit and (ii) metal showing no fatigue limit.

3.2.1 Fatigue Testing

A component or structure in service may be subjected to fluctuating or alternating cycles of stress but rarely can it be found that one constant type of loading cycle applies during the whole of the life of a component. Laboratory fatigue tests tend to be based on some uniform type of stress cycle be it alternating, repeating or fluctuating (Figure 3.4) applied in a systematic manner.

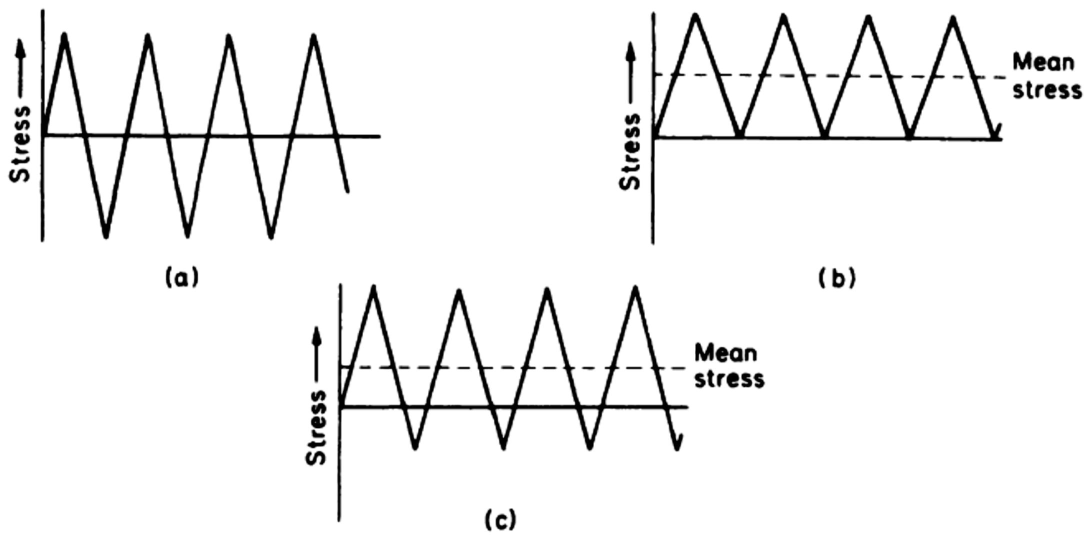


Figure 3.4: Types of stress cycle: (a) alternating; (b) repeating; (c) fluctuating

There are several tests based on the rotating bending principle. Of these, the **Wohler rotating cantilever** and the **four-point bending system** are used widely (Figure 3.5). In both of these tests, at any instant in time, one element of the surface of the test-piece is stressed in tension while that element of the surface diametrically opposed to the first is stressed in compression. During one complete revolution of the test-piece anyone section of the surface will go through a complete stress cycle, with a mean stress of zero.

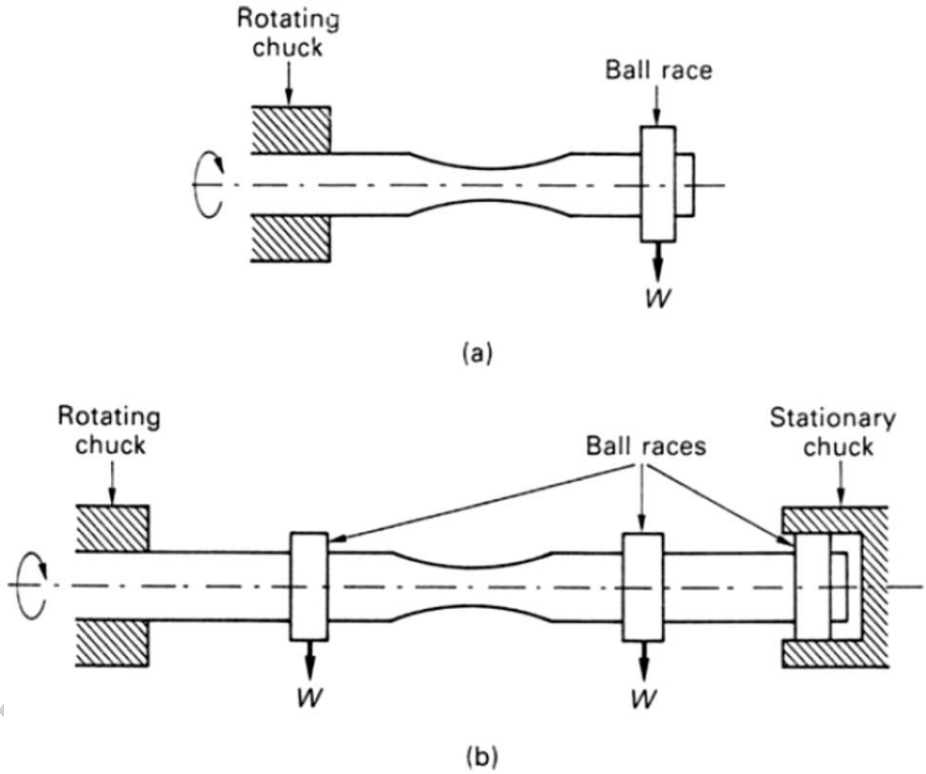


Figure 3.5: Principle of rotating bending fatigue tests: (a) Wohler rotating cantilever test; (b) four-point bending rotating test.

The results of fatigue tests are shown generally in the form of *S*-log *N* curves and it is important, when presenting fatigue results that the method of **stressing**, **type of machine used**, **test-piece dimensions** and the **cycle frequency** be quoted. Data may also be presented in tabulated form. The terms ***fatigue life*** and ***endurance*** refer to the number of cycles to failure and normally the values of endurance are 10^6 cycles for structural steels and 10^7 cycles for other steels and non-ferrous metals. The terms ***fatigue strength*** and ***endurance limit*** are used to denote the maximum level of stress which will give a finite life, i.e. no failure in some specified number of cycles.

3.3 Creep

Creep is the continued slow straining of a material under constant load. Another phenomenon, related to creep, is ***relaxation***. This is the reduction in the level of stress within a material with time when the strain is constant. For metals, this is at temperatures in excess of 0.5 T_m, where T_m is the **melting point** in Kelvin. A typical creep curve for a metal is shown in Figure 3.6. It will be seen that the curve comprises three distinct portions. These are ***primary***, or ***transient*** *creep*, ***secondary*** or ***steady state*** *creep* and ***tertiary*** *creep*. This last phase leads to rapid failure.

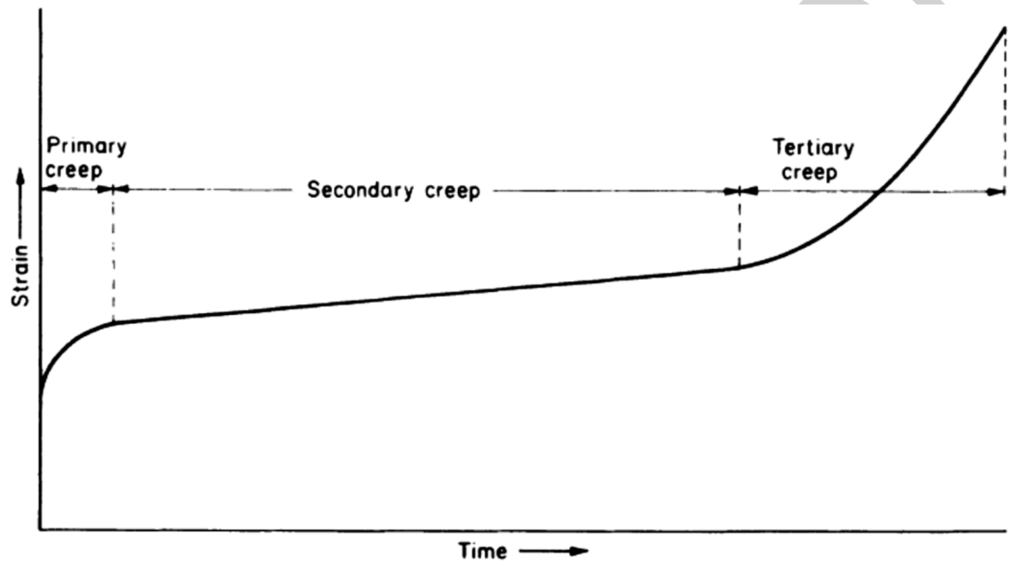


Figure 3.6: Typical creep curve for a metal.

Creep is highly temperature-dependent and the effects of increasing temperature, with loading conditions maintained at constant level, on creep rates are shown in Figure 3.7. At low temperatures, there may be transient creep only while, at very high temperatures, primary creep may merge directly into tertiary creep. Secondary creep rates are also stress-dependent. An increase in stress, σ, will increase the rate of creep strain, $d\epsilon/dt$, following the relationship:

$$d\epsilon/dt = C\,\sigma^n$$

where C and n are constants of the material. Figure 3.7 shows a series of creep curves for a material at constant temperature but with different loads.

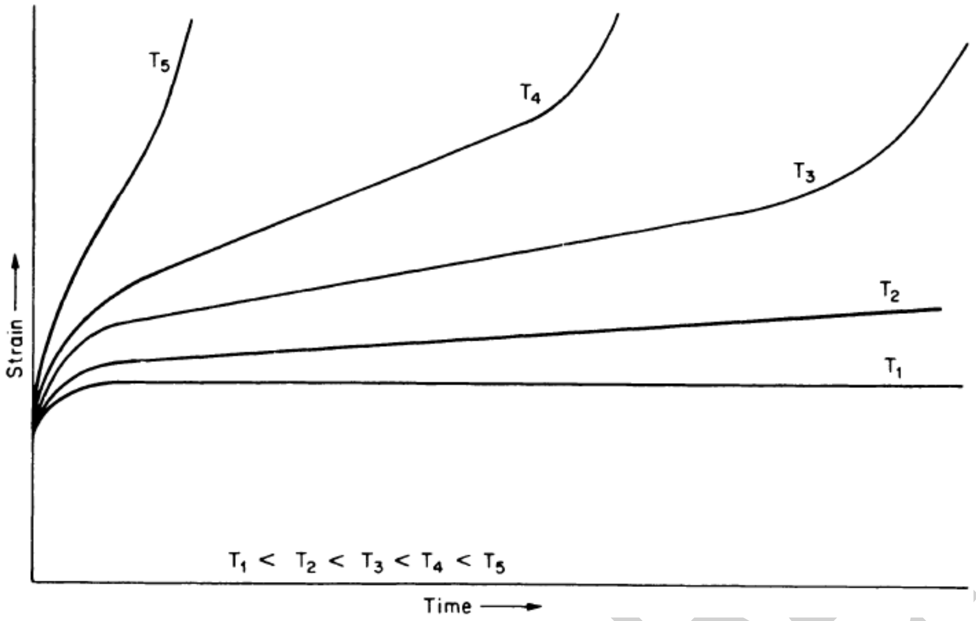


Figure 3.7: Variation of creep rate with temperature - constant load.

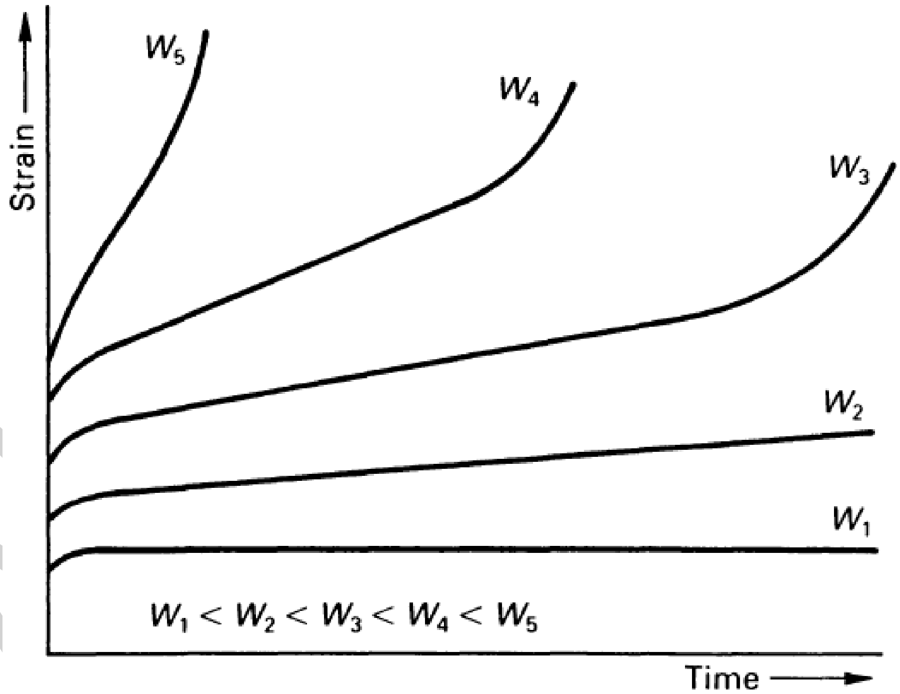


Figure 3.8: Variation of creep rate at constant temperature with different loads. *W*.

3.3.1 Creep Testing

Almost all creep testing is conducted in the tensile mode and the test specimens are similar in form to those used in tensile testing. Test-pieces for tensile creep testing may be of either **circular** or **rectangular** cross-section but there are no standard sizes. The actual dimensions of the test-pieces used will depend upon the type of creep testing machine used. The basic requirements for a creep testing machine are

1- That it must possess means for applying and maintaining a constant tensile load.

2- There must be a furnace capable of keeping the temperature of the test-piece at the desired value to within very close limits.

3- There should be means for the accurate measurement of test-piece extension.

This last requirement is not necessary if the equipment is to be used only for the determination of stress-to-rupture data.

3.4 Hardness and its Measurement

The property of hardness is not a fundamental property of a material. The term *hardness* may be defined in more than one way. It may be regarded as the resistance of the material to abrasion, or as the resistance to localised plastic deformation. The various types of hardness test which have been devised are based on the measurement of one or other of these characteristics of a material. The test types which involve localised plastic deformation can, of course, only be used in connection with those materials which are capable of being deformed plastically, namely metals and thermoplastics. These tests are indentation-type tests and may be either **static** or **dynamic**. In the **static indentation** tests, which are the more commonly used, an indentation is made in the surface of the material under a pre-determined load and the size of the indentation measured. **The larger an indentation is, the softer is the material, and vice versa**. Although indentation tests do not measure the resistance to abrasion, in general, a material of high hardness, as determined by an indentation method, will possess a good resistance to abrasion and wear. **Dynamic indentation** tests involve a free falling weight or a pendulum impacting with a material. Some of the energy of the striker will be absorbed in causing some plastic deformation of the material while the remainder of the impact energy will remain in the striker causing it to rebound. A hard material will not absorb much energy, as it will not greatly deform plastically, so giving a large striker rebound height. This type of test is particularly suited to extremely hard metals.

3.4.1 Static Indentation Tests

The various forms of static indentation test all involve forcing an indentor into the surface of the material being tested under the action of an applied force. The indentor causes localised deformation of the material. When the force is being applied, the deformation of the material is, in part, elastic and, in part, plastic. When the force is removed, the elastic strain in the material is recovered but the plastic strain remains leaving a permanent impression in the surface of the material. A dimension of this impression, either its depth or area, is measured and used in the determination of a hardness number for the material. There are three types of static indentation test commonly used. These are the ***Vickers Diamond*** test, the ***Brinell*** test and the ***Rockwell*** test. The degree of surface preparation of the test-piece is not critical but surface dirt must be removed.

- **The Brinell Hardness Test**

The Brinell test was the first static indentation test to come into general use. In its original form, it utilised a hardened steel ball indentor of 10 mm diameter forced into the surface of the metal being tested under a static load of 3000 kg (29.43 kN) and the load maintained for 10 to 15 seconds. The diameter of the resulting impression is then measured with the aid of a calibrated microscope. The Brinell hardness number, H_B, is given by

$$H_B = \frac{\text{Applied load (kg)}}{\text{Surface area of the impression (mm}^2\text{)}}$$

The problem associated with the Brinell test is that the impressions made by a spherical indentor are not **geometrically similar**. In other words, if two tests are made on the same material, one using a large static load and one using a small load the hardness values obtained will differ. Figure 3.9 shows two impressions, one shallow and one deep. This leads to that the hardness number obtained from a Brinell test will not be independent of the load used.

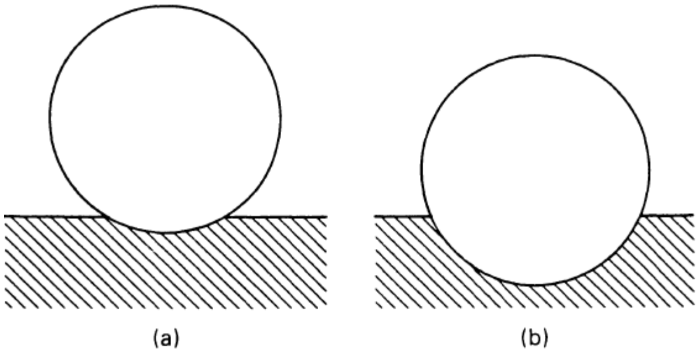


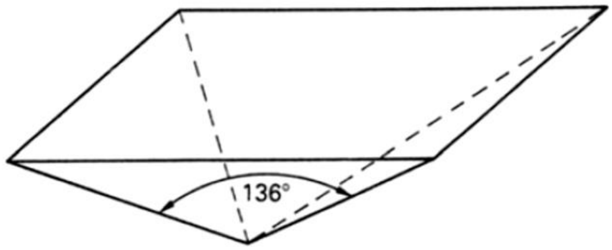
Figure 3.9: (a) Shallow impression. (b) Deep impression; the impressions are not geometrically similar.

- **The Vickers Diamond Hardness Test**

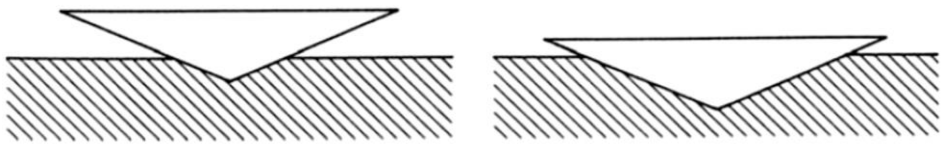
In the Vickers diamond test, the indentor used is a pyramidal shaped diamond and, as in the Brinell test, the indentor is forced into the surface of the material under the action of a static load for 10 to 15 seconds (Figure 3.10). The Vickers Diamond hardness number, H_D, is given by

$$H_D = \frac{\text{Applied load (kg)}}{\text{Surface area of impression (mm}^2)}$$

The standard indentor is a square pyramid shape with an angle of 136° between opposite faces. One advantage of the Vickers test over the Brinell test is that the square impressions made are always geometrically similar, irrespective of size. In consequence, the hardness value obtained is independent of the magnitude of the indenting force used. After an impression has been made, the size of the impression is measured accurately using a microscope.



(a)



(b)

Figure 3.10: (a) Pyramid shaped diamond indentor, (b) Shallow and deep diamond impressions showing geometrical similarity.

- **The Rockwell Hardness Test**

The Rockwell test machine is a rapid action direct-reading machine. This provides a very convenient method for speedy comparative testing. In this test, the depth of the impression is measured and directly indicated by a pointer on a dial calibrated, inversely, into 100 divisions (1 scale division = 0.01 mm of impression depth). Consequently, a low scale number indicates a deep impression, hence a soft material, and vice versa.