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SCHOOL OF MECHANICAL ENGINEERING
DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – I- Aircraft Materials– SAEA1201

Unit I

Elements of Aero Materials

INTRODUCTION

Three States of Matter:

- Solids
- Liquids
- Gases

Solids

The aggregates of atoms which preserve their volumes and shapes unless subjected to large external force are called solids".

There are two types of solids :

- Amorphous (non-crystalline)
- Crystalline

Difference Between Amorphous and Crystalline Solids Amorphous

• **Amorphous solids** (means without form) are the solids which lacks the regular arrangement of atoms or molecules and hence they have a short range order or no order in their structure : ABCBBACBCACCB...

• Do not have sharp melting point (because all bonds are not equally strong)

• Isotropic (Physical properties are same in different directions)

• Examples: glass, wax, plastics, etc.

Crystalline

• A crystalline solid is the one in which there is a regular repeating pattern in the structure, or in other words, there is long- range order : ABCABCABCABC…

• Have sharp melting point (because all bond are equally strong)

• Anisotropic (Physical properties are different in different directions)

- Examples: diamond, table salt, ice, methanol, sodium chloride, etc.

CRYSTAL LATTICES

A lattice is an infinite, regular array of points in space.

In the definition it should be noticed that no mention is made of atoms or any physical objects, just points in space - no more, no less. Hence we treat the lattice as a mathematical abstraction. Therefore, it is clear that there is no lattice inside the crystal. Even if we look the crystal through a powerful microscope we will not be able to see the lattice points, but rather atoms or groups of atoms. The lattice provides the 'recipe' that determines how the atomic or molecular units are to be repeated throughout the space to make the crystal structure.

Plane Lattice

Consider an array of points in such a way that the environment about any point is identical with the environment about any other point. Such an array of points in two dimensions is called a plane lattice. For constructing a two dimensional lattice, choose any two convenient axis such that the points lie at equal intervals a and b along these axis. There are generally 5 lattices in two dimensions: Oblique, Square, Hexagonal, Rectangular and Centered Rectangular lattice.

Space Lattice

If this array of points is extended to three dimensions then the array of points is called space lattice. For constructing the space lattice the points are arranged at equal intervals c in the third direction also. There are 14 space lattices in total, called Bravais Lattice. Thus a lattice may also be defined as a parallel net like arrangement of points such that the environment about any point is identical with the environment about any other point.

Basis

A basis is defined as an assembly of atoms, ions or molecules identical in composition, arrangement and orientation. Basis consists of the simplest arrangement of atoms which is repeated at every point in the lattice to build up the crystal structure. The number of atoms in a basis may be one as in case of many metals and inert gases, but could be as large as 1000 in many structures. In ionic crystals, a basis is composed of two distinct types of ions. For example, Na+ and Cl- in a NaCl crystal.

When basis is attached identically to each lattice point, the actual crystal structure is formed.

The relation can be written as **Lattice + Basis = Crystal Structure**

UNIT CELL

A unit cell is a region of space which when repeated by primitive translation vectors fills all space. Thus a unit cell is defined as the smallest geometrical figure, the repetitions of which give the actual crystal structure. The choice of the unit cell is not unique. It can be constructed in a number of ways, but the unit cell should be chosen in such a way that it conveys all the symmetry of a crystal lattice, by having shortest possible size, which makes the mathematical calculations easy. Each atom or molecule in a unit cell is considered as a lattice point. The distance between the two atoms or ions of the same type is the ‘length of the unit cell’.

Primitive and Non - primitive unit cell

A unit cell which contain just one lattice point is called primitive unit cell. This cell is the smallest part of the lattice which when repeated would reconstruct the entire crystal structure. It is a minimum volume unit cell and is denoted by the letter p.

A unit cell which contain more than one lattice point is called non - primitive unit cell.

For a three dimensional case, the unit cell is a parallelopiped formed by basic vectors a, b and c as concurrent edges and the angles α, β and γ, between (b, c), (c, a), and (a, b) respectively.

Thus, in general, a unit cell may be defined as the smallest volume of a solid from which the entire crystal may be constructed by translational repetitions in 3-dimension and which represent fully all the characteristics of a particular crystal.

Lattice Parameters

In a unit cell the vectors a, b and c are called translation vectors or primitive basis vectors. In two dimensionsn the area of the unit cell is (a x b) while in three dimension the volume of the unit cell is □(a x b).c □. The direction of the primitive basis vectors defines the crystallographic axis. The angles between these axis are called interfacial angles, which are α, β and γ, between (b, c), (c, a), and (a, b) respectively. Primitive vectors and interfacial angles together are called lattice parameters.

CRYSTAL SYSTEMS AND BRAVAIS LATTICES

Crystals of different substances have similar shapes and hence the crystals are classified into the so called crystal systems depending upon their axial ratio and the interfacial angles α, β and γ. In three-dimension, there are 7 crystal systems. Bravais showed that throughout the seven crystal systems there are fourteen unique lattice types possible. These are known as Bravais or space lattices.

These seven crystal systems with examples are :

- Cubic(CsCl, NaCl, Cu)
- Tetragonal(SnO2)
- Orthorhombic(PbSO4, MgSO4)
- Monoclinic(FeSO4, LiSO4 · H2O)
- Triclinic(FeSO4 · 5H2O, K2Cr2O7)
- Trigonal (Rhombohedral)(Sb, As, CaCO3)
- Hexagonal(Zn, Cd, Ni, As, SiO2)

The characteristics features of these crystal systems and the corresponding Bravais lattices are as follows:

	Crystal class	Intercepts on Axes	Angles between Axes	Bravais space lattice
1	Cubic	a = b = c	α = β = γ = 900	Simple, body-centred, face-centred
2	Tetragonal	a = b ≠ c	α = β = γ = 900	Simple, body-centred
3	Orthorhombic	a ≠ b ≠ c	α = β = γ = 900	Simple, body-centred, face-centred, Base(side)-centred
4	Trigonal	a = b = c	α = β = γ ≠ 900	Simple
5	Hexagonal	a = b ≠ c	α = β = 900 , γ = 1200	Simple
6	Monoclinic	a ≠ b ≠ c	α = γ = 900 ≠ β	Simple, base-centred
7	Triclinic	a ≠ b ≠ c	α ≠ β ≠ γ	Simple

MILLER INDICES

The crystal structure may be regarded as made up of an aggregate of a set of parallel equidistant planes passing through at least one lattice point or a number of lattice points. These planes are known as Lattice Planes. For a given crystal, lattice planes can be chosen in different ways.

In order to designate a lattice plane, British mineralogist William H. Miller, in 1839, developed a method by using three numbers (h k l) which are known as Miller Indices. Miller Indices are the three smallest possible integers, which have the same ratio as the reciprocals of intercepts of the plane concerned on the three axis.

Miller indices are integer sets that were created to distinguish directions and planes in a lattice. They are used primarily in crystalline structures because they describe planes in relation to a larger lattice in relative terms, as opposed to absolute terms. An example of this is describing planes in a building, Miller indices would distinguish the floor from the walls, and north wall from west wall, however it would not distinguish the 4th floor from the 5th floor. This is useful in crystal lattices because the planes are the same in many directions(like floors in a tall building).

Important points:

- Miller indices define the orientation of the plane within the unit cell
- If a set of planes is perpendicular to any of the axes, it would cut that axes at ∞, hence the Miller index along that direction is $1/\infty = 0$.
- If a plane to be indexed has an intercept along the negative portion of a coordinate axis, a minus sign is placed over the corresponding index.
- The Miller Index defines a set of planes parallel to one another (remember the unit cell is a subset of the “infinite” crystal), e.g., (002) planes are parallel to (001) planes, and so on.

Physical Parameters for Crystal Structure

(i)Number of Atoms per Unit Cell

Number of atoms per unit cell determines how closely the solid is packed and is given by

$$\mathbf{N = Nc/8 + Nf/2 + Ni}$$

Here,

Nc is the number of corner atoms,

Nf the number of face centred atoms and

Ni the number of body centred atoms.

For SC crystal : In a SC crystal, there are 8 atoms only, each at one corner. Each atom is shared by 8 unit cells. Therefore, we have N = Nc/8 = 8/8 = 1

For BCC crystal :N = Nc/8 + Nf/2 + Ni = 8/8 + 0 + 1 = 2

For FCC crystal :N = Nc/8 + Nf/2 + Ni = 8/8 + 6/2 + 0 = 4

(ii) Coordination Number (CN)

In a crystal, the number of nearest neighbours of the same type and at equal distances from the given atom is called coordination number.

For SC : The corner atoms are the nearest neighbours of each other. Here CN = 6 which is a group of 8 unit cell and atom at the centre has six corner atoms as its nearest neighbours).

For BCC : In this case all the corner atoms are at equal distances from the body centered atom. Hence CN = 8.

For FCC : Here the nearest neighbours of any corner atom are the face centered atoms of the surrounding unit cells. Now for any corner atom there are 4 face centered atoms in each plane and there are three such planes. Therefore, CN = 12.

(iii) Atomic Radius and Nearest Neighbour Distance (NND)

In a crystal the atoms are assumed to be spheres in contact. Now atomic radius is defined as half the distance between the nearest neighbours in a crystal of pure element, i.e., the distance between the centres of neighbouring atoms.

For SC : In a SC structure, corner atoms are the nearest neighbours and are in touch with each other. If the side of the unit cell is ‘a’ and ‘r’ be the radius , then 2r = a or r = a/2 Now Nearest Neighbour Distance(NND) is given by 2r Therefore, NND = 2r = a

For FCC : r = √2 a/4 NND = a/√2

For BCC : r = √3 a/4 NND = √3 a/2.

(iv) Atomic Packing Fraction (or Factor) (APF)

It is defined as the ratio of the volume of the atoms occupying the unit cell to the volume of the unit cell. It is also called relative packing density. APF = Volume occupied by the atoms in a unit cell / Volume of the unit cell.

SC Crystal : No. of atoms/unit cell = 1 Volume of one atom = 4/3 πr3 Side of the unit cell = a = 2r Volume of the unit cell = a3 APF = = = π/6 = 0.52 = 52%.

BCC Crystal : No. of atoms/unit cell = 2 Volume of two atoms = 2x4/3 πr3 Side of the unit cell = a = 4r/√3 Volume of the unit cell = a3 APF = = = √3π/8 = 0.68 = 68%.

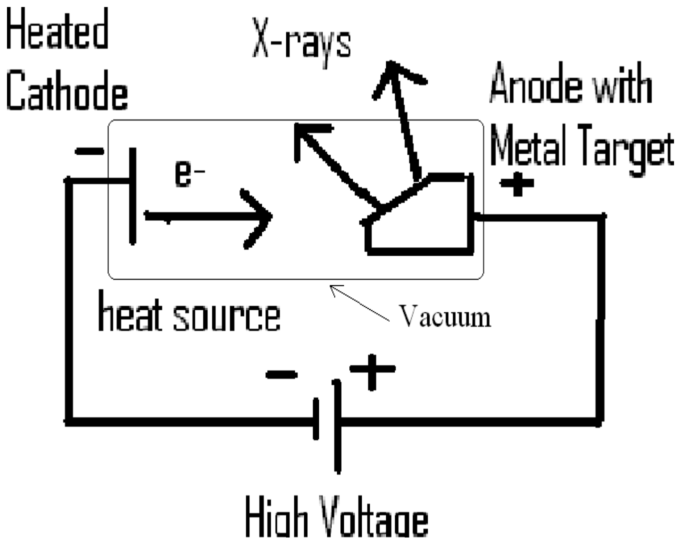
FCC Crystal : No. of atoms/unit cell = 4 Volume of four atoms = 4x4/3 πr3 Side of the unit cell = a = 4r/√2 Volume of the unit cell = a3 APF = = = √2π/6 = 0.74 = 74%.

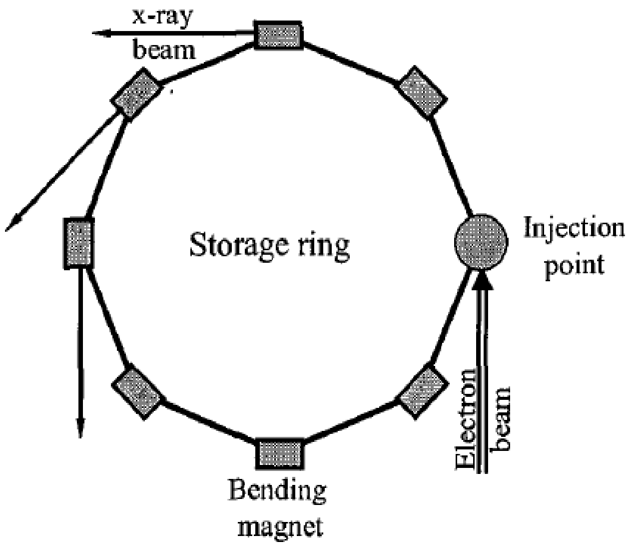
Hexagonal Close Packed Structure (hcp)

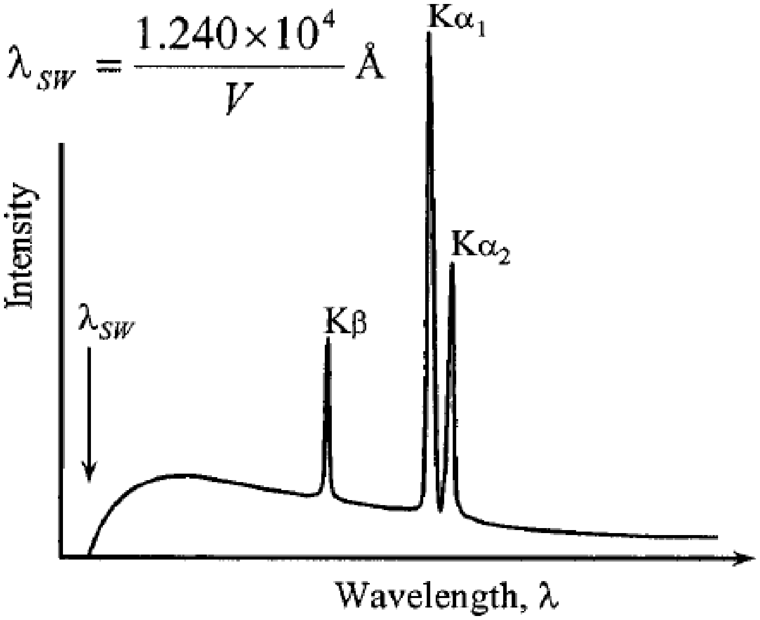
In a closed packed structure the constituent atoms are so arranged as to occupy minimum possible volume. Here identical spheres(atoms) are arranged in a single close packed layer(say ‘A’) with each sphere touching six other spheres in a plane. This layer then assumes hexagonal shape. A second layer can now be added over this by placing spheres in the hollows ‘B’ which are formed by three spheres in the bottom layer. Now in the third layer the spheres are placed directly over the spheres of first layer, i.e., ‘A’. In this case the stacking is AB AB AB …, and the resulting three- dimensional structure is termed as hexagonal closed packed (hcp).

X-ray Generation & typical spectrum

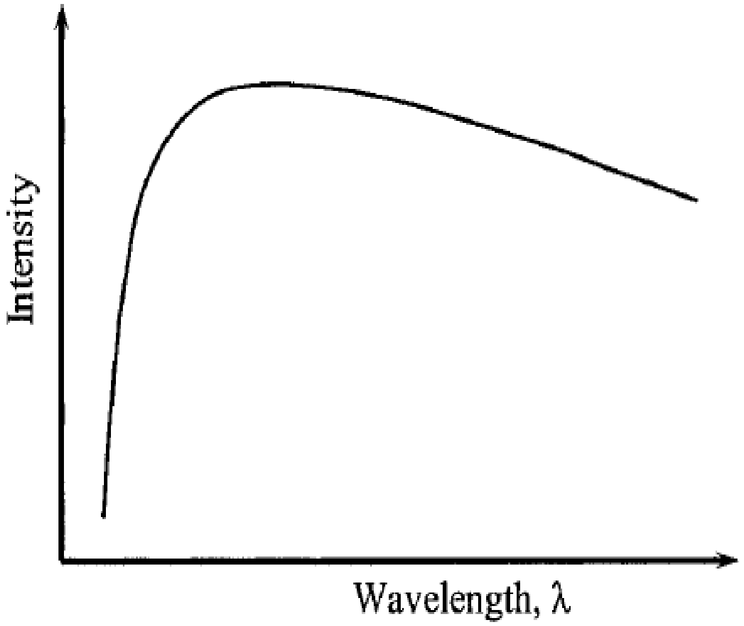
Conventional X-ray Source & Synchrotron:



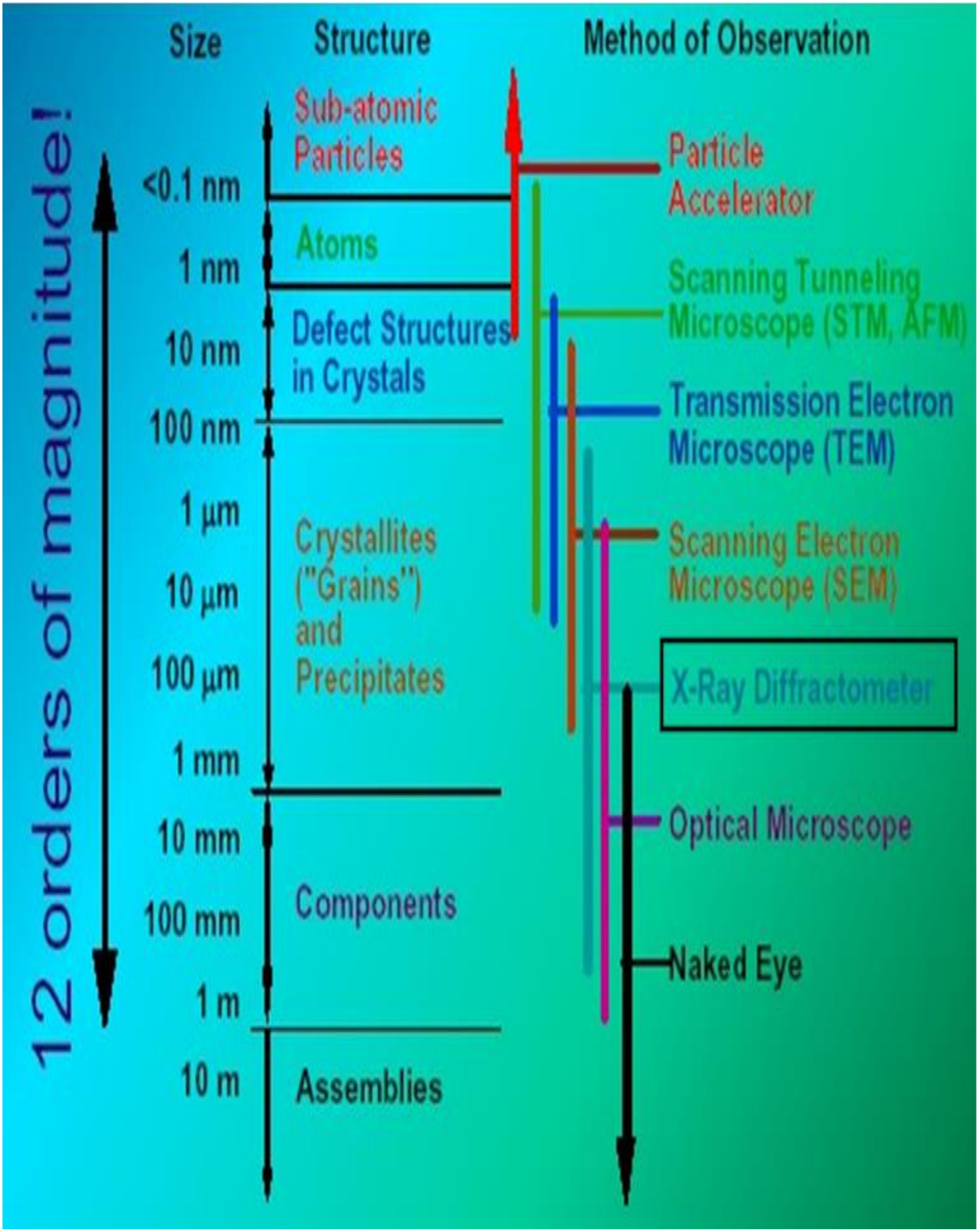




$$\lambda_{SW} = \frac{1.240\times 10^4}{V}\,\text{Å}$$



Scale of Structure Organization



Diffraction Basics

- **For electromagnetic radiation to be diffracted the spacing in the gratingshould be of the same order as the wavelength**

- **In crystals the typical interatomic spacing ~ 2-3 Å so the suitable radiation isX-rays**

- **Hence, X-rays can be used for the study of crystal structures**

- **Neutrons and Electrons are also used for diffraction studies from materials.**

- **Neutron diffraction is especially useful for studying the magnetic ordering in materials**

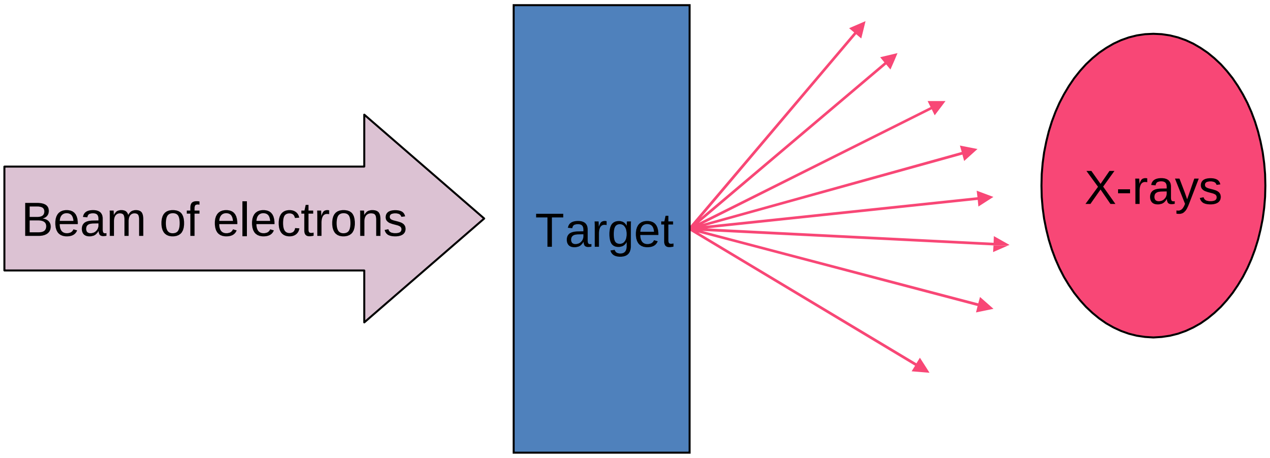
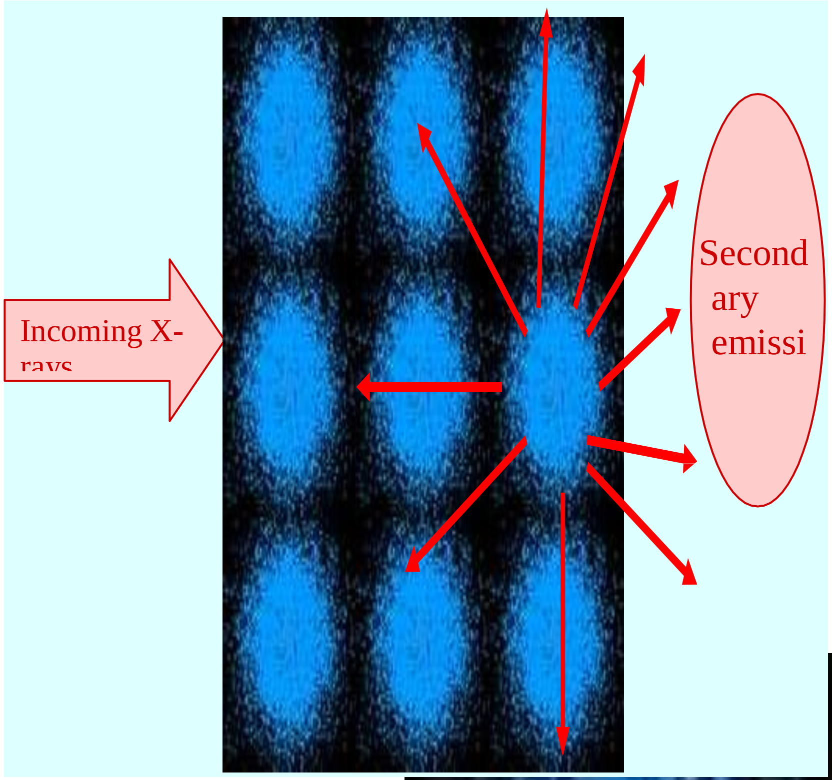


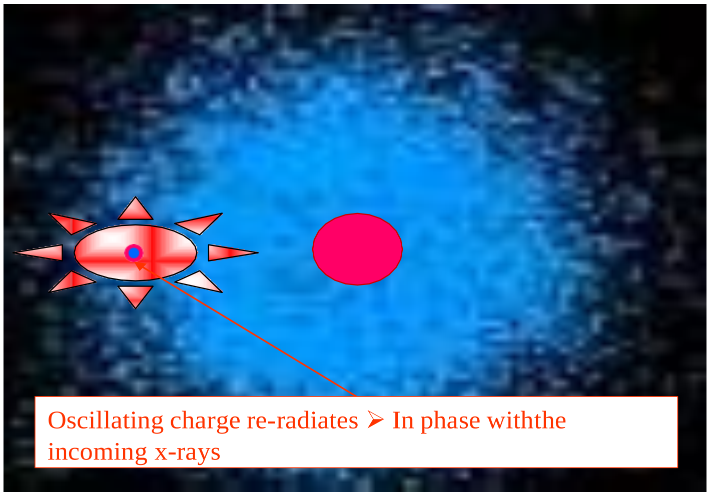
Fig:1.1 A accelerating charge radiates electromagnetic radiation

XRD the first step

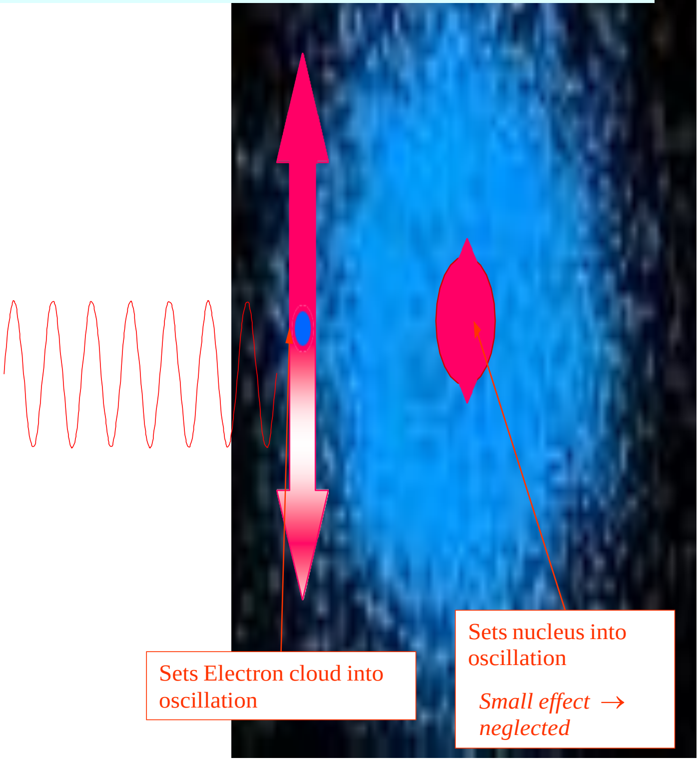
- A beam of X-rays directed at a crystal interacts with the electrons of the atoms in the crystal.
- The electrons oscillate under the influence of the incoming X-Rays and become secondarysources of EM radiation.
- The secondary radiation is in all directions.
- The waves emitted by the electrons have the same frequency as the incoming X-rays

- *coherent.*
- The emission can undergo constructive or destructive **interference.**




Oscillating charge re-radiates ➢ In phase withthe incoming x-rays

Schematics


Sets Electron cloud into oscillation

Sets nucleus into oscillation

Small effect → neglected

Crystallographic defect

Crystallographic defects are interruptions of regular patterns in crystalline solids. They are common because positions of atoms or molecules at repeating fixed distances determined by the unit cell parameters in crystals, which exhibit a periodic crystal structure, are usually imperfect.

Point defects

Point defects are defects that occur only at or around a single lattice point. They are not extended in space in any dimension. Strict limits for how small a point defect is are generally not defined explicitly. However, these defects typically involve at most a few extra or missing atoms. Larger defects in an ordered structure are usually considered dislocation loops. For historical reasons, many point defects, especially in ionic crystals, are called centers: for example a vacancy in many ionic solids is called a luminescence center, a color center, or F-center. These dislocations permit ionic transport through crystals leading to electrochemical reactions.

Vacancy defects are lattice sites which would be occupied in a perfect crystal, but are vacant. If a neighboring atom moves to occupy the vacant site, the vacancy moves in the opposite direction to the site which used to be occupied by the moving atom. The stability of the surrounding crystal structure guarantees that the neighboring atoms will not simply collapse around the vacancy. In some materials, neighboring atoms actually move away from a vacancy, because they experience attraction from atoms in the surroundings. A vacancy (or pair of vacancies in an ionic solid) is sometimes called a Schottky defect.

Interstitial defects are atoms that occupy a site in the crystal structure at which there is usually not an atom. They are generally high energy configurations. Small atoms (mostly impurities) in some crystals can occupy interstices without high energy, such as hydrogen in palladium.

A nearby pair of a vacancy and an interstitial is often called a Frenkel defect or Frenkel pair. This is caused when an ion moves into an interstitial site and creates a vacancy.

Due to fundamental limitations of material purification methods, materials are never 100% pure, which by definition induces defects in crystal structure. In the case of an impurity, the atom is often incorporated at a regular atomic site in the crystal structure. This is neither a vacant site nor is the atom on an interstitial site and it is called a substitutional defect. The atom is not supposed to be anywhere in the crystal, and is thus an impurity. In some cases where the radius of the substitutional atom (ion) is substantially smaller than that of the atom (ion) it is replacing, its equilibrium position can be shifted away from the lattice site. These types of substitutional defects are often referred to as off-center ions. There are two different types of substitutional defects: Isovalent substitution and aliovalent substitution. Isovalent substitution is where the ion that is substituting the original ion is of the same oxidation state as the ion it is replacing. Aliovalent substitution is where the ion that is substituting the original ion is of a different oxidation state than the ion it is replacing. Aliovalent substitutions change the overall charge within the ionic compound, but the ionic compound must be neutral. Therefore, a charge compensation mechanism is required. Hence either one of the metals is partially or fully oxidised or reduced, or ion vacancies are created.

Line defects

Dislocations are linear defects, around which the atoms of the crystal lattice are misaligned. There are two basic types of dislocations, the edge dislocation and the screw dislocation. "Mixed" dislocations, combining aspects of both types, are also common.

Edge dislocations are caused by the termination of a plane of atoms in the middle of a crystal. In such a case, the adjacent planes are not straight, but instead bend around the edge of the terminating plane so that the crystal structure is perfectly ordered on either side. The analogy with a stack of paper is apt: if a half a piece of paper is inserted in a stack of paper, the defect in the stack is only noticeable at the edge of the half sheet.

The screw dislocation is more difficult to visualise, but basically comprises a structure in which a helical path is traced around the linear defect (dislocation line) by the atomic planes of atoms in the crystal lattice.

Planar defects

Grain boundaries occur where the crystallographic direction of the lattice abruptly changes. This usually occurs when two crystals begin growing separately and then meet.

Antiphase boundaries occur in ordered alloys: in this case, the crystallographic direction remains the same, but each side of the boundary has an opposite phase: For example, if the ordering is usually ABABABAB (hexagonal close-packed crystal), an antiphase boundary takes the form of ABABBABA.

Stacking faults occur in a number of crystal structures, but the common example is in close-packed structures. They are formed by a local deviation of the stacking sequence of layers in a crystal. An example would be the ABABCABAB stacking sequence.

A twin boundary is a defect that introduces a plane of mirror symmetry in the ordering of a crystal. For example, in cubic close-packed crystals, the stacking sequence of a twin boundary would be ABCABCBACBA.

On planes of single crystals, steps between atomically flat terraces can also be regarded as planar defects. It has been shown that such defects and their geometry have significant influence on the adsorption of organic molecules

Bulk defects

Three-dimensional macroscopic or bulk defects, such as pores, cracks, or inclusions

Voids — small regions where there are no atoms, and which can be thought of as clusters of vacancies

Impurities can cluster together to form small regions of a different phase. These are often called precipitates.

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Unit-II

Mechanical Behaviour of Materials

Linear elasticity predicts

(i) that the stress in the material is always proportional to the strain,

(ii) that a material will continue to deform with increasing load forever and

(iii) that on release of the load the deformation will entirely disappear.

Linear elastic materials are characterized by an elastic potential of which only the quadratic terms in the strain are kept. It can be defined in a isotropic, orthotropic or fully anisotropic version. Isotropic linear elastic materials are characterized by their Young's modulus and Poisson's coefficient.

Elasticity, ability of a deformed material body to return to its original shape and size when the forces causing the deformation are removed. A body with this ability is said to behave (or respond) elastically.

For many materials, linear elastic models do not accurately describe the observed material behaviour. The most common example of this kind of material is rubber, whose stress-strain relationship can be defined as non-linearly elastic, isotropic, incompressible and generally independent of strain rate.

Elasticity is the property of solid materials to return to their original shape and size after the forces deforming them have been removed. Recall Hooke's law — first stated formally by Robert Hooke in The True Theory of Elasticity or Springiness (1676)… As extension, so force.

Elasticity is the ability of a material to regain its own original shape after being stretched according to which, rubber is the most elastic substance. But when we define elasticity in physics it is the ratio of stress to strain. It means that the shape which has more resistance to change is more elastic.

Rubber bands and elastic and other stretchy materials display elasticity. Modeling clay, on the other hand, is relatively inelastic and retains a new shape even after the force that caused it to change is no longer being exerted.

Nonlinear elastic materials present nonlinear stress-strain relationships even at infinitesimal strains — as opposed to hyperelastic materials, where stress-strain curves become significantly nonlinear at moderate to large strains.

A nonlinear material model can be defined as nonlinear elastic where the part returns to a zero strain state when the load is removed, or elasto-plastic where permanent strain begins to accumulate after reaching the yield strength of the material

In materials science and engineering, the **yield point** is the point on a stress-strain curve that indicates the limit of elastic behavior and the beginning of plastic behavior. Below the yield point, a material will deform elastically and will return to its original shape when the applied stress is removed.

Strain Hardening is when a metal is strained beyond the yield point. An increasing stress is required to produce additional plastic deformation and the metal apparently becomes stronger and more difficult to deform.

Fracture involves the forced separation of a material into two or more parts. Brittle Fracture involves fracture without any appreciable plastic deformation (i.e. energy absorption). Ductile Fracture in the converse and involves large plastic deformation before separation.

Fracture strength, also known as breaking strength, is the stress at which a specimen fails via fracture. This is usually determined for a given specimen by a tensile test, which charts the stress-strain curve. The final recorded point is the fracture strength.

Brittle fractures occur when the material is subject to stresses that are smaller than the yield limit of the material. Machine design normally is based on ductile material; and the design criteria are meant to avoid plastic deformation and, in certain cases, elastic deformations.

Fracture is the separation of an object or material into two or more pieces under the action of stress. The fracture of a solid usually occurs due to the development of certain displacement discontinuity surfaces within the solid.

The true fracture stress is the load at fracture divided by the cross-sectional area at fracture. This stress should be corrected for the, triaxial state of stress existing in the tensile specimen at fracture.

The Fracture Point can be defined as the breaking limit of a material beyond which if further stress is applied it will rupture and break apart. It is basically a material strength gauging parameter.
Breaking load
failure load
fracture load
ultimate load
The load which, if placed upon a structure or test piece, is just great enough to break it.

Brittle Fracture Is More Dangerous Than Ductile Fracture Because No Warning Sign Crack Propagates At Very High Speeds No Need For Extra Stress During Crack Propagation All That Mentioned.

When does brittle fracture is noticed? Explanation: Brittle fracture occurs on sudden loading. This dynamic loading leads to an abrupt failure.

Brittle fractures are characterised as having little or no plastic deformation prior to failure. Materials that usually fracture in a brittle manner are glasses, ceramics, and some polymers and metals. ... The crack propagates through the material by a process called cleavage.

There are several types of test used to measure fracture toughness of materials, which generally utilise a notched specimen in one of various configurations. A widely utilized standardized test method is the Charpy impact test whereby a sample with a V-notch or a U-notch is subjected to impact from behind the notch.

Fracture toughness tests measure a material's ability to resist the growth or propagation of a pre-existing flaw. The flaw or defect may be in the form of a fatigue crack, void, or any other inconsistency in the test material.

Tensile strength

It is defined as the amount of tensile stress a material can withstand before breaking and denoted by s. The formula is: σ = F/A. Where, σ is the tensile stress. F is the force acting.

What is the formula for stress and strain?

stress = (elastic modulus) × strain. As we can see from dimensional analysis of this relation, the elastic modulus has the same physical unit as stress because strain is dimensionless.

Deformation can be of two types as follows: Permanent Deformation – Also known as plastic deformation, it is irreversible. It is a type of deformation that stays even after the removal of applied forces. Temporary Deformation – Also known as elastic deformation, it is reversible.

For example, in SI system, we measure force in newton, work in joule, power in watt... But the unit of fracture toughness, i.e. KIC, is too lengthy to pronounce: (mega) pascal-underoot-meter.

For new equipment, brittle fracture is best prevented by using the current ASME Boiler and Pressure Vessel Code to specify and incorporate materials designed specifically for low temperature conditions, including upset and auto-refrigeration events.

There are two types of fracture: brittle fracture and ductile fracture. Brittle fracture involves crack growth with little or no ductile deformation of the material around the crack tip. ... As a result, ductile fracture is the preferred failure mode for damage-tolerant materials.

A cup and cone fracture is a type of failure observed in ductile metals and plastics that are subjected to a uniaxial force. It is essentially the separation of a body into two separate pieces due to the application of excessive tensile stress.

Toughness is ability of material to resist fracture. The general factors, affecting the toughness of a material are: temperature, strain rate, relationship between the strength and ductility of the material and presence of stress concentration (notch) on the specimen surface.

Diamond. Unmatched in its ability to resist being scratched, this much-loved gemstone ranks the highest in terms of hardness. Diamond is a naturally occurring ceramic made of carbon atoms strongly bound together in a lattice. It is used in drill bits, sandpaper, and saws to cut, grind, and polish.

Up to a temperature of 100 °C the toughness behaviour changes only a little, but if the temperature is continues to rise, the fracture toughness increases rapidely

Ductility is the percent elongation reported in a tensile test is defined as the maximum elongation of the gage length divided by the original gage length.

Strain deals mostly with the change in length of the object. Strain = Δ L L = Change in Length Original Length . ... Strain=LΔL=Original LengthChange in Length. Since strain is the ratio of two quantities with the same dimensions, it has no unit.

The stress equation is: σ = F/A. F denotes the force acting on a body and A denotes the area. Units of stress are the same as units of pressure - Pascals (symbol: Pa) or Newtons per squared meter. Positive stress means that the object is in tension - it "wants" to elongate.

The unit for strain in the SI (Système International) is “one” i.e. 1 ε= 1 = 1 m/m. In practice, the “unit” for strain is called “strain” and the symbol e is used. Usually, strain is in the order of um/m, i.e. 10-6, and therefore, the unit “με” (microstrain) is most commonly used.

Strain is a measure of deformation representing the displacement between particles in the body relative to a reference length. A general deformation of a body can be expressed in the form x = F(X) where X is the reference position of material points in the body. ... A deformation has units of length.

Creep may be defined as a time-dependent deformation at elevated temperature and constant stress. It follows, then, that a failure from such a condition is referred to as a creep failure or, occasionally, a stress rupture. The temperature at which creep begins depends on the alloy composition.

The Griffith theory states that a crack will propagate when the reduction in potential energy that occurs due to crack growth is greater than or equal to the increase in surface energy due to the creation of new free surfaces. This theory is applicable to elastic materials that fracture in a brittle fashion.

Creep failure is the time-dependent and permanent deformation of a material when subjected to a constant load or stress. This deformation typically occurs at elevated temperatures, although it may occur under ambient temperatures as well.

There are three stages of fatigue fracture: initiation, propagation, and final rupture.

The Bauschinger effect refers to a property of materials where the material's stress/strain characteristics change as a result of the microscopic stress distribution of the material. For example, an increase in tensile yield strength occurs at the expense of compressive yield strength. The effect is named after German engineer Johann Bauschinger.

A notch is basically each change of the cross-section of a component. It may come from drill holes, grooves or cross-sectional variations. Notches result in uneven stress distribution, leading to stress peaks – known as the notch effect.

What is the necessity of making a notch in impact test specimen? The notch serves as a stress concentration zone and some materials are more sensitive towards notches than others. The notch depth and tip radius are therefore very important. The notch fixes the particular place where you want your specimen to fail.

Also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition.

Factors Affecting Charpy Impact Energy
Yield strength and ductility.
Notches.
Temperature and strain rate.
Fracture mechanism.

Notch toughness testing is a method used to quantify a material's ability to withstand an impact with a flaw present in the material. More specifically, a notch toughness test measures the amount of energy a material can absorb.

In mechanical engineering and materials science, a **notch** refers to a deliberately introduced v-shaped, u-shaped or circular defect in a planar material. ... Notches are used in materials characterization to determine fracture mechanics related properties such as fracture toughness and rates of fatigue crack growth.

In materials science, fatigue is the initiation and propagation of cracks in a material due to cyclic loading. Once a fatigue crack has initiated, it grows a small amount with each loading cycle, typically producing striations on some parts of the fracture surface.

Fatigue is a failure mechanism that involves the cracking of materials and structural components due to cyclic (or fluctuating) stress. While applied stresses may be tensile, compressive or torsional, crack initiation and propagation are due to the tensile component.

Fatigue failure may occur when a cyclic tensile stress is applied to a component or structure. Failure is progressive, each stress cycle causing incremental growth of the fatigue crack. Fatigue crack surfaces are often characterised by regular steps, each step being due to the crack growth during one cycle.

An estimate of the fatigue life of a component can be made using a crack growth equation by summing up the width of each increment of crack growth for each loading cycle.

Fatigue failure is the formation and propagation of cracks due to a repetitive or cyclic load. Most fatigue failures are caused by cyclic loads significantly below the loads that would result in yielding of the material.

Load ratio R is defined as the ratio of the minimum and maximum loads during the fatigue loading. Without environmental effects, the load ratio has a more significant effect on the stages I and III fatigue crack growth rates than in Stage II

Most steels have an endurance or fatigue limit about half the Tensile Strength. Tensile Strength - (Ultimate Tensile Strength) - of a material is the limit stress at which the material actually breaks, with sudden release of the stored elastic energy.

A quick analysis of the fracture surface of a fatigue failure will often show features casually referred to as “beach marks”. These indicate the propagation of the failure from the initial cracks. Once the crack size has reached a critical level, it will propagate very rapidly until the fracture is complete.

Creep And Fatigue are the phenomenon that lead to deformation and eventually failure of Components. Fatigue is a situation in which component is subjected to cyclic loading. ... Creep is a situation in which a component experiences deformation under constant load with time as it is put into use.

Which material doesn't show fatigue limit? Explanation: Steels and titanium alloys show fatigue limit. It means that there is a stress level below which fatigue failure doesn't occur. Aluminium doesn't show fatigue limit.

Fatigue Reduction

Use stronger, more capable materials. ...
Reduce the margin of errors in assembly and manufacture. ...
Avoid, soften when inevitable, stress concentrations. ...
Keep residual stress at surface, if any, in compression. ...
Take service environment into account. ...
Schedule routine maintenance, firm and thorough.

In structural design, the number of repetitions of load assumed to act on a structure during its lifetime; used as a criterion in determining the fatigue strength of the structure.

A SN-Curve (sometimes written S-N Curve) is a plot of the magnitude of an alternating stress versus the number of cycles to failure for a given material. Typically both the stress and number of cycles are displayed on logarithmic scales.

When the fatigue occurs above 103 cycles (usually 104 or more), it is usually called **High-cycle fatigue.** The material is subject to lower loads, usually less than 2/3 of the yield stress. The deformation is in elastic range. The fatigue life is "high-cycle" (103 ~ 106). The S-N Curve.

Creep resistance is a term used in materials science that refers to a solid material's ability to resist “creep,” which refers to the tendency of a material to slowly deform over a long period of exposure to high levels of stress.

Repeated stress refers to a stress varying from zero to a maximum value of same nature. Reversed stress of cyclic stress varies from one value of tension to the same value of compression.

There are several methods for determining that a metal is starting to become fatigued:
Visual inspection. Detection of cracks or other deformations.
Noise analysis. Damaged metal makes a specific rattling noise.
Ultrasonic and X-ray inspection. ...
Fluorescent dyes. ...
Magnetic powders.

Liquid Penetrate Inspection:

Dye penetrant inspection (DP), also called liquid penetrate inspection (LPI) or penetrant testing (PT), is a widely applied and low-cost inspection method used to check surface-breaking defects in all non-porous materials (metals, plastics, or ceramics). The penetrant may be applied to all non-ferrous materials and ferrous materials, although for ferrous components magnetic-particle inspection is often used instead for its subsurface detection capability. LPI is used to detect casting, forging and welding surface defects such as hairline cracks, surface porosity, leaks in new products, and fatigue cracks on in-service components.

Principles

DPI is based upon capillary action, where low surface tension fluid penetrates into clean and dry surface-breaking discontinuities. The penetrant may be applied to the test component by dipping, spraying, or brushing. After adequate penetration time has been allowed, the excess penetrant is removed and a developer is applied. The developer helps to draw penetrant out of the flaw so that an invisible indication becomes visible to the inspector. Inspection is performed under ultraviolet or white light, depending on the type of dye used - fluorescent or nonfluorescent (visible).

Inspection steps

Below are the main steps of Liquid Penetrant Inspection:

1. Pre-cleaning:

The test surface is cleaned to remove any dirt, paint, oil, grease or any loose scale that could either keep penetrant out of a defect or cause irrelevant or false indications. Cleaning methods may include solvents, alkaline cleaning steps, vapour degreasing, or media blasting. The end goal of this step is a clean surface where any defects present are open to the surface, dry, and free of contamination. Note that if media blasting is used, it may "work over" small discontinuities in the part, and an etching bath is recommended as a post-blasting treatment.

2. Application of Penetrant:

The penetrant is then applied to the surface of the item being tested. The penetrant is usually a brilliant coloured mobile fluid with high wetting capability. The penetrant is allowed "dwell time" to soak into any flaws (generally 5 to 30 minutes). The dwell time mainly depends upon the penetrant being used, the material being tested and the size of flaws sought. As expected, smaller flaws require a longer penetration time. Due to their incompatible nature, one must be careful not to apply solvent-based penetrant to a surface which is to be inspected with a water-washable developer.

3. Excess Penetrant Removal:

The excess penetrant is then removed from the surface. The removal method is controlled by the type of penetrant used. Water-washable, solvent-removable, lipophilic post-emulsifiable, or hydrophilic post-emulsifiable are the common choices. Emulsifiers represent the highest sensitivity level, and chemically interact with the oily penetrant to make it removable with a water spray. When using solvent remover and lint-free cloth it is important to not spray the solvent on the test surface directly, because this can remove the penetrant from the flaws. If excess penetrant is not properly removed, once the developer is applied, it may leave a background in the developed area that can mask indications or defects. In addition, this may also produce false indications severely hindering the ability to do a proper inspection. Also, the removal of excessive penetrant is done towards one direction either vertically or horizontally as the case may be.

4. Application of Developer:

After excess penetrant has been removed, a white developer is applied to the sample. Several developer types are available, including: non-aqueous wet developer, dry powder, water-suspendable, and water-soluble. Choice of developer is governed by penetrant compatibility (one can't use water-soluble or -suspendable developer with water-washable penetrant), and by inspection conditions. When using non-aqueous wet developer (NAWD) or dry powder, the sample must be dried prior to application, while soluble and suspendable developers are applied with the part still wet from the previous step. NAWD is commercially available in aerosol spray cans, and may employ acetone, isopropyl alcohol, or a propellant that is a combination of the two. Developer should form a semi-transparent, even coating on the surface.

The developer draws penetrant from defects out onto the surface to form a visible indication, commonly known as bleed-out. Any areas that bleed out can indicate the location, orientation and possible types of defects on the surface. Interpreting the results and characterizing defects from the indications found may require some training and/or experience [the indication size is not the actual size of the defect].

5. Inspection:

The inspector will use visible light with adequate intensity (100 foot-candles or 1100 lux is typical) for visible dye penetrant. Ultraviolet (UV-A) radiation of adequate intensity (1,000 micro-watts per centimetre squared is common), along with low ambient light levels (less than 2 foot-candles) for fluorescent penetrant examinations. Inspection of the test surface should take place after 10- to 30-minute development time, and is dependent on the penetrant and developer used. This time delay allows the blotting action to occur. The inspector may observe the sample for indication formation when using visible dye. It is also good practice to observe indications as they form because the characteristics of the bleed out are a significant part of interpretation characterization of flaws.

6. Post Cleaning:

The test surface is often cleaned after inspection and recording of defects, especially if post-inspection coating processes are scheduled.

Advantages and disadvantages

The main advantages of DPI are the speed of the test and the low cost. Disadvantages include the detection of only surface flaws, skin irritation, and the inspection should be on a smooth clean surface where excessive penetrant can be removed prior to being developed. Conducting the test on rough surfaces, such as "as-welded" welds, will make it difficult to remove any excessive penetrant and could result in false indications. Water-washable penetrant should be considered here if no other option is available. Also, on certain surfaces, a great enough colour contrast cannot be achieved or the dye will stain the workpiece.

Limited training is required for the operator — although experience is quite valuable. Proper cleaning is necessary to assure that surface contaminants have been removed and any defects present are clean and dry. Some cleaning methods have been shown to be detrimental to test sensitivity, so acid etching to remove metal smearing and re-open the defect may be necessary.
Penetrant inspection can only be applied on non-porous materials

Radiographic Testing

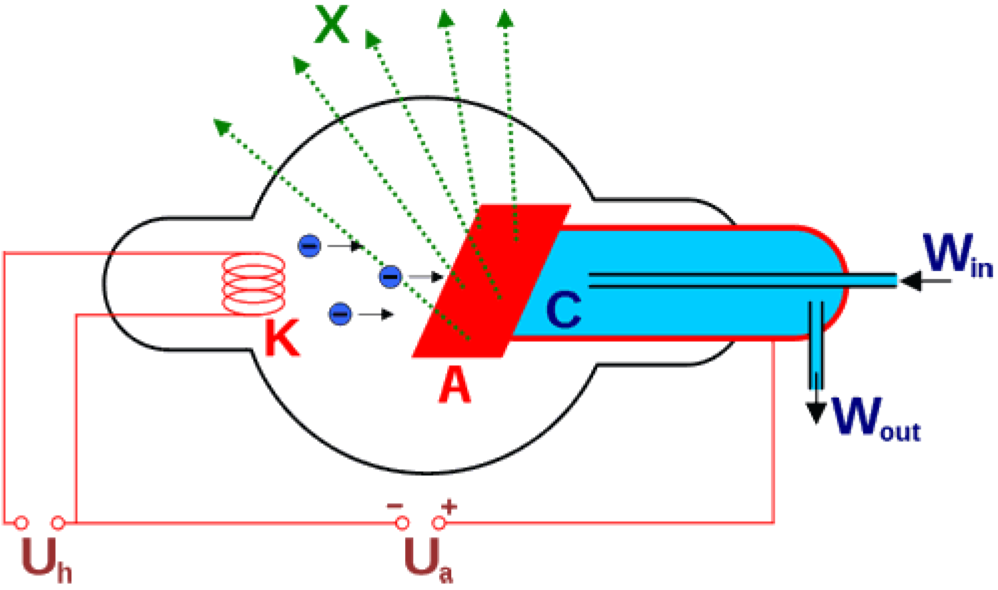
Radiographic Testing (RT or X-ray or Gamma ray) is a non-destructive testing (NDT) method that examines the volume of a specimen. Radiography (X-ray) uses X-rays and gamma-rays to produce a radiograph of a specimen, showing any changes in thickness, defects (internal and external), and assembly details to ensure optimum quality in your operation.

RT usually is suitable for testing welded joints that can be accessed from both sides, with the exception of double-wall signal image techniques used on some pipe. Although this is a slow and expensive NDT method, it is a dependable way to detect porosity, inclusions, cracks, and voids in weld interiors.

RT makes use of X-rays or gamma rays. X-rays are produced by an X-ray tube, and gamma rays are produced by a radioactive isotope.

WATER COOLED X-RAY TUBE

- K - cathode (electron source)
- A - anode (target electrons)
- C - cooling Water
- UH - heating voltage
- UA - accelerating voltage
- X - X-radiation (X-rays)



The method is based on the same principle as medical radiography in a hospital. A piece of radiographic film is placed on the remote side of the material under inspection and radiation is then transmitted through from one side of the material to the remote side where the radiographic film is placed.

The radiographic film detects the radiation and measures the various quantities of radiation received over the entire surface of the film. This film is then processed under dark room conditions and the various degrees of radiation received by the film are imaged by the display of different degrees of black and white, this is termed the film density and is viewed on a special light emitting device.

Discontinuities in the material affect the amount of radiation being received by the film through that particular plane of the material. Qualified inspectors can interpret the resultant images and record the location and type of defect present in the material. Radiography can be used on most materials and product forms, e.g. welds, castings, composites etc.

Radiographic testing provides a permanent record in the form of a radiograph and provides a highly sensitive image of the internal structure of the material.

The amount of energy absorbed by the object depends on its thickness and density. Energy not absorbed by the object causes exposure of the radiographic film. These areas will be dark when the film is developed. Areas of the film exposed to less energy remain lighter. Therefore, areas of the object where the thickness has been changed by discontinuities, such as porosity or cracks, will appear as dark outlines on the film. Inclusions of low density, such as slag, will appear as dark areas on the film, while inclusions of high density, such as tungsten, will appear as light areas.

All discontinuities are detected by viewing the weld shape and variations in the density of the processed film. This permanent film record of weld quality is relatively easy to interpret if personnel are properly trained. Only qualified personnel should conduct radiography and radiographic interpretation because false readings can be expensive and can interfere seriously with productivity, and because invisible X-ray and gamma radiation can be hazardous.

Limitations:
High risk of radiation hazard.
Can be sensitive to defect orientation and could miss planar flaws.
Has limited ability to detect fine cracks.
Access is required to both sides of the object.
Thickness limitation of the materials can be penetrated.
Skilled radiographic interpretation is required.

Advantages:
There are many advantages to radiography, including:
Inspection capability for many types of material with varying density.
Ability to inspect assembled components.
Minimal surface preparation required.
Determination of crack growth.
Detection of both surface and subsurface defects.
Permanent record of the inspection.

Magnetic Particle Inspection

Magnetic particle inspection (often abbreviated MT or MPI) is a nondestructive inspection method that provides detection of linear flaws located at or near the surface of ferromagnetic materials. It is viewed primarily as a surface examination method.

Magnetic Particle Inspection (MPI) is a very effective method for location of surface breaking and slight sub-surface defects such as cracking, pores, cold lap, lack of sidewall fusion in welds etc in magnetic materials.

There are many different techniques. The most versatile technique is using a 110v AC hand held electromagnetic yoke magnet, a white strippable paint as contrast background and a magnetic "ink" composed of iron powder particles in a liquid carrier base.

The area is magnetised with the yoke magnet. In the event of a surface or slightly sub surface defect being present, the lines of magnetic force will deform around the defect.

The magnetic ink is applied and the iron powder particles will bridge the gap caused by the defect and give a visible indication against the white contrast background.

Magnetic Particle Inspection (MPI) provides very good defect resolution and is used extensively on:
Welded fabrications in magnetic material, Castings, Locating fatigue cracks in items subject to cyclical stress

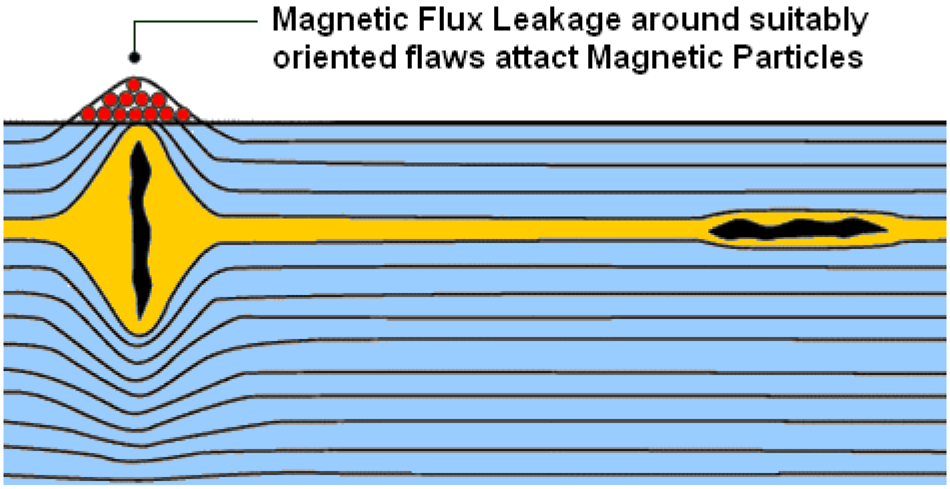


Fig:2.2 Schematic of flux lines flowing past both a perpendicular and parallel defect, and flux leakage occurring around the perpendicular flaw.

MAGNETIC PARTICLE INSPECTION IS PERFORMED IN FOUR STEPS:
Induce a magnetic field in the specimen
Apply magnetic particles to the specimen's surface
View the surface, looking for particle groupings that are caused by defects
Demagnetize and clean the specimen

ADVANTAGES OF MAGNETIC PARTICLE INSPECTION

Can find both surface and near sub-surface defects

Some inspection formats are extremely portable and low cost

Rapid inspection with immediate results

Indications are visible to the inspector directly on the specimen surface

Can detect defects that have been smeared over

Can inspect parts with irregular shapes (external splines, crankshafts, connecting rods, etc.)

LIMITATIONS OF MAGNETIC PARTICLE INSPECTION

The specimen must be ferromagnetic (e.g. steel, cast iron)

Paint thicker than about 0.005" must be removed before inspection

Post cleaning and post demagnetization is often necessary

Maximum depth sensitivity is typically quoted as 0.100" (deeper under perfect conditions)

Alignment between magnetic flux and defect is important

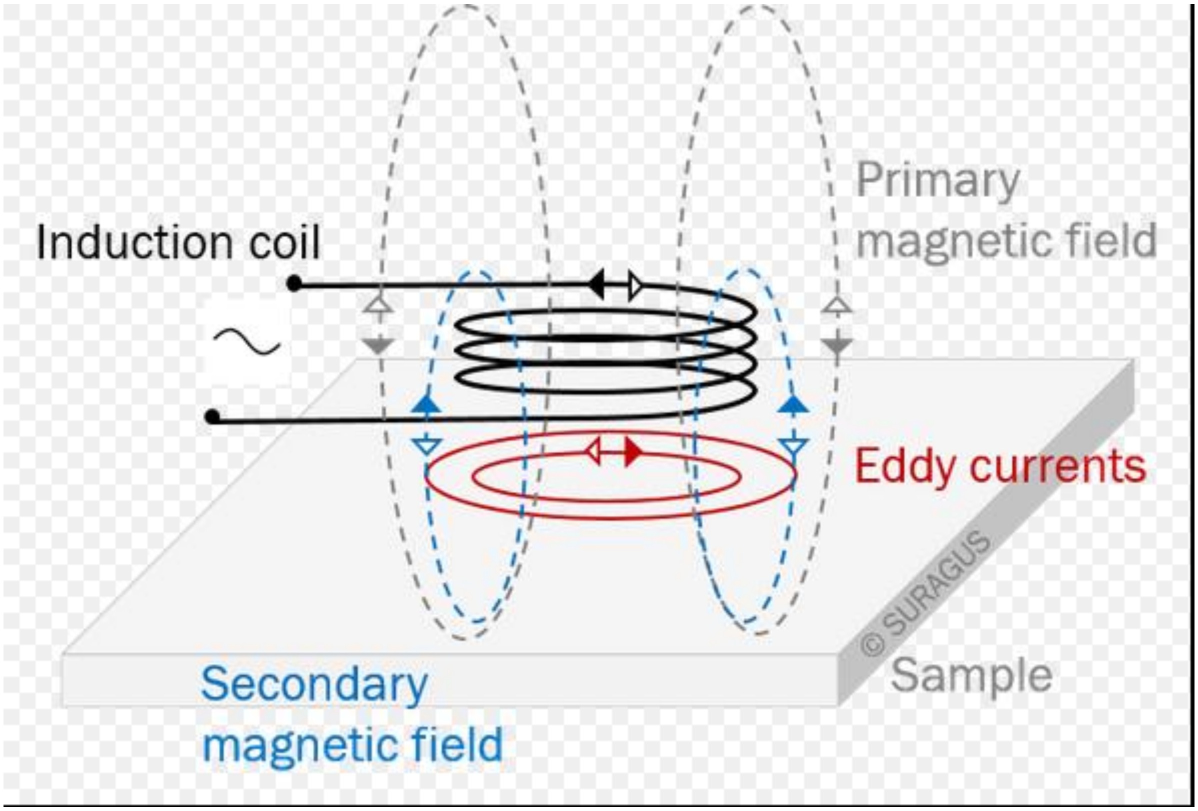
Eddy-current testing

ECT principle

In its most basic form — the single-element ECT probe — a coil of conductive wire is excited with an alternating electrical current. This wire coil produces an alternating magnetic field around itself. The magnetic field oscillates at the same frequency as the current running through the coil. When the coil approaches a conductive material, currents opposite to the ones in the coil are induced in the material — eddy currents.

Variations in the electrical conductivity and magnetic permeability of the test object, and the presence of defects causes a change in eddy current and a corresponding change in phase and amplitude that can be detected by measuring the impedance changes in the coil, which is a telltale sign of the presence of defects. This is the basis of standard (pancake coil) ECT. NDT kits can be used in the eddy current testing process.

ECT has a very wide range of applications. Since ECT is electrical in nature, it is limited to conductive material. There are also physical limits to generating eddy currents and depth of penetration (skin depth).



Applications

The two major applications of eddy current testing are surface inspection and tubing inspections. Surface inspection is used extensively in the aerospace industry, but also in the petrochemical industry. The technique is very sensitive and can detect tight cracks. Surface inspection can be performed both on ferromagnetic and non-ferromagnetic materials.

Tubing inspection is generally limited to non-ferromagnetic tubing and is known as conventional eddy current testing. Conventional ECT is used for inspecting steam generator tubing in nuclear plants and heat exchangers tubing in power and petrochemical industries. The technique is very sensitive to detect and size pits. Wall loss or corrosion can be detected but sizing is not accurate.

A variation of conventional ECT for partially magnetic materials is full saturation ECT. In this technique, permeability variations are suppressed by applying a magnetic field. The saturation probes contain conventional eddy current coils and magnets. This inspection is used on partially ferromagnetic materials such as nickel alloys, duplex alloys, and thin-ferromagnetic materials such as ferritic chromium molybdenum stainless steel. The application of a saturation eddy current technique depends on the permeability of the material, tube thickness, and diameter.

A method used for carbon steel tubing is remote field eddy current testing. This method is sensitive to general wall loss and not sensitive to small pits and cracks.

ECT on surfaces

When it comes to surface applications, the performance of any given inspection technique depends greatly on the specific conditions — mostly the types of materials and defects, but also surface conditions, etc. However, in most situations, the following are true:

Effective on coatings/paint: yes
Computerized record keeping: partial
3D/Advanced imaging: none
User dependence: high
Speed: low
Post-inspection analysis: none
Requires chemicals/consumables: no

Other applications

ECT is also useful in making electrical conductivity and coating thickness measurements, among others.

Other eddy current testing techniques

To circumvent some of the shortcomings of conventional ECT, other eddy current testing techniques were developed with various successes.

Eddy current array

Eddy current array (ECA) and conventional ECT share the same basic working principles. ECA technology provides the ability to electronically drive an array of coils (multiple coils) arranged in specific pattern called a topology that generates a sensitivity profile suited to the target defects. Data acquisition is achieved by multiplexing the coils in a special pattern to avoid mutual inductance between the individual coils. The benefits of ECA are:

Faster inspections
Wider coverage
Less operator dependence — array probes yield more consistent results compared to manual raster scans
Better detection capabilities
Easier analysis because of simpler scan patterns
Improved positioning and sizing because of encoded data

Array probes can easily be designed to be flexible or shaped to specifications, making hard-to-reach areas easier to inspect

ECA technology provides a remarkably powerful tool and saves significant time during inspections. ECA inspection in carbon steel welds is regulated by ASTM standard E3052.

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DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – III- Aircraft Materials– SAEA1201

Unit III

Corrosion and Heat Treatment of Metals and Alloys

Corrosion:

1.Introduction:

1.1 All designers, maintainers, inspectors and owners have a part to play in preventing aircraft being adversely affected by metallic corrosion. They must think about different types of corrosion and those factors that need to be considered during design, design approval and subsequent maintenance. Pilots, aircraft owners and inspectors should also be aware of the possible effects that corrosion might have on an aircraft, what to look for during their routine checks and the potential safety impact if corrosion is overlooked.

1.2 Aircraft designers and inspectors should also be aware of the relevant corrosion protection, inspection and related inspection access design requirements of BCAR Section S, EASA CS-VLA and Acceptable Means of Compliance, (that achieve an equivalent level of safety), when undertaking design approval and acceptance inspections respectively – references are included in the following text.

1.3 General guidance is provided in this publication on the design, assembly and inspection of various parts of an aircraft structure. Those areas that because of their remoteness, complexity or boxed-in nature and are not readily accessible during routine maintenance or require attention in the light of operational experience are highlighted.

1.4 Corrosion can result in a significant decrease in the thickness of original load bearing material that can lead to a loss of structural integrity and potentially to catastrophic failure. In the case of more highly stressed parts, finding and rectifying corrosion damage can help to prevent the early initiation of fatigue cracking from corrosion pits that can also lead to premature structural and catastrophic failures. This has been observed in aluminium alloy forgings and light aircraft landing gear components, where a mixture of exfoliation and pitting corrosion on the flash line initiated stress corrosion cracking that then lead to corrosion fatigue, normal fatigue and exfoliation.

1.5 Routine in-service inspections that lead to the early detection of corrosion and consequent rectification can also prevent more costly, extensive and invasive repair actions later. This can be achieved on Primary structures that are not concealed and can be easily inspected for condition in-service.

1.6 Deterioration of aircraft structure may arise from various causes and can affect all parts of the structure according to the design of the aircraft and the uses to which it is put. This publication should be read in conjunction with the appropriate manufacturer's publications, where provided i.e. OEM Standard Practices and the Maintenance Programme for the aircraft concerned. In addition further information on corrosion can be found as referenced in chapter 14.

1.7 Although guidance may be given in publications as to suitable opportunities for inspecting normally inaccessible structures (e.g. when a wing tip is removed permitting access to the adjacent wing structure) experience should indicate to the operator further opportunities for such inspections which can be included in the Maintenance Programme. Apart from the airworthiness aspects, these combined inspections could often be to the operator's advantage, since they could reduce or remove the need for future dismantling that might otherwise be dedicated to periodic corrosion driven inspections. Thus when access has been gained to a part of the airframe which is normally inaccessible, advantage should be taken of this dismantling to inspect all parts of systems and structures thus exposed.

1.8 When evidence of corrosion is found it is critical that the full extent and nature of the corrosion be established and repaired, even if these means additional access, dismantling or a special inspection technique to facilitate such deeper inspection and subsequent rectification actions.

1.9 The presence of corrosion in aircraft will lead to deterioration in the aircraft's structure which may eventually lead to catastrophic failure. It is therefore essential that any signs of corrosion are detected in the earliest stages of its development, assessed and addressed as appropriate. Development of corrosion over time is influenced by a variety of factors as will be described subsequently.

1.10 Prevention is always better than cure, and by ensuring suitable corrosion protection on individual detail parts prior to and during assembly the onset of corrosion can be prevented or significantly delayed.

2. Theory of corrosion

2.1 Metal corrosion is the deterioration of the metal by chemical or electrochemical attack. This type of damage can take place internally as well as on the surface. As in the rotting of wood, this deterioration may change the smooth surface, weaken the interior, or damage or loosen adjacent parts.

2.2 Water or water vapour containing salt combines with oxygen in the atmosphere to produce the main source of corrosion in aircraft. Aircraft operating in a marine environment, or in areas where the atmosphere contains industrial fumes that are corrosive, are particularly susceptible to corrosive attacks.

Fig:3.1 Direct chemical attack in a battery compartment

2.3 If left unchecked, corrosion can cause eventual structural failure. The appearance of corrosion varies with the metal. On the surface of aluminium alloys and magnesium, it appears as pitting and etching, and is often combined with a grey or white powdery deposit. On copper and copper alloys, the corrosion forms a greenish film; on steel, a reddish corrosion by-product commonly referred to as rust. When the grey, white, green, or reddish deposits are removed, each of the surfaces may appear etched and pitted, depending upon the length of exposure and severity of attack. If these surface pits are not too deep, they may not significantly alter the strength of the metal; however, the pits may become sites for crack development, particularly if the part is highly stressed. Some types of corrosion burrow between the inside of surface coatings and the metal surface, and can spread until the part fails.

Types of Corrosion

2.4 There are two general classifications of corrosion that cover most of the specific forms: direct chemical attack and electrochemical attack. In both types of corrosion, the metal is converted into a metallic compound such as an oxide, hydroxide, or sulphate. The corrosion process always involves two simultaneous changes: The metal that is attacked or oxidized suffers what may be called anodic change, and the corrosive agent is reduced and may be considered as undergoing cathodic change.

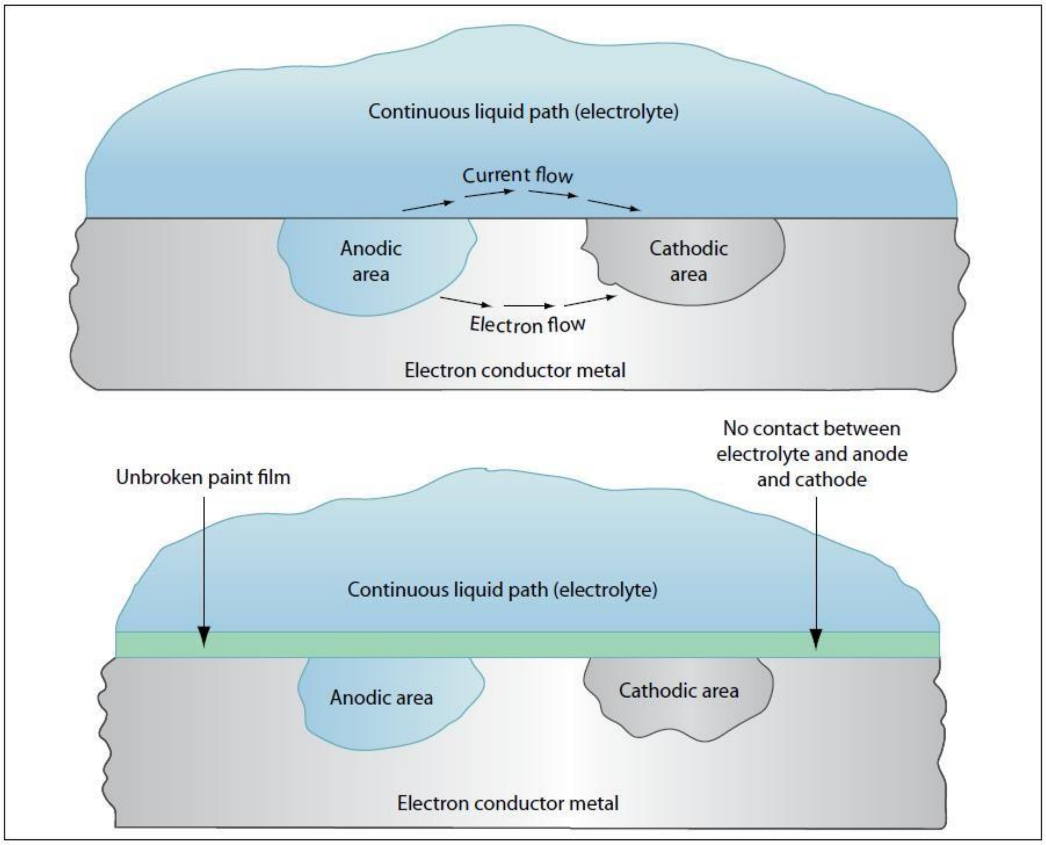


Fig:3.2 Electrochemical attack

Direct Chemical Attack

2.5 Direct chemical attack, or pure chemical corrosion, is an attack resulting from a direct exposure of a bare surface to caustic liquid or gaseous agents. Unlike electrochemical attack where the anodic and cathodic changes may be taking place a measurable distance apart, the changes in direct chemical attack are occurring simultaneously at the same point. The most common agents causing direct chemical attack on aircraft are:

Spilled battery acid or fumes from batteries;

Residual flux deposits resulting from inadequately cleaned, welded, brazed, or soldered joints; and

Entrapped caustic cleaning solutions.

2.6 With the introduction of sealed lead-acid batteries and the use of nickel-cadmium batteries, spilled battery acid is becoming less of a problem. The use of these closed units lessens the hazards of acid spillage and battery fumes.

2.7 Many types of fluxes used in brazing, soldering, and welding are corrosive, and they chemically attack the metals or alloys with which they are used. Therefore, it is important to remove residual flux from the metal surface immediately after the joining operation. Flux residues are hygroscopic in nature; that is, they absorb moisture, and unless carefully removed, tend to cause severe pitting.

2.8 Caustic cleaning solutions in concentrated form should be kept tightly capped and as far from aircraft as possible. Some cleaning solutions used in corrosion removal are, in themselves, potentially corrosive agents; therefore, particular attention should be directed toward their complete removal after use on aircraft. Where entrapment of the cleaning solution is likely to occur, use a noncorrosive cleaning agent, even though it is less efficient.

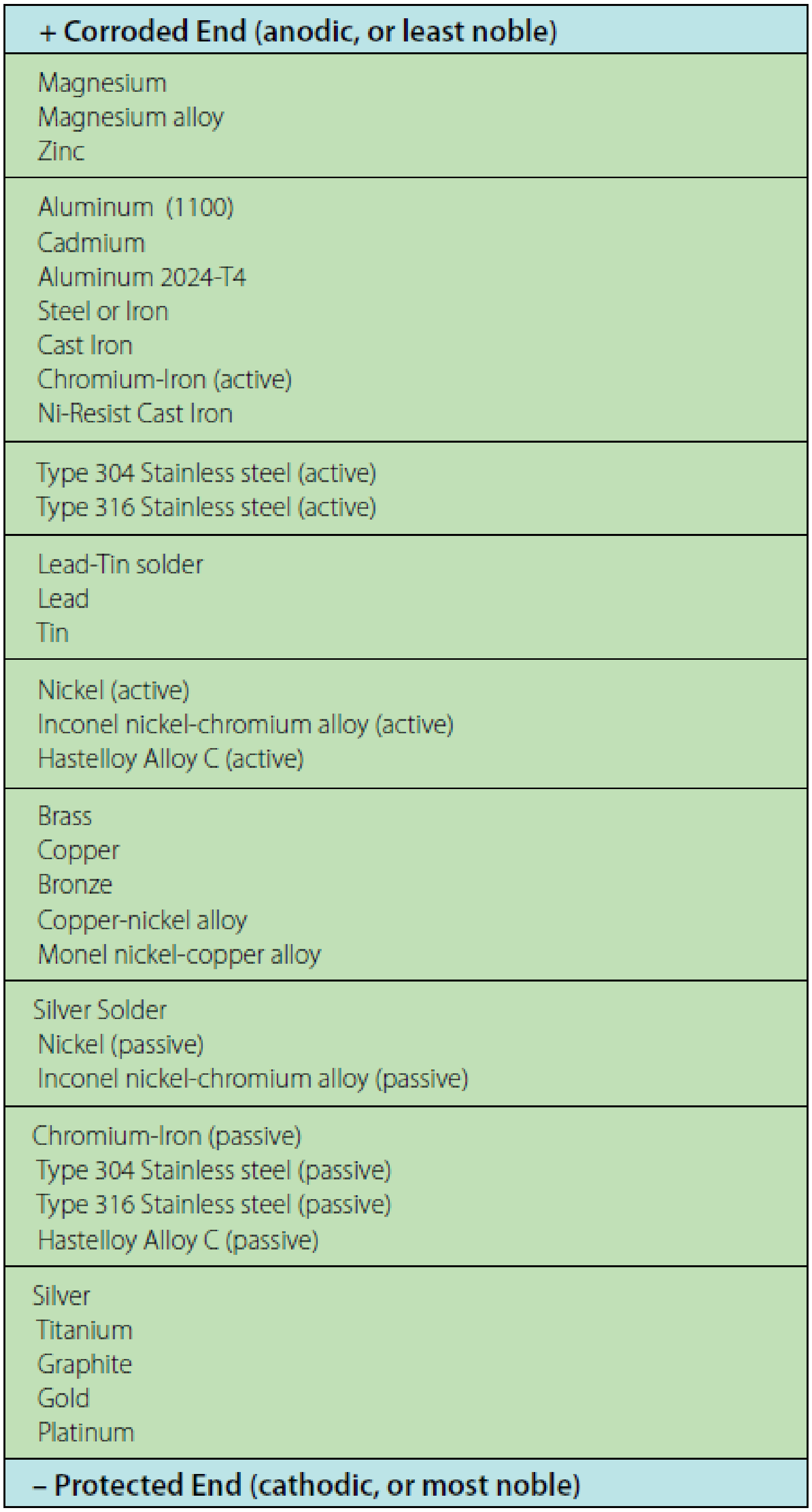
Electrochemical Attack

2.9 An electrochemical attack may be likened chemically to the electrolytic reaction that takes place in electroplating, anodizing, or in a dry cell battery. The reaction in this corrosive attack requires a medium, usually water, which is capable of conducting a tiny current of electricity. When a metal comes in contact with a corrosive agent and is also connected by a liquid or gaseous path through which electrons may flow, corrosion begins as the metal decays by oxidation. During the attack, the quantity of corrosive agent is reduced and, if not renewed or removed, may completely react with the metal, becoming neutralized. Different areas of the same metal surface have varying levels of electrical potential and, if connected by a conductor, such as salt water, will set up a series of corrosion cells and corrosion will commence.

2.10 All metals and alloys are electrically active and have a specific electrical potential in a given chemical environment. This potential is commonly referred to as the metal's "nobility." The less noble a metal is, the more easily it can be corroded. The metals chosen for use in aircraft structures are a studied compromise with strength, weight, corrosion resistance, workability, and cost balanced against the structure's needs.

2.11 The constituents in an alloy also have specific electrical potentials that are generally different from each other. Exposure of the alloy surface to a conductive, corrosive medium causes the more active metal to become anodic and the less active metal to become cathodic, thereby establishing conditions for corrosion. These are called local cells. The greater the difference in electrical potential between the two metals, the greater will be the severity of a corrosive attack, if the proper conditions are allowed to develop.

2.12 The conditions for these corrosion reactions are the presence of a conductive fluid and metals having a difference in potential. If, by regular cleaning and surface refinishing, the medium is removed and the minute electrical circuit eliminated, corrosion cannot occur. This is the basis for effective corrosion control. The electrochemical attack is responsible for most forms of corrosion on aircraft structure and component parts.



+ Corroded End (anodic, or least noble)

Magnesium
Magnesium alloy
Zinc

Aluminum (1100)
Cadmium
Aluminum 2024-T4
Steel or Iron
Cast Iron
Chromium-Iron (active)
Ni-Resist Cast Iron

Type 304 Stainless steel (active)
Type 316 Stainless steel (active)

Lead-Tin solder
Lead
Tin

Nickel (active)
Inconel nickel-chromium alloy (active)
Hastelloy Alloy C (active)

Brass
Copper
Bronze
Copper-nickel alloy
Monel nickel-copper alloy

Silver Solder
Nickel (passive)
Inconel nickel-chromium alloy (passive)

Chromium-Iron (passive)
Type 304 Stainless steel (passive)
Type 316 Stainless steel (passive)
Hastelloy Alloy C (passive)

Silver
Titanium
Graphite
Gold
Platinum

– Protected End (cathodic, or most noble)

Fig:3.3The galvanic series of metals and alloys.

3. Types of corrosion

3.1 Corrosion comes in many forms and can be found on the surface and therefore can be penetrating inside the material; thus the removal of the surface products of corrosion followed by re-protection may not always be effective. Minor corrosion on the surface may hide more significant corrosion within the material structure, this can be true of intergranular corrosion, pitting corrosion as well as stress corrosion cracking. Once the surface is penetrated the reduction in strength due to loss of material can be disproportionate to the reduction in thickness of the metal as the corrosion initiates cracking mechanisms. Voids in structural joints that could allow water /condensate ingress leading to corrosion should be prevented. Means must be provided to allow inspection of Primary Structures in order to ensure that a satisfactory continued airworthy condition is maintained.

3.2 Initial presentation of exfoliation corrosion in components made from aluminium alloy extrusion, plate and bar may show itself as slight dark lines along the grain direction. Exfoliation corrosion is specific to wrought aluminium alloys and occurs due to developed grain structure ‘flat pancake grains’, this grain structure is not developed in any other metallic material. It is a form of intergranular corrosion. These lines are not to be confused with machining marks, as these corrosion marks will be along the axis of the material and not around the circumference. Left untreated this will develop into full scale Exfoliation or surface eruptions and material flakes. Component thickness will increase, as the grain separation forces the material apart, before complete structural failure occurs. Quilting or pin cushioning occurs because the volume of aluminium alloy corrosion is significantly greater than the metal volume. This is a phenomenon that is seen with aluminium alloy structures.

3.3 When general surface corrosion occurs within faying/fastened structures where layers of material are nested together in a joint, a similar characteristic quilting or pin cushion effect can be observed where the surface bulges and distorts outwards between the fasteners due to the expanding pressure of corrosion products.

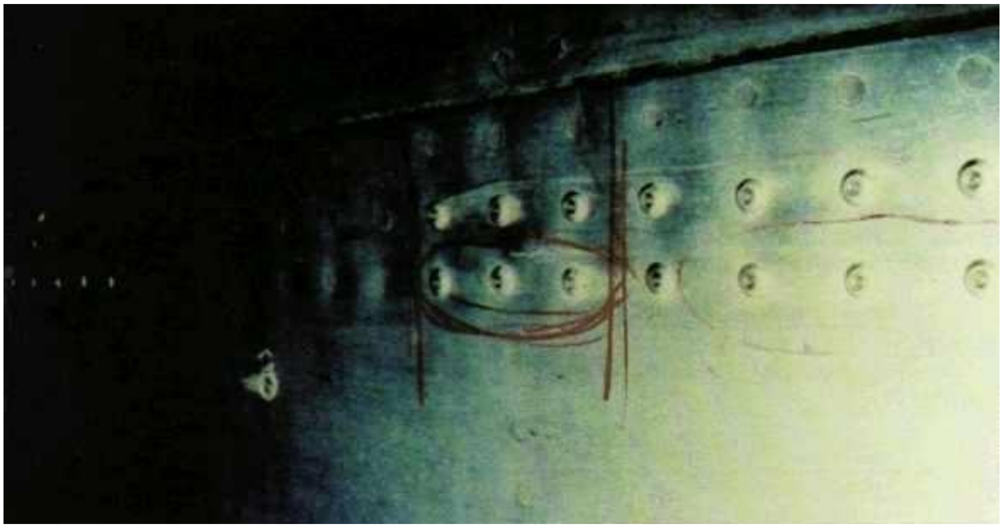


Fig:3.4 Pin cushion effect at a fuselage lap joint – in more extreme case and more particularly with countersunk fasteners the fastener heads can either pull through or fail entirely

3.4 It may not be possible to determine the deterioration of material strength in Aluminium Alloy Primary Structure items, when assessing the extent of sub- surface corrosion using any known methods i.e. x-ray, ultrasound, and thus component replacement may be the only safe solution. Suitably effective individual part corrosion protection applied both before and during assembly can help to delay if not prevent corrosion in joints.

3.5 The following content is generally reflective of the typical types of corrosion as found with aluminium alloys, which tend to be more commonly used in the construction of light aircraft, however it should be borne in mind that most non- noble metals can corrode. Alloys including titanium alloys and steels can similarly be prone to corrosion. Even “non-corroding”/stainless types can corrode when exposed to particularly aggressive environments, (industrial chemical/saline etc., atmospheres under severe corrosion conditions), and stainless steel may also be prone to cracking when subjected to higher temperatures. Note that corrosion symptoms may present slightly differently in these other materials when compared to corrosion of aluminium alloys indeed it should be noted that different classes of alloy (2000 series, 6000 series, 7000 series) differ greatly in their corrosion resistance.

Anodic (Galvanic) corrosion

3.6 This form of corrosion arises when two dissimilar metals are in contact in the presence of an electrolyte, (usually present in the form of precipitation and condensation combined with atmospheric pollutants and spillages). Aluminium alloy is by its very nature of being an alloy, is comprised of dissimilar metals, (mainly aluminium, plus copper, magnesium and manganese), therefore any exposure of that base alloy material to water in service without suitable protection will produce corrosion which will not necessarily be restricted to the surface where powder-like white or grey deposits can be observed. Note that carbon fibres in contact with aluminium can also set up a galvanic cell and an interfay material such a glass fibre / epoxy scrim on the surface of the carbon composite can be successfully employed as a barrier layer. Surface protection can generally assist in prevention, but using the same material in contact in a joint or a more careful choice of the materials that are closer on the electrochemical scale is generally seen as an effective preventative measure - it is not always feasible or practical to prevent dissimilar metal on metal contact when constructing traditional metallic fastener joined structures made of metals or carbon fibre reinforced materials. Joint protection provided by using a "surplus of approved jointing compound" for the prevention of joint internal voids as a preventative of water ingress into joint by capillary action can be employed.

Fig:3.5 Aluminium alloy fitting attachments used to mount carbon fibre composite flying surfaces to fuselage - absence of paint / interfaying GRP shim has allowed aluminium on carbon contact creating a galvanic cell with the aluminium "sacrificed".

Intergranular Corrosion

3.7 This form of corrosion usually presents itself as cracking and tends to accelerate with the passage of time. A combination of chemical and electrolytic actions attack the material along the grain boundaries when the surface protective coating is damaged allowing moisture and corrosive agents to enter. A series of protective barriers comprising paint, primer and using a cladded aluminium sheet or plate material (i.e. a near pure aluminium outer clad layer) can help to protect the base structural material. All exposure of the Aluminium Alloy base metal from drilling or sheared edges produced during initial assembly, will remove or bypass the clad surface protection applied by the material manufacturer, and breaches in the cladding should be suitably re-protected from corrosion preferably by anodising or as a minimum by acid etch painting to be applied before final assembly with the use of, where applicable, an approved joint sealant. After final assembly, it is advisable that all joints should be sprayed with an acid etch primer, this will have the advantage of protecting newly formed rivet tails, exposed bolt threads and by leaching into any unprotected gaps/surfaces. This should prevent the capillary action of water condensate occupying those potential voids, and has the additional benefit of providing a suitable keying surface for subsequent additional painting.

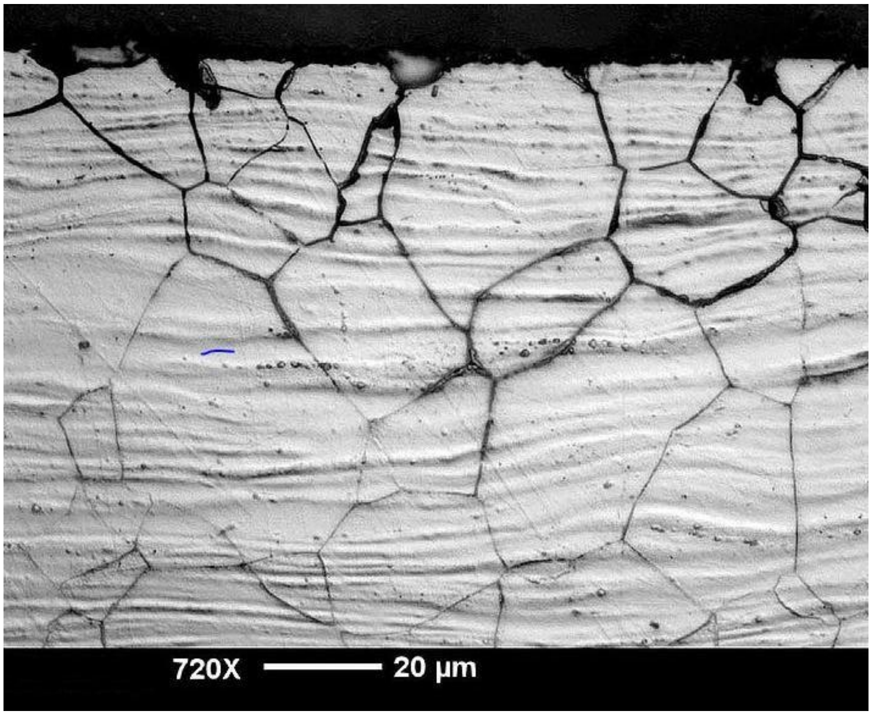


Fig:3.5 Intergranular corrosion in austenitic cold rolled stainless steel

Filiform surface corrosion

3.8 In this case the corrosion presents as random threadlike filaments under the paint often with the paint bulging in blisters raised by the corrosion products. Cracks or damage to the paint allow corrosive moisture ingress and surface localized active corrosion cells. More severe in high humidity, marine and industrially polluted environments.

Fig:3.6 Filiform corrosion example

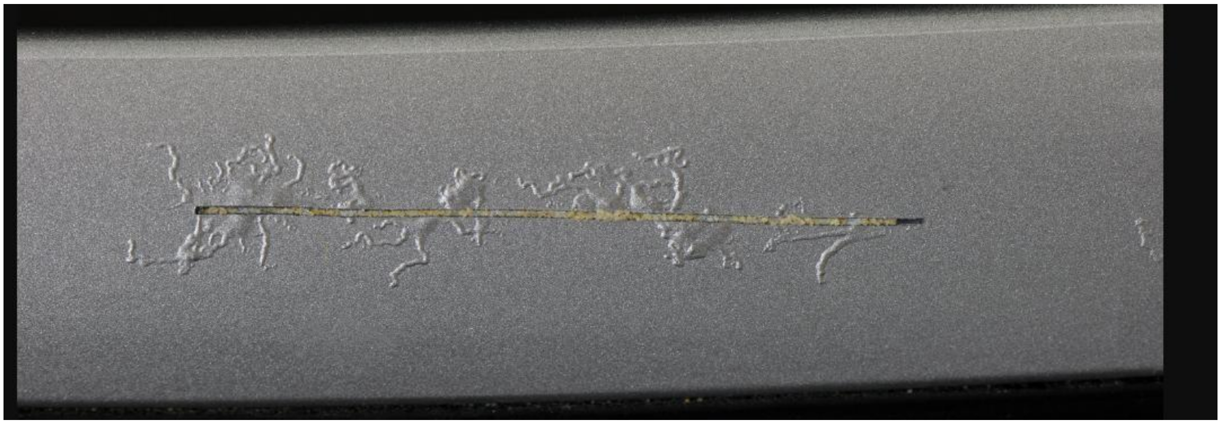


Fig:3.7 Filiform corrosion spreading from scribe on painted aluminium after complete accelerated corrosion testing

Pitting or General Surface Corrosion

3.9 As the name implies the former involves the creation of localized pits / small holes in the material surface which can be deep and significant to structural integrity whilst the latter corrosion form starts with a more widely dispersed uniform surface etching that dulls the surface and can progress to generate a rougher or frosted surface appearance.

3.10 Corrosive agents create a local electrolytic cell when the protective surface coating is no longer in a good condition particularly in conjunction with unclean surface conditions that help to harbour moisture / corrosive medium. Pitting traps the electrolyte within the pit and the composition of the electrolyte will change as the corrosion progresses. With the change in electrolyte composition the corrosion can accelerate and/or change form to stress corrosion cracking or corrosion fatigue.

Fig:3.8 GA aircraft empennage structure – surface and pitting corrosion of tailplane internal rib section found after accident damaged parts were removed for component replacement.

Fig:3.9 Pitting seen on vintage aircraft engine crankshaft

Stress Corrosion Cracking

3.11 Presents generally as cracking only, (usually fast crack growth), especially in higher strength alloy materials with negligible corrosion product. This phenomenon arises due to a combination of high tensile stresses, (standing and/or alternating stress usually approaching the tensile yield strength of the material), together with a corrosive environment. Such stresses can arise due to locked-in stresses resulting from some aspects of material heat treatment, incorrect fits and tolerances on mating parts or inappropriate assembly practices. Rapid crack growth can lead to sudden and complete failure of structural parts.

4. Causes of corrosion

4.1 Many factors affect the type, speed, cause, and seriousness of metal corrosion. Some of these factors can be controlled and some cannot.

Climate

4.2 The environmental conditions under which an aircraft is maintained and operated greatly affect corrosion characteristics. In a predominately marine environment (with exposure to sea water and salt air), moisture-laden air is considerably more detrimental to an aircraft than it would be if all operations were conducted in a dry climate. Temperature considerations are important because the speed of electrochemical attack is increased in a hot, moist climate.

Foreign Material

4.3 Among the controllable factors which affect the onset and spread of corrosive attack is foreign material that adheres to the metal surfaces. Such foreign material includes:
Soil and atmospheric dust.
Oil, grease, and engine exhaust residues.
Salt water and salt moisture condensation.
Spilled battery acids and caustic cleaning solutions.
Welding and brazing flux residues.

4.4 It is important that aircraft be kept clean. How often and to what extent an aircraft should be cleaned depends on several factors, including geographic location, model of aircraft, and type of operation.

5. Environment

5.1 Low temperature corrosive attack on an aircraft structure will not occur without the presence of water in some form in contact with an exposed metallic surface as corrosion requires the presence of an electrolyte to conduct electrons and positive ions for it to occur. However, a fact less well appreciated is that, in a wide variety of ambient conditions, condensation will form on various parts of the structure and inside structure members i.e. tube assemblies, both welded and bolted and this moisture is one of the main causes of corrosion. This type of corrosion may exhibit no external evidence of the internal deterioration presenting particular inspection and detection challenges.

5.2 By the nature of their operation, aircraft are exposed to frequent changes of atmospheric temperature and pressure and to varying conditions of relative humidity; therefore, all parts of the structure , even those considered as “closed” or “sealed” can be subject over time to the progressive ingress of moist air leading to condensation. The resultant water takes into solution a number of corrosive agents from the atmosphere or from spillages (which convert the water into a weak acid) and which will corrode most metal surfaces where the protective treatment has been damaged or is inadequate. Cases of serious corrosion have been found in both closed and exposed parts of structures of aircraft operated under a wide variety of conditions.

6. Spillage

6.1 Spillage or system leaks of extraneous fluids which may penetrate the structure during maintenance, repair or operation of the aircraft, should be carefully traced and thoroughly cleaned out. Where required, any protective treatment should be restored. Fluids such as ester-based engine oils, Hydraulic oils, coolant fluid, glycol defrosting fluids, etc., will damage most protective treatments not intended to be in contact with them. Accidental spillage of refreshments such as mineral waters, coffee, etc., can have a particularly deleterious effect on floor structures.

6.2 Battery compartments should be examined for any signs of acid corrosion. Compartment vents should be clean and undamaged and the anti-sulphuric protective treatment should be carefully maintained. Special attention should be given to the structure in the immediate vicinity of the battery for any signs of corrosion caused by acid spillage or a damaged battery. It should be noted that heavy concentrations of battery fumes, resulting from faulty compartment venting or a runaway battery, may also lead to corrosion in the surrounding structure.

Note: If there is any indication of corrosion, the parts affected should be cleaned with a solution of water and washing soda, then rinsed with fresh water and dried out. After 24 hours a re-check should be made to further test all joints suspected of contact with spillage of acid with litmus paper, this area may be treated with alkaline, baking powder, checked for signs of corrosion and, if satisfactory, the protective treatment should then be restored.

6.3 The spillage of mercury in an aircraft can have devastating effects on any aluminium alloy skin or structure with which it comes into contact, (the mercury creates an amalgam with any exposed aluminium, removing the normal protective aluminium oxide layer and commences a cycle of rapid chemical degradation which can result in a write-off for the structure). Thus carriage of mercury or items containing mercury by aircraft should generally be avoided or handled with appropriate “dangerous goods” precautions for packaging, handling etc., in order to minimize the probability of a spill.

7. Exhaust gasses

7.1 Structural parts which are exposed to exhaust gases are prone to corrosion due to the sulphur content of exhaust gases and jet efflux. Although this problem can be reduced by regular and thorough cleaning, particular attention should be given to the condition of the protective treatment of these structures

Fig:3.10 Auxiliary Power Unit (APU) exhaust as well as engine exhaust areas need particular protection and regular inspection

8. Corrosion prevention

8.1 The manufacturer's publications may give general guidance on the inspection of those parts of the structure which are most likely to be attacked by corrosion. Nevertheless, it should be noted that, in the light of operational experience, other parts of the structure may require special attention. Engineers and Inspectors should be on the alert for any signs of corrosion in parts of the structure not specifically mentioned in the manufacturer's publications or instructions. Amateur builders/designers may not always be fully aware of the BCAR Section S609, 611 and EASA CS VLA 609, 611, 627 design requirements, and therefore those organizations charged with Inspecting and approving those designs as suitable for the issue of a Permit to Fly should check to ensure compliance with those requirements particularly with respect to Primary Structure items. Where direct compliance with the design requirements cannot be shown an Alternative Means of Compliance which has a comparable level of safety should be established.

8.2 GRP bonding to painted surfaces should be avoided as the painted surface may be adversely affected during the subsequent GRP resin cure with the resultant bond strength restricted to that provided by the impaired painted surface.

8.3 Where primary structural items are bonded (for example metallic fittings attached to Glass Reinforced Polymer (GRP) structural assemblies), it is essential that precautions are taken to ensure all surfaces within bonded areas comply with suitable and compatible corrosion protection procedures.

8.4 In 'blind' or boxed-in structures where accessibility is difficult and where cleaning and maintenance are awkward, swarf, dirt and dust tend to collect and lodge in various parts. This material can act as a 'wick' resulting in capillary action for moisture which, in the course of time, will work through any inadequate protective treatment and penetrate to the metal to act as an electrolyte. Even on new aircraft the problem is still present in some boxed-in or intricate structures.

Note: Protective treatments with a rough surface finish, such as primer paints, tend to hold dust and dirt and cleaning is rendered more difficult because of this tendency of swarf, dust and dirt to adhere to such surfaces. Dust allows a Wick effect to collect condensate, which is why steel tubes corrode on the top surfaces first. Hard gloss finishes, such as epoxy resin paints, will provide a more effective and lasting protection. Water based paints by their very nature are less tolerant of joint sealant and oils and grease on surfaces, and they may also not be compatible with previous coats of paint on the structure such as acid etch primer or cellulose-based primers. In addition water based paints tend to have lower joint penetration capability due to water surface tension. Therefore it is preferred that after structural assembly that further corrosion protection is provided by acid etch and cellulose based paints, this will allow joint penetration by capillary action of that corrosion preventive and will therefore be more effective.

8.5 Completely boxed-in structures should be adequately vented to prevent stagnation of the internal air. It is important to ensure that vents and drain holes are clear, are of the correct size and are unobstructed by ice in freezing conditions on the ground, nor obstructed by any dirt or debris, excess paint or protective compounds. Designs should aim if possible, to provide positive ventilation to reduce condensation.

8.6 Honeycomb structures, especially those in components of small cross-sectional area (e.g. wing flaps, rudders, ailerons and spoilers), are often prone to the collection of water if careful attention has not been given to the sealing around attachment screw holes and at skin joints to prevent the ingress of moisture. Water can also accumulate from condensation of moist air when drawn into the structure by changes in operating altitude and pressure, when sealing of the structure has not been initially achieved or as a result of deterioration of that sealing, Cases are known where the trapped water in the structure has frozen and caused distortion of the outer skin of the component due to internal expansion – both this expansion and internal corrosion can lead to separation of the skin from the internal honeycomb which means that the sandwich panel loses structural stiffness and structural integrity can be lost leading to component failure. In addition it should be noted that water trapped inside trailing edges can affect the balance of control surfaces that could potentially lead to control flutter, surface failure and loss of control. Similarly it should be noted that GRP covered foam core structures and control surfaces can also be susceptible to water ingress particularly when the surface protection is damaged or degraded and when aircraft are stored outside.

8.7 Fuselage keel areas, structures concealed by upholstery and the double skin of baggage or freight bay floors, are typical areas liable to corrosion. Special attention should be given to all faying surfaces in these areas where layers of material are nested together in a joint and particularly the faying surfaces of bulkheads and stringers to skin panels and skin lap joints. In general, visual inspection supplemented by radiological methods of examination is a satisfactory way of detecting corrosion, provided it is expertly carried out and proper correlation between the findings of each method is maintained. In some instances, however, normal methods of visual inspection supplemented by radiological examination have not proved satisfactory and dismantling of parts of the structure may be required to verify the condition of the faying surfaces.

8.8 Structures manufactured from light gauge materials which are spot-welded together, such as the faying surfaces of stringers mentioned in the previous paragraph, are liable to serious and rapid corrosion as this method of attachment precludes the normal anti-corrosive treatments (e.g. jointing compound) at the joined surfaces. Cases of serious corrosion have also been found in similar structures riveted together where the jointing compound has been found to be inadequate or non-existent. It is recommended that all mechanically fastened joints should be assembled with a surplus of approved jointing compound, and after compression of the joint upon assembly any surplus jointing compound is then wiped away, to leave a small bead of jointing compound around the joint, this will have an added protection for any Alclad sheet exposed alloy material edges on items forming the structure. The application of acid etch paint by spraying after assembly is recommended; this paint penetrates by capillary action into joint gaps, filling voids and protecting any untreated edges. Acid etch primer will also provide a strong key to secure further paint coatings.

8.9 In some instances, where stringers are of top-hat section and are bonded to the panel by a thermosetting adhesive, corrosion has been known to affect the stringers, the panel and the bonding medium; such stringers are often sealed at their ends to prevent the ingress of moisture. Unfortunately moisture can be drawn and trapped inside these components This can trap water inside the stringer and corrosion can develop should any breach of protection occur, Where adhesive is used to attach a doubler to a skin, corrosion can occur between the surfaces and will eventually be indicated by a quilted appearance. It is preferable for designers to use L or Z section stringers for structural support which do not have internal cavities

8.10 Where light alloy is spot-welded and for other assemblies that cannot be assembled with a jointing compound such as Duralac or JC5, to consider the use of a water dispersant such as ACF 50 on the completed structure.

8.11 Avoid over over-painting joints with only top coat paint, especially when the joint corrosion protection is not entirely suitable. Over-coating with poorly adhered top coating paint may allow water to penetrate by capillary action under that top coat paint and result in more severe joint corrosion forming under and concealed by that paint in service.

8.12 A basic level of corrosion protection is inherent on aluminium alloy parts by surface oxidation. This may be significantly enhanced by surface conversion i.e. anodising. Further protection may be achieved by application of acid etch or chromate primer and paint. Application of Alocrom 1200 process protection by brush, swab, spay or dip methodology is also worth noting as an easier alternative to anodizing. Any degradation of any one of these layers of protection, when cutting or machining during construction, repair or modification, needs to be reinstated in an appropriate manner. If this cannot be achieved for example at fastener holes, suitable protection for prevention of water contact at those areas without surface corrosion protection may be achieved by using an approved jointing compound, also called "wet assembly". This will reduce water penetration which would otherwise allow corrosion between dissimilar metals used in that assembly due to the formation of galvanic cells inside that joint.

8.13 Alloy steels may be protected by cadmium or zinc plating – disruption of these layers during assembly or manufacture should also be similarly repaired with joints protected from water ingress. Note that cadmium plating of high strength steels and subsequent hydrogen de-embrittlement processes need to be tightly controlled by an approved heat treatment supplier in order to prevent premature internal component failures due to hydrogen embrittlement.

8.14 Alclad alloy sheet or plate material as previously noted is manufactured with a very thin layer of almost pure aluminium for surface corrosion protection on each face which can be damaged by careless storage, handling, scribing etc.,. Additional protection can be afforded by suitable painting to provide a barrier to guard against condensation and moisture ingress etc., in service. Care should be taken prior to or during assembly to paint and protect the sheet/plate material edges where the core load bearing alloy material would otherwise be exposed. Internal wing and fuselage tailplane skin and frame surfaces that are not generally accessible in service should be painted to prevent corrosion salt spots forming at dust accumulations in service.

8.15 Care is needed in anodizing high strength alloys as this can lead to reduced fatigue characteristics. Anodising is more often used on machined parts rather than Alclad sheet. Welded steel tube assemblies ideally should be internally treated with lanolin or similar materials and then sealed off to prevent corrosion. Unprotected welded steel tube assemblies may corrode internally and display no external evidence of corrosion and thus may require X/Ray inspections to validate. Many aircraft, in particular of foreign construction, do not receive such internal surface protective treatments, so need careful frequent inspection during the aircraft life. Corrosion progresses even during storage, as well as during active operation.

8.16 Protection against crevice corrosion can be afforded by ensuring that joints are assembled using a suitable jointing compound, avoiding voids in the assembly to prevent water ingress caused by the capillary action. Crevice corrosion arises due to the increased concentration of the electrolyte within a crevice due to repeated wetting and evaporation. This may result in oxygen concentration cells concealed within the joint faying surfaces.

Heat Treatment Process

Introduction

- Heat treating is a group of industrial and metalworking processes used to alter the physical, and sometimes chemical, properties of a material.
- The most common application is metallurgical.
- Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material.
- Heat treatment techniques include annealing, case hardening, precipitation, strengthening,
temperingand quenching.
- It is noteworthy that while the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding.

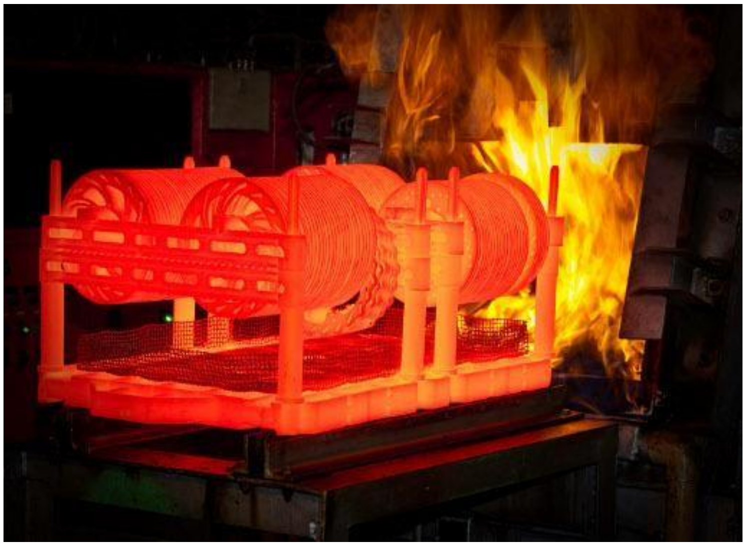


Fig:3.11 Heat Treating Plate

Annealing

Annealing is a rather generalized term. Annealing consists of heating a metal to a specific temperature and then cooling at a rate that will produce a refined microstructure. The rate of cooling is generally slow. Annealing is most often used to soften a metal for cold working, to improve machinability, or to enhance properties like electrical conductivity.

In ferrous alloys, annealing is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation of pearlite. In both pure metals and many alloys that cannot be heat treated, annealing is used to remove the hardness caused by cold working. The metal is heated to a temperature where recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have little effect. Most non- ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working. These may be slowly cooled to allow full precipitation of the constituents and produce a refined microstructure.

Ferrous alloys are usually either "full annealed" or "process annealed." Full annealing requires very slow cooling rates, in order to form coarse pearlite. In process annealing, the cooling rate may be faster; up to, and including normalizing. The main goal of process annealing is to produce a uniform microstructure. Non-ferrous alloys are often subjected to a variety of annealing techniques, including "recrystallization annealing," "partial annealing," "full annealing," and "final annealing." Not all annealing techniques involve recrystallization, such as stress relieving.

Normalizing

Normalizing is a technique used to provide uniformity in grain size and composition throughout an alloy. The term is often used for ferrous alloys that have been austenitized and then cooled in open air. Normalizing not only produces pearlite, but also bainite sometimes martensite, which gives harder and stronger steel, but with less ductility for the same composition than full annealing.

Stress relieving

Stress relieving is a technique to remove or reduce the internal stresses created in a metal. These stresses may be caused in a number of ways, ranging from cold working to non-uniform cooling. Stress relieving is usually accomplished by heating a metal below the lower critical temperature and then cooling uniformly.

Aging

Some metals are classified as precipitation hardening metals. When a precipitation hardening alloy is quenched, its alloying elements will be trapped in solution, resulting in a soft metal. Aging a "solutionized" metal will allow the alloying elements to diffuse through the microstructure and form intermetallic particles. These intermetallic particles will nucleate and fall out of solution and act as a reinforcing phase, thereby increasing the strength of the alloy. Alloys may age "naturally" meaning that the precipitates form at room temperature, or they may age "artificially" when precipitates only form at elevated temperatures. In some applications, naturally aging alloys may be stored in a freezer to prevent hardening until after further operations - assembly of rivets, for example, may be easier with a softer part.

Examples of precipitation hardening alloys include 2000 series, 6000 series, and 7000 series aluminium alloy, as well as some super alloys and some stainless steels. Steels that harden by aging are typically referred to as maraging steels, from a combination of the term "martensite aging."

Quenching

Quenching is a process of cooling a metal at a rapid rate. This is most often done to produce a martensite transformation. In ferrous alloys, this will often produce a harder metal, while non-ferrous alloys will usually become softer than normal.

To harden by quenching, a metal (usually steel or cast iron) must be heated above the upper critical temperature and then quickly cooled. Depending on the alloy and other considerations (such as concern for maximum hardness vs. cracking and distortion), cooling may be done with forced air or other gases, (such as nitrogen). Liquids may be used, due to their better thermal conductivity, such as oil, water, a polymer dissolved in water, or a brine. Upon being rapidly cooled, a portion of austenite (dependent on alloy composition) will transform to martensite, a hard, brittle crystalline structure. The quenched hardness of a metal depends on its chemical composition and quenching method. Cooling speeds, from fastest to slowest, go from fresh water, brine, polymer (i.e. mixtures of water + glycol polymers), oil, and forced air. However, quenching a certain steel too fast can result in cracking, which is why high-tensile steels such as AISI 4140 should be quenched in oil, tool steels such as ISO 1.2767 or H13 hot work tool steel should be quenched in forced air, and low alloy or medium-tensile steels such as XK1320 or AISI 1040 should be quenched in brine.

However, most non-ferrous metals, like alloys of copper, aluminum, or nickel, and some high alloy steels such as austenitic stainless steel (304, 316), produce an opposite effect when these are quenched: they soften. Austenitic stainless steels must be quenched to become fully corrosion resistant, as they work- harden significantly.

Tempering

Untampered martensitic steel, while very hard, is too brittle to be useful for most applications. A method for alleviating this problem is called tempering. Most applications require that quenched parts be tempered. Tempering consists of heating steel below the lower critical temperature, (often from 400 to 1105 ˚F or 205 to 595 ˚C, depending on the desired results), to impart some toughness. Higher tempering temperatures (may be up to 1,300 ˚F or 700 ˚C, depending on the alloy and application) are sometimes used to impart further ductility, although some yield strength is lost.

Tempering may also be performed on normalized steels. Other methods of tempering consist of quenching to a specific temperature, which is above the martensite start temperature, and then holding it there until pure bainite can form or internal stresses can be relieved. These include austempering and martempering.

Tempering colors of steel

Steel that has been freshly ground or polished will form oxide layers when heated. At a very specific temperature, the iron oxide will form a layer with a very specific thickness, causing thin-film interference. This causes colors to appear on the surface of the steel. As temperature is increased, the iron oxide layer grows in thickness, changing the color.[19] These colors, called tempering colors, have been used for centuries to gauge the temperature of the metal. At around 350˚F (176˚C) the steel will start to take on a very light, yellowish hue. At 400˚F (204˚C), the steel will become a noticeable light-straw color, and at 440˚F (226˚C), the color will become dark-straw. At 500˚F (260˚C), steel will turn brown, while at 540˚F (282˚C) it will turn purple. At 590˚F (310˚C) the steel turns a very deep blue, but at 640˚F (337˚C) it becomes a rather light blue.

The tempering colors can be used to judge the final properties of the tempered steel. Very hard tool steel is often tempered in the light to dark straw range, whereas spring steel is often tempered to the blue. However, the final hardness of the tempered steel will vary, depending on the composition of the steel. The oxide film will also increase in thickness over time. Therefore, steel that has been held at 400˚F for a very long time may turn brown or purple, even though the temperature never exceeded that needed to produce a light straw color. Other factors affecting the final outcome are oil films on the surface and the type of heat source used.

Many heat treating methods have been developed to alter the properties of only a portion of an object. These tend to consist of either cooling different areas of an alloy at different rates, by quickly heating in a localized area and then quenching, by thermochemical diffusion, or by tempering different areas of an object at different temperatures, such as in differential tempering.

Differential hardening

A differentially hardened katana. The bright, wavy line following the hamon, called the nioi, separates the martensitic edge from the pearlitic back. The inset shows a close-up of the nioi, which is made up of individual martensite grains (niye) surrounded by pearlite. The wood-grain appearance comes from layers of different composition.

Some techniques allow different areas of a single object to receive different heat treatments. This is called differential hardening. It is common in high quality knives and swords. The Chinese jian is one of the earliest known examples of this, and the Japanese katana may be the most widely known. The Nepalese Khukuri is another example. This technique uses an insulating layer, like layers of clay, to cover the areas that are to remain soft. The areas to be hardened are left exposed, allowing only certain parts of the steel to fully harden when quenched.

Flame hardening

Flame hardening is used to harden only a portion of a metal. Unlike differential hardening, where the entire piece is heated and then cooled at different rates, in flame hardening, only a portion of the metal is heated before quenching. This is usually easier than differential hardening, but often produces an extremely brittle zone between the heated metal and the unheated metal, as cooling at the edge of this heat affected zone is extremely rapid.

Induction hardening

Induction hardening is a surface hardening technique in which the surface of the metal is heated very quickly, using a no-contact method of induction heating. The alloy is then quenched, producing a martensite transformation at the surface while leaving the underlying metal unchanged. This creates a very hard, wear resistant surface while maintaining the proper toughness in the majority of the object. Crankshaft journals are a good example of an induction hardened surface.

Case hardening

Case hardening is a thermochemical diffusion process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness.

Laser surface engineering is a surface treatment with high versatility, selectivity and novel properties. Since the cooling rate is very high in laser treatment, metastable even metallic glass can be obtained by this method.

Cold and cryogenic treating

Although quenching steel causes the austenite to transform into martensite, all of the austenite usually does not transform. Some austenite crystals will remain unchanged even after quenching below the martensite finish (Mf) temperature. Further transformation of the austenite into martensite can be induced by slowly cooling the metal to extremely low temperatures. Cold treating generally consists of cooling the steel to around -115 ˚F (-81 ˚C), but does not eliminate all of the austenite. Cryogenic treating usually consists of cooling to much lower temperatures, often in the range of -315 ˚F (-192 ˚C), to transform most of the austenite into martensite.

Cold and cryogenic treatments are typically done immediately after quenching, before any tempering, and will increase the hardness, wear resistance, and reduce the internal stresses in the metal but, because it is really an extension of the quenching process, it may increase the chances of cracking during the procedure. The process is often used for tools, bearings, or other items that require good wear resistance. However, it is usually only effective in high-carbon or high-alloy steels in which more than 10% austenite is retained after quenching.

Decarburization

The heating of steel is sometimes used as a method to alter the carbon content. When steel is heated in an oxidizing environment, the oxygen combines with the iron to form an iron-oxide layer, which protects the steel from decarburization. When the steel turns to austenite, however, the oxygen combines with iron to form slag, which provides no protection from decarburization. The formation of slag and scale actually increases decarburization, because the iron oxide keeps oxygen in contact with the decarburization zone even after the steel is moved into an oxygen-free environment, such as the coals of a forge. Thus, the carbon atoms begin combining with the surrounding scale and slag to form both carbon monoxide and carbon dioxide, which is released into the air.

Steel contains a relatively small percentage of carbon, which can migrate freely within the gamma iron. When austenized steel is exposed to air for long periods of time, the carbon content in the steel can be lowered. This is the opposite from what happens when steel is heated in a reducing environment, in which carbon slowly diffuses further into the metal. In an oxidizing environment, the carbon can readily diffuse outwardly, so austenized steel is very susceptible to decarburization. This is often used for cast steel, where a high carbon-content is needed for casting, but a lower carbon-content is desired in the finished product. It is often used on cast-irons to produce malleable cast iron, in a process called "white tempering." This tendency to decarburize is often a problem in other operations, such as blacksmithing, where it becomes more desirable to austenize the steel for the shortest amount of time possible to prevent too much decarburization.

Specification

Usually the end condition is specified instead of the process used in heat treatment.

Case hardening

A modern, fully computerized case hardening furnace.

Case hardening is specified by hardness and case depth. The case depth can be specified in two ways: total case depth or effective case depth. The total case depth is the true depth of the case. For most alloys, the effective case depth is the depth of the case that has a hardness equivalent of HRC50; however, some alloys specify a different hardness (40-60 HRC) at effective case depth; this is checked on a Tukonmicrohardness tester. This value can be roughly approximated as 65% of the total case depth; however the chemical composition and hardenability can affect this approximation. If neither type of case depth is specified the total case depth is assumed.

For case hardened parts the specification should have a tolerance of at least ±0.005 in (0.13 mm). If the part is to be ground after heat treatment, the case depth is assumed to be after grinding.

The Rockwell hardness scale used for the specification depends on the depth of the total case depth, as shown in the table below. Usually hardness is measured on the Rockwell "C" scale, but the load used on the scale will penetrate through the case if the case is less than 0.030 in (0.76 mm). Using Rockwell "C" for a thinner case will result in a false reading.

Rockwell scale required for various case depths

Total case depth, min. [in]	Rockwell scale
0.030	C
0.024	A
0.021	45N
0.018	30N
0.015	15N
Less than 0.015	"File hard"

For cases that are less than 0.015 in (0.38 mm) thick a Rockwell scale cannot reliably be used, so file hard is specified instead. File hard is approximately equivalent to 58 HRC.

When specifying the hardness either a range should be given or the minimum hardness specified. If a range is specified at least 5 points should be given.

Through hardening

Only hardness is listed for through hardening. It is usually in the form of HRC with at least a five point range.

Annealing

The hardness for an annealing process is usually listed on the HRB scale as a maximum value. It is a process to refine grain size, improve strength, remove residual stress and affect the electromagnetic properties.

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UNIT – IV- Aircraft Materials– SAEA1201

Unit IV

Ceramics and Composites

AIRCRAFT COMPOSITE

What is a composite? A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc. Give some examples of naturally found composites. Examples include wood, where the lignin matrix is reinforced with cellulose fibers and bones in which the bone-salt plates made of calcium and phosphate ions reinforce soft collagen.

What are advanced composites? Advanced composites are composite materials that are traditionally used in the aerospace industries. These composites have high performance reinforcements of a thin diameter in a matrix material such as epoxy and aluminum. Examples are graphite/epoxy, Kevlar R†/epoxy, and boron/ aluminum composites. These materials have now found applications in commercial industries as well.

Drawbacks and limitations in use of composites include:

1. High cost of fabrication of composites is a critical issue
2. Mechanical characterization of a composite structure is more complex than that of a metal structure. Unlike metals, composite materials are not isotropic, that is, their properties are not the same in all directions.
3. Repair of composites is not a simple process compared to that for metals. Sometimes critical flaws and cracks in composite structures may go undetected.
4. Composites do not have a high combination of strength and fracture toughness

* compared to metals. Composites do not necessarily give higher performance in all the properties used for material selection. What fiber factors contribute to the mechanical performance of a composite?

Four fiber factors contribute to the mechanical performance of a composite:

- **Length:** The fibers can be long or short. Long, continuous fibers are easy to orient and process, but short fibers cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish, and dimensional stability. However, short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures. Short fibers have fewer flaws and therefore have higher strength.

- **Orientation:** Fibers oriented in one direction give very high stiffness and strength in that direction. If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations. However, for the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of unidirectional composites.

- **Shape:** The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and squareshaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.

- **Material**: The material of the fiber directly influences the mechanical performance of a composite. Fibers are generally expected to have high elastic moduli and strengths. This expectation and cost have been key factors in the graphite, aramids, and glass dominating the fiber market for composites.

What are the matrix factors that contribute to the mechanical performance of composites? Use of fibers by themselves is limited, with the exceptions of ropes and cables. Therefore, fibers are used as reinforcement to matrices. The matrix functions include binding the fibers together, protecting fibers from the environment, shielding from damage due to handling, and distributing the load to fibers. Although matrices by themselves generally have low mechanical properties compared to those of fibers, the matrix influences many mechanical properties of the composite. These properties include transverse modulus and strength, shear modulus and strength, compressive strength, interlaminar shear strength, thermal expansion coefficient, thermal resistance, and fatigue strength. Other than the fiber and the matrix, what other factors influence the mechanical performance of a composite? Other factors include the fiber–matrix interface. It determines how well the matrix transfers the load to the fibers. Chemical, mechanical, and reaction bonding may form the interface.

In most cases, more than one type of bonding occurs.

- Chemical bonding is formed between the fiber surface and the matrix. Some fibers bond naturally to the matrix and others do not. Coupling agents* are often added to form a chemical bond.

- The natural roughness or etching of the fiber surface causing interlocking may form a mechanical bond between the fiber and matrix.

- If the thermal expansion coefficient of the matrix is higher than that of the fiber, and the manufacturing temperatures are higher than the operating temperatures, the matrix will radially shrink more than the fiber. This causes the matrix to compress around the fiber.

- Reaction bonding occurs when atoms or molecules of the fiber and the matrix diffuse into each other at the interface. This interdiffusion often creates a distinct interfacial layer, called the interphase, with different properties from that of the fiber or the matrix. Although this thin interfacial layer helps to form a bond, it also forms micro cracks in the fiber. These micro cracks reduce the strength of the fiber and thus that of the composite. How are composites classified? Composites are classified by the geometry of the reinforcement — particulate, flake, and fibers or by the type of matrix — polymer, metal, ceramic, and carbon.

- **Particulate composites** consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.

- **Flake composites** consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake compos ites provide advantages such as high out-of-plane flexural modulus,*higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.

- **Fiber composites** consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic†and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics such as calcium–alumino silicate. Continuous fiber composites are emphasized in this book and are further discussed in this chapter by the types of matrices: polymer, metal, ceramic, and carbon. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.

• **Nanocomposites** consist of materials that are of the scale of nanometers (10–9 m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm. At this scale, the properties of materials are different from those of the bulk material. Generally, advanced composite materials have constituents on the microscale (10–6 m). By having materials at the nanometer scale, most of the properties of the resulting composite material are better than the ones at the microscale. Not all properties of nanocomposite are better; in some cases, toughness and impact strength can decrease.

Applications of nanocomposite include packaging applications for the military in which nanocomposite films show improvement in properties such as elastic modulus, and transmission rates for water vapor, heat distortion, and oxygen. Polymer Matrix Composites What are the most common advanced composites? The most common advanced composites are polymer matrix composites (PMCs) consisting of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin diameter fibers (e.g., graphite, aramids, boron). For example, graphite/epoxy composites are approximately five times stronger than steel on a weight for-weight basis. The reasons why they are the most common composites include their low cost, high strength, and simple manufacturing principles.

What are the drawbacks of polymer matrix composites? The main drawbacks of PMCs include low operating temperatures, high coefficients of thermal and moisture expansion,* and low elastic properties in certain directions. Give names of various polymers used in advanced polymer composites. These polymers include epoxy, phenolics, acrylic, urethane, and polyamide. Why are there so many resin systems in advanced polymer composites? Each polymer has its advantages and drawbacks in its use:

• **Polyesters:** The advantages are low cost and the ability to be made translucent; drawbacks include service temperatures below 170°F (77°C), brittleness, and high shrinkage* of as much as 8% during curing.

• **Phenolics:** The advantages are low cost and high mechanical strength; drawbacks include high void content. • Epoxies: The advantages are high mechanical strength and good adherence to metals and glasses; drawbacks are high cost and difficulty in processing. Mechanics Terminology How is a composite structure analyzed mechanically? A composite material consists of two or more constituents; thus, the analysis and design of such materials is different from that for conventional materials such as metals.

The approach to analyze the mechanical behavior of composite structures is as follows.

1. Find the average properties of a composite ply from the individual properties of the constituents. Properties include stiffness, strength, thermal, and moisture expansion coefficients. Note that average properties are derived by considering the ply to be homogeneous. At this level, one can optimize for the stiffness and strength requirements of a lamina. This is called the micromechanics of a lamina. Schematic of analysis of laminated composites.

2. Develop the stress–strain relationships for a unidirectional/bidirectional lamina. Loads may be applied along the principal directions of symmetry of the lamina or off-axis. Also, one develops relationships for stiffness, thermal and moisture expansion coefficients, and strengths of angle plies. Failure theories of a lamina are based on stresses in the lamina and strength properties of a lamina. This is called the macromechanics of a lamina.

A structure made of composite materials is generally a laminate structure made of various laminas stacked on each other. Knowing the macromechanics of a single lamina, one develops the macromechanics of a laminate. Stiffness, strengths, and thermal and moisture expansion coefficients can be found for the whole laminate. Laminate failure is based on stresses and application of failure theories to each ply. This knowledge of analysis of composites can then eventually form the basis for the mechanical design of structures made of composites.

Several terms are defined to develop the fundamentals of the mechanical behavior of composites. These include the following. What is an isotropic body? An isotropic material has properties that are the same in all directions. For example, the Young‘s modulus of steel is the same in all directions. What is a homogeneous body? A homogeneous body has properties that are the same at all points in the body. A steel rod is an example of a homogeneous body. However, if one heats this rod at one end, the temperature at various points on the rod would be different. Because Young‘s modulus of steel varies with temperature, one no longer has a homogeneous body. The body is still isotropic because the properties at a particular point are still identical in all directions.

Are composite materials isotropic and/or homogeneous? Most composite materials are neither isotropic nor homogeneous. For example, consider epoxy reinforced with long glass fibers. If one chooses a location on the glass fiber, the properties are different from a location on the epoxy matrix. This makes the composite material nonhomogeneous (not homogeneous). Also, the stiffness in the direction parallel to the fibers is higher than in the direction perpendicular to the fibers and thus the properties are not independent of the direction. This makes the composite material anisotropic (not isotropic).

What is an anisotropic material? At a point in an anisotropic material, material properties are different in all directions. What is a nonhomogeneous body? A nonhomogeneous or inhomogeneous body has material properties that are a function of the position on the body. What is a lamina? A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix. What is a laminate? A laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be made up of different material systems. What is a hybrid laminate? Hybrid composites contain more than one fiber or one matrix system in a laminate.

The main four types of hybrid laminates follow. • Interply hybrid laminates contain pliesmade of two or more different composite systems. Examples include car bumpers made of glass/epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also lower the cost of the bumper. • Intraply hybrid composites consist of two or more different fibers used in the same ply. Examples include golf clubs that use graphite and aramid fibers. Graphite fibers provide the torsional rigidity and the aramid fibers provide tensile strength and toughness.

• An interply–intraply hybrid consists of plies that have two or more different fibers in the same ply and distinct composite systems in more than one ply.

• Resin hybrid laminates combine two or more resins instead of combining two or more fibers in a laminate. Generally, one resin is flexible and the other one is rigid. Tests have proven that these resin hybrid laminates can increase shear and work of fracture properties by more than 50% over those of all-flexible or all-rigid resins.

Ceramic Materials:

A ceramic is any of the various hard, brittle, heat-resistant and corrosion-resistant materials made by shaping and then firing a nonmetallic mineral, such as clay, at a high temperature. Common examples are earthenware, porcelain, and brick.

The crystallinity of ceramic materials ranges from highly oriented to semi-crystalline, vitrified, and often completely amorphous (glasses). Most often, fired ceramics are either vitrified or semi-vitrified as is the case with earthenware, stoneware, and porcelain. Varying crystallinity and electron composition in the ionic and covalent bonds cause most ceramic materials to be good thermal and electrical insulators (researched in ceramic engineering). With such a large range of possible options for the composition/structure of a ceramic (nearly all of the elements, nearly all types of bonding, and all levels of crystallinity), the breadth of the subject is vast, and identifiable attributes (hardness, toughness, electrical conductivity) are difficult to specify for the group as a whole. General properties such as high melting temperature, high hardness, poor conductivity, high moduli of elasticity, chemical resistance and low ductility are the norm, with known exceptions to each of these rules (piezoelectric ceramics, glass transition temperature, superconductive ceramics). Many composites, such as fiberglass and carbon fiber, while containing ceramic materials are not considered to be part of the ceramic family.

The earliest ceramics made by humans were pottery objects (pots or vessels) or figurines made from clay, either by itself or mixed with other materials like silica, hardened and sintered in fire. Later, ceramics were glazed and fired to create smooth, colored surfaces, decreasing porosity through the use of glassy, amorphous ceramic coatings on top of the crystalline ceramic substrates. Ceramics now include domestic, industrial and building products, as well as a wide range of ceramic art. In the 20th century, new ceramic materials were developed for use in advanced ceramic engineering, such as in semiconductors.

The word "ceramic" comes from the Greek word (keramikos), "of pottery" or "for pottery", from (keramos), "potter's clay, tile, pottery". The earliest known mention of the root "ceram-" is the Mycenaean Greek ke-ra-me-we, workers of ceramic written in Linear B syllabic script. The word "ceramic" may be used as an adjective to describe a material, product or process, or it may be used as a noun, either singular, or more commonly, as the plural noun "ceramics".

Materials:

Ceramic material is an inorganic, non-metallic, often crystalline oxide, nitride, or carbide material. Some elements, such as carbon or silicon, may be considered ceramics. Ceramic materials are brittle, hard, strong in compression, and weak in shearing and tension. They withstand chemical erosion that occurs in other materials subjected to acidic or caustic environments. Ceramics generally can withstand very high temperatures, ranging from 1,000 °C to 1,600 °C (1,800 °F to 3,000 °F). Glass is often not considered a ceramic because of its amorphous (noncrystalline) character. However, glassmaking involves several steps of the ceramic process, and its mechanical properties are similar to ceramic materials.

Traditional ceramic raw materials include clay minerals such as kaolinite, whereas more recent materials include aluminum oxide, more commonly known as alumina. The modern ceramic materials, which are classified as advanced ceramics, include silicon carbide and tungsten carbide. Both are valued for their abrasion resistance and hence find use in applications such as the wear plates of crushing equipment in mining operations. Advanced ceramics are also used in the medicine, electrical, electronics industries, and body armor.

Crystalline ceramics

Crystalline ceramic materials are not amenable to a great range of processing. Methods for dealing with them tend to fall into one of two categories – either make the ceramic in the desired shape, by reaction in situ, or by "forming" powders into the desired shape, and then sintering to form a solid body. Ceramic forming techniques include shaping by hand (sometimes including a rotation process called "throwing"), slip casting, tape casting (used for making very thin ceramic capacitors), injection molding, dry pressing, and other variations.

Noncrystalline ceramics

Noncrystalline ceramics, being glass, tend to be formed from melts. The glass is shaped when either fully molten, by casting, or when in a state of toffee-like viscosity, by methods such as blowing into a mold. If later heat treatments cause this glass to become partly crystalline, the resulting material is known as a glass-ceramic, widely used as cook-tops, and also as a glass composite material for nuclear waste disposal.

Properties

The physical properties of any ceramic substance are a direct result of its crystalline structure and chemical composition. Solid-state chemistry reveals the fundamental connection between microstructure and properties, such as localized density variations, grain size distribution, type of porosity, and second-phase content, which can all be correlated with ceramic properties such as mechanical strength σ by the Hall-Petch equation, hardness, toughness, dielectric constant, and the optical properties exhibited by transparent materials.

Ceramography is the art and science of preparation, examination, and evaluation of ceramic microstructures. Evaluation and characterization of ceramic microstructures are often implemented on similar spatial scales to that used commonly in the emerging field of nanotechnology: from tens of angstroms (A) to tens of micrometers (µm). This is typically somewhere between the minimum wavelength of visible light and the resolution limit of the naked eye.

The microstructure includes most grains, secondary phases, grain boundaries, pores, micro-cracks, structural defects, and hardness micro indentions. Most bulk mechanical, optical, thermal, electrical, and magnetic properties are significantly affected by the observed microstructure. The fabrication method and process conditions are generally indicated by the microstructure. The root cause of many ceramic failures is evident in the cleaved and polished microstructure. Physical properties which constitute the field of materials science and engineering include the following:

Mechanical properties

Mechanical properties are important in structural and building materials as well as textile fabrics. In modern materials science, fracture mechanics is an important tool in improving the mechanical performance of materials and components. It applies the physics of stress and strain, in particular the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials in order to predict the macroscopic mechanical failure of bodies. Fractography is widely used with fracture mechanics to understand the causes of failures and also verify the theoretical failure predictions with real-life failures.

Ceramic materials are usually ionic or covalent bonded materials, and can be crystalline or amorphous. A material held together by either type of bond will tend to fracture before any plastic deformation takes place, which results in poor toughness in these materials. Additionally, because these materials tend to be porous, the pores and other microscopic imperfections act as stress concentrators, decreasing the toughness further, and reducing the tensile strength. These combine to give catastrophic failures, as opposed to the more ductile failure modes of metals.

These materials do show plastic deformation. However, because of the rigid structure of the crystalline materials, there are very few available slip systems for dislocations to move, and so they deform very slowly. With the non-crystalline (glassy) materials, viscous flow is the dominant source of plastic deformation, and is also very slow. It is therefore neglected in many applications of ceramic materials.

To overcome the brittle behavior, ceramic material development has introduced the class of ceramic matrix composite materials, in which ceramic fibers are embedded and with specific coatings are forming fiber bridges across any crack. This mechanism substantially increases the fracture toughness of such ceramics. Ceramic disc brakes are an example of using a ceramic matrix composite material manufactured with a specific process.

Ice-templating for enhanced mechanical properties

If ceramic is subjected to substantial mechanical loading, it can undergo a process called ice-templating, which allows some control of the microstructure of the ceramic product and therefore some control of the mechanical properties. Ceramic engineers use this technique to tune the mechanical properties to their desired application. Specifically, strength is increased, when this technique is employed. Ice templating allows the creation of macroscopic pores in a unidirectional arrangement. The applications of this oxide strengthening technique are important for solid oxide fuel cells and water filtration devices.[clarification needed][citation needed]

To process a sample through ice templating, an aqueous colloidal suspension is prepared to contain the dissolved ceramic powder evenly dispersed throughout the colloid,[clarification needed] for example Yttria-stabilized zirconia (YSZ). The solution is then cooled from the bottom to the top on a platform that allows for unidirectional cooling. This forces ice crystals to grow in compliance with the unidirectional cooling and these ice crystals force the dissolved YSZ particles to the solidification front of the solid-liquid interphase boundary, resulting in pure ice crystals lined up unidirectionally alongside concentrated pockets of colloidal particles. The sample is then simultaneously heated and the pressure is reduced enough to force the ice crystals to sublimate and the YSZ pockets begin to anneal together to form macroscopically aligned ceramic microstructures. The sample is then further sintered to complete the evaporation of the residual water and the final consolidation of the ceramic microstructure.[citation needed]

During ice-templating, a few variables can be controlled to influence the pore size and morphology of the microstructure. These important variables are the initial solids loading of the colloid, the cooling rate, the sintering temperature and duration, and the use of certain additives which can influence the microstructural morphology during the process. A good understanding of these parameters is essential to understanding the relationships between processing, microstructure, and mechanical properties of anisotropically porous materials.

Electrical properties

Semiconductors

Some ceramics are semiconductors. Most of these are transition metal oxides that are II-VI semiconductors, such as zinc oxide. While there are prospects of mass-producing blue LEDs from zinc oxide, ceramicists are most interested in the electrical properties that show grain boundary effects. One of the most widely used of these is the varistor. These are devices that exhibit the property that resistance drops sharply at a certain threshold voltage. Once the voltage across the device reaches the threshold, there is a breakdown of the electrical structure in the vicinity of the grain boundaries, which results in its electrical resistance dropping from several megohms down to a few hundred ohms. The major advantage of these is that they can dissipate a lot of energy, and they self-reset; after the voltage across the device drops below the threshold, its resistance returns to being high. This makes them ideal for surge-protection applications; as there is control over the threshold voltage and energy tolerance, they find use in all sorts of applications. The best demonstration of their ability can be found in electrical substations, where they are employed to protect the infrastructure from lightning strikes. They have rapid response, are low maintenance, and do not appreciably degrade from use, making them virtually ideal devices for this application. Semiconducting ceramics are also employed as gas sensors. When various gases are passed over a polycrystalline ceramic, its electrical resistance changes. With tuning to the possible gas mixtures, very inexpensive devices can be produced.

Superconductivity

Under some conditions, such as extremely low temperature, some ceramics exhibit high-temperature superconductivity.[clarification needed] The reason for this is not understood, but there are two major families of superconducting ceramics.

Ferroelectricity and supersets

Piezoelectricity, a link between electrical and mechanical response, is exhibited by a large number of ceramic materials, including the quartz used to measure time in watches and other electronics. Such devices use both properties of piezoelectrics, using electricity to produce a mechanical motion (powering the device) and then using this mechanical motion to produce electricity (generating a signal). The unit of time measured is the natural interval required for electricity to be converted into mechanical energy and back again.

The piezoelectric effect is generally stronger in materials that also exhibit pyroelectricity, and all pyroelectric materials are also piezoelectric. These materials can be used to inter-convert between thermal, mechanical, or electrical energy; for instance, after synthesis in a furnace, a pyroelectric crystal allowed to cool under no applied stress generally builds up a static charge of thousands of volts. Such materials are used in motion sensors, where the tiny rise in temperature from a warm body entering the room is enough to produce a measurable voltage in the crystal.

In turn, pyroelectricity is seen most strongly in materials that also display the ferroelectric effect, in which a stable electric dipole can be oriented or reversed by applying an electrostatic field. Pyroelectricity is also a necessary consequence of ferroelectricity. This can be used to store information in ferroelectric capacitors, elements of ferroelectric RAM.

The most common such materials are lead zirconate titanate and barium titanate. Aside from the uses mentioned above, their strong piezoelectric response is exploited in the design of high-frequency loudspeakers, transducers for sonar, and actuators for atomic force and scanning tunneling microscopes.

Positive thermal coefficient

Temperature increases can cause grain boundaries to suddenly become insulating in some semiconducting ceramic materials, mostly mixtures of heavy metal titanates. The critical transition temperature can be adjusted over a wide range by variations in chemistry. In such materials, current will pass through the material until joule heating brings it to the transition temperature, at which point the circuit will be broken and current flow will cease. Such ceramics are used as self-controlled heating elements in, for example, the rear-window defrost circuits of automobiles.

At the transition temperature, the material's dielectric response becomes theoretically infinite. While a lack of temperature control would rule out any practical use of the material near its critical temperature, the dielectric effect remains exceptionally strong even at much higher temperatures. Titanates with critical temperatures far below room temperature have become synonymous with "ceramic" in the context of ceramic capacitors for just this reason.

Products

By usage

For convenience, ceramic products are usually divided into four main types; these are shown below with some examples:

Structural, including bricks, pipes, floor and roof tiles
Refractories, such as kiln linings, gas fire radiants, steel and glass making crucibles
Whitewares, including tableware, cookware, wall tiles, pottery products and sanitary ware
Technical, also known as engineering, advanced, special, and fine ceramics. Such items include:
gas burner nozzles
ballistic protection, vehicle armor
nuclear fuel uranium oxide pellets
biomedical implants
coatings of jet engine turbine blades
Ceramic matrix composite gas turbine parts
Reinforced carbon–carbon ceramic disk brakes
missile nose cones
bearing (mechanical)
tiles used in the Space Shuttle program

Ceramics made with clay

Main article: Pottery

Frequently, the raw materials of modern ceramics do not include clays.[17] Those that do are classified as follows:

Earthenware, fired at lower temperatures than other types
Stoneware, vitreous or semi-vitreous
Porcelain, which contains a high content of kaolin
Bone china

Classification

Ceramics can also be classified into three distinct material categories:

Oxides: alumina, beryllia, ceria, zirconia
Non-oxides: carbide, boride, nitride, silicide
Composite materials: particulate reinforced, fiber reinforced, combinations of oxides and nonoxides.

Each one of these classes can be developed into unique material properties because ceramics tend to be crystalline.

Applications

Knife blades: blade of a ceramic knife will stay sharp for much longer than that of a steel knife, although it is more brittle and susceptible to breaking.

Carbon-ceramic brake disks: for vehicles are resistant to brake fade at high temperatures.

"Advanced composite ceramic and metal matrices" have been designed for most modern armoured fighting vehicles because they offer superior penetrating resistance against shaped charges (HEAT rounds) and kinetic energy penetrators.

"Ceramics such as alumina and boron carbide" have been used in ballistic armored vests to repel high-velocity rifle fire. Such plates are known commonly as small arms protective inserts, or SAPIs. Similar material is used to protect the cockpits of some military airplanes, because of the low weight of the material.

Ceramics can be used in place of steel for ball bearings. Their higher hardness means they are much less susceptible to wear and typically last for triple the lifetime of a steel part. They also deform less under load, meaning they have less contact with the bearing retainer walls and can roll faster. In very high-speed applications, heat from friction during rolling can cause problems for metal bearings, which are reduced by the use of ceramics. Ceramics are also more chemically resistant and can be used in wet environments where steel bearings would rust. In some cases, their electricity-insulating properties may also be valuable in bearings. Two drawbacks to ceramic bearings are a significantly higher cost and susceptibility to damage under shock loads.

In the early 1980s, Toyota researched production of an adiabatic engine using ceramic components in the hot gas area. The ceramics would have allowed temperatures of over 1650°C. The expected advantages would have been lighter materials and a smaller cooling system (or no need for one at all), leading to a major weight reduction. The expected increase of fuel efficiency of the engine (caused by the higher temperature, as shown by Carnot's theorem) could not be verified experimentally; it was found that the heat transfer on the hot ceramic cylinder walls was higher than the transfer to a cooler metal wall as the cooler gas film on the metal surface works as a thermal insulator. Thus, despite all of these desirable properties, such engines have not succeeded in production because of costs for the ceramic components and the limited advantages. (Small imperfections in the ceramic material with its low fracture toughness lead to cracks, which can lead to potentially dangerous equipment failure.) Such engines are possible in laboratory settings, but mass production is not feasible with current technology.[citation needed]

Work is being done in developing ceramic parts for gas turbine engines. Currently, even blades made of advanced metal alloys used in the engines' hot section require cooling and careful limiting of operating temperatures. Turbine engines made with ceramics could operate more efficiently, giving aircraft greater range and payload for a set amount of fuel.

Recent advances have been made in ceramics which include bioceramics, such as dental implants and synthetic bones. Hydroxyapatite, the natural mineral component of bone, has been made synthetically from several biological and chemical sources and can be formed into ceramic materials. Orthopedic implants coated with these materials bond readily to bone and other tissues in the body without rejection or inflammatory reactions so are of great interest for gene delivery and tissue engineering scaffolds. Most hydroxyapatite ceramics are very porous and lack mechanical strength, and are used to coat metal orthopedic devices to aid in forming a bond to bone or as bone fillers. They are also used as fillers for orthopedic plastic screws to aid in reducing inflammation and increase the absorption of these plastic materials. Work is being done to make strong, fully dense nanocrystalline hydroxyapatite ceramic materials for orthopedic weight bearing devices, replacing foreign metal and plastic orthopedic materials with a synthetic, but naturally occurring bone mineral. Ultimately, these ceramic materials may be used as bone replacements or with the incorporation of protein collagens, synthetic bones.

Durable actinide-containing ceramic materials have many applications such as in nuclear fuels for burning excess Pu and in chemically-inert sources of alpha irradiation for power supply of unmanned space vehicles or to produce electricity for microelectronic devices. Both use and disposal of radioactive actinides require their immobilization in a durable host material. Nuclear waste long-lived radionuclides such as actinides are immobilized using chemically-durable crystalline materials based on polycrystalline ceramics and large single crystals.

High-tech ceramic is used in watchmaking for producing watch cases. The material is valued by watchmakers for its lightweight, scratch resistance, durability, and smooth touch. IWC is one of the brands that initiated the use of ceramic in watchmaking.

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SCHOOL OF MECHANICAL ENGINEERING
DEPARTMENT OF AERONAUTICAL ENGINEERING

UNIT – V- Aircraft Materials– SAEA1201

Unit V

Introduction:

Forty years ago, aluminum dominated the aerospace industry. As the new kid on the block, it was considered to be lightweight, inexpensive, and state-of-the-art. In fact, as much as 70% of an aircraft was once made of aluminum. Other new materials such as composites and alloys were also used, including titanium, graphite, and fiberglass, but only in very small quantities – 3% here and 7% there. Readily available, aluminum was used everywhere from the fuselage to main engine components.

Times have changed. A typical jet built today is as little as 20% pure aluminum. Most of the non-critical structural material – paneling and aesthetic interiors – now consist of even lighter-weight carbon fiber reinforced polymers (CFRPs) and honeycomb materials. Meanwhile, for engine parts and critical components, there is a simultaneous push for lower weight and higher temperature resistance for better fuel efficiency, bringing new or previously impractical-to-machine metals into the aerospace material mix.

Aerospace unique among industries

Aerospace manufacturing is unique among other volume manufacturing sectors, and this is especially true of aerospace engine manufacturing. The engine is the most complex element of an aircraft, houses the most individual components, and ultimately determines fuel efficiency. The advent of lean-burn engines, with temperature potentials as high as 3,800°F (2,100°C), has helped drive demand for these new materials. Considering that the melting point of current super alloys is around 3,360°F (1,850°C), the challenge becomes finding materials that will withstand hotter temperatures.

To meet these temperature demands, heat-resistant super alloys (HRSAs), including titanium alloys, nickel alloys, and some nonmetal composite materials such as ceramics, are now being brought into the material equation. These materials tend to be more difficult to machine than traditional aluminum, historically meaning shorter tool life and less process security.

There’s also a high process risk in machining aerospace parts. Because margins for error are non-existent at 35,000ft cruising altitude, tolerances in aerospace are more precise than almost any other industry. This level of precision takes time. Longer machining times are required for each component, and more time per part makes scrap relatively expensive, when factoring in time investment. Also, compared to other industries, aerospace component orders often consist of short run quantities and long lead times, rendering scheduling for productivity, throughput, and profitability difficult.

Unlike any other industry but oil and gas, which also has high temperature, pressure, and corrosion requirements, aerospace materials themselves impact component design. Design for manufacturability (DFM) is the engineering art of designing components with a balanced approach, taking into consideration both component function and its manufacturing requirements. This approach is being applied more and more in aerospace component design because its components have to accomplish certain loads and temperature resistances, and some materials can only accommodate so much. Material and component designs truly drive one another, as opposed to one following the other. This give-and-take relationship between material and design is a particular consideration when investigating next-generation materials. Aerospace manufacturers are a breed apart for all of these reasons. It’s not surprising that their assortment of materials is unique.

New material landscape

Standard aerospace aluminums – 6061, 7050, and 7075 – and traditional aerospace metals – nickel 718, titanium 6Al4V, and stainless 15-5PH – still have applications in aerospace. These metals, however, are currently ceding territory to new alloys designed to improve cost and performance. To be clear, these new metals aren’t always new, some having been available for decades. Rather, they are new to practical production application, as machine tools, tooling technology, and insert coatings have sufficiently advanced to tackle difficult-to-machine alloys.

Even though the amount of aluminum is declining in aircraft, its use is not completely disappearing. In fact, aluminum is coming back, especially in cases where the move to CFRP has been cost prohibitive or unsuccessful. But the reappearing aluminum is not your father’s aluminum. Titanium aluminide (TiAl) and aluminum lithium (Al-Li), for example, which have been around since the 1970s, have only been gaining traction in aerospace since the turn of the century.

Similar to nickel alloy in its heat-resisting properties, TiAl retains strength and corrosion resistance in temperatures up to 1,112°F (600°C). But TiAl is more easily machined, exhibiting similar machinability characteristics to alpha-beta titanium, such as Ti6Al4V. Perhaps more importantly, TiAl has the potential to improve the thrust-to-weight ratio in aircraft engines because it’s only half the weight of nickel alloys. Case in point, both low-pressure turbine blades and high-pressure compressor blades, traditionally made of dense Ni-based super alloys are now being machined from TiAl-based alloys. General Electric was a pioneer in this development and uses TiAl low-pressure turbine blades on its GEnx engine, the first large-scale use of this material on a commercial jet engine – in this case in the Boeing 787 Dreamliner.

Another re-introduction of aluminum to aerospace is found in weight-saving Al-Li, specifically designed to improve properties of 7050 and 7075 aluminum. Overall, the addition of lithium strengthens aluminum at a lower density and weight, two catalysts of the aerospace material evolution. Al-Li alloys' high strength, low density, high stiffness, damage tolerance, corrosion resistance, and weld-friendly nature make it a better choice than traditional aluminums in commercial jetliner airframes. Airbus is currently using AA2050. Meanwhile, Alcoa is using AA2090 T83 and 2099 T8E67. The alloy can also be found in the fuel and oxidizer tanks in the SpaceX Falcon 9 launch vehicle, and is used extensively in NASA rocket and shuttle projects.

Titanium 5553 (Ti-5553) is another metal that is reasonably new to aerospace, exhibiting high strength, light weight, and good corrosion resistance. Major structural components that need to be stronger and lighter than the previously used stainless steel alloys are perfect application points for this titanium alloy. Nicknamed triple 5-3, this has been a notoriously difficult material to machine – until recently. Extensive research and development has been devoted to making the metal practical to machine, and triple 5-3 has recently proven to be very predictable with machining consistency similar to more traditional titanium alloys like the aforementioned Ti6Al4V. The variances in the two materials require the use of different cutting data to obtain similar tool life. But once an operator has proper parameters set, triple 5-3 machines predictably. The key with triple 5-3 is to run a bit slower and optimize the tool path and coolant system to achieve a good balance of tool life and tool security.

Some structural pieces, like fasteners, landing gear, and actuators, require raw strength, with lightweight properties being less of a priority. In such cases, Carpenter Technology Ferrium S53 steel alloy has provided mechanical properties equal to or better than conventional ultra-high-strength steels, such as 300M and SAE 4340, with the added benefit of general corrosion resistance. This can eliminate the need for cadmium coating and the subsequent related processing.

Composites hit their stride

Composite materials also represent a growing piece of the aerospace material pie. They reduce weight and increase fuel efficiency while being easy to handle, design, shape, and repair. Once only considered for light structural pieces or cabin components, composites' aerospace application range now reaches into true functional components – wing and fuselage skins, engines, and landing gear.

Also important, composite components can be formed into complex shapes that, for metallic parts, would require machining and create joints. Pre-formed composite components aren't just lightweight and strong, they reduce the number of heavy fasteners and joints – which are potential failure points – within the aircraft. In doing so, composite materials are helping to drive an industry-wide trend of fewer components in overall assemblies, using one-piece designs wherever possible.

While CFRPs represent the lion's share of composite material in both cabin and functional components, and honeycomb materials provide effective and lightweight internal structural components, next-generation materials include ceramic-matrix composites (CMCs), which are emerging in practical use after decades of testing. CMCs are comprised of a ceramic matrix reinforced by a refractory fiber, such as silicon carbide (SiC) fiber. They offer low density/weight, high hardness, and most importantly, superior thermal and chemical resistance. Like CFRPs, they can be molded to certain shapes without any extra machining, making them ideal for internal aerospace engine components, exhaust systems, and other "hot-zone" structures – even replacing the latest in HRSA metals listed earlier.

New materials address a new aerospace reality

Metallic and composite materials alike continue to be developed and improved to offer ever-increasing performance, whether that's lighter weight, greater strength, or better heat and corrosion resistance. Accelerating this evolution of new materials, advancements in machining and cutting technology give manufacturers unprecedented access to materials previously deemed impractical or too difficult to machine. New material adoption is happening exceptionally quickly in aerospace, requiring DFM-minded interaction between material characteristics and component design. The two must be in balance, and one can't really exist outside of the context of the other.

Meanwhile, one-piece designs are continuing to reduce the number of components in overall assemblies. In general, this bodes well for composites in aerospace, which can be formed instead of machined. A variation of this trend exists in metallic structures, as more components are conditioned in forgings to get to near-net shape, reducing the amount of machining. Elephant skins, roughed-in shapes, and thin floor sections all reduce material costs and the total number of components, but setup and fixturing continue to be challenges. Some manufacturers are turning to waterjet and other technologies to reduce or eliminate raw stock materials in need of removal. Still, difficulties exist in workholding, surface finish, and CAM tool paths. But designers, machinists, engineers, and machine tool/cutting tool partners are developing new solutions to keep the evolution churning forward.

The mix of materials in aerospace will continue to change in coming years with composites, freshly machineable metals, and new metals increasingly occupying the space of traditional materials. The industry continues to march toward components of lighter weights, increased strengths, and greater heat and corrosion resistance. Component counts will decrease in favor of stronger, near-net shapes, and design will continue its close collaboration with material characteristics. Machine tools builders and cutting tool manufacturers will continue to develop tools to make currently unviable materials machineable, and even practical. And it’s all done in the name of reducing the cost of aerospace manufacture, improving fuel economy through efficiency and lightweighting, and making air travel a more cost-effective means of transportation.

Advanced Materials

Composite fiber and matrix materials developments today contrast with the situation that existed during the evolution of aluminum. The gradual dominance of aluminum as an aircraft material was seen by aluminum manufacturers as only one of a great many potential uses, which included large-scale consumer product manufacturers. The relatively low volume required for any one of the many advanced airframe and engine materials today poses a problem for the materials development industry. Economics dictate that this industry concentrate on materials research and development for applications of the largest scale. This makes a persuasive argument for government involvement in advanced aerospace materials research and development in the 1990s. Furthermore, the time between conception and application of new structural materials is very long, largely because ultraconservatism must be exercised by responsible structural designers. There is also a need for extensive data bases adequate to ensure substantiation.

Airframe Applications

Manufacturing economics is one of the serious roadblocks to the use of advanced composites for the airframe structures of subsonic transports, short-haul aircraft, and rotorcraft. This situation will continue until major improvements are made in integrating design and manufacturing with composites.

Beyond integration, however, composite applications to primary structures, such as wings and fuselages, will require extensive development of individual engineering design, tooling, and manufacturing techniques if the industry is to realize the weight benefits possible for advanced subsonic transport and HSCT aircraft. Even then, the pace and direction of past and current programs indicate that composite applications to primary structures such as wings will be easier to implement, whereas fuselage applications will be more difficult.

Foreign competitors are applying composites and superplastic forming of metals aggressively and are gaining valuable experience in their use in structural design. Improving U.S. application of composites, advanced metallics, and superplastic forming, to a lesser extent, will improve weight and cost, and is necessary to improve our competitive position.

HSCT airframes will require application of mixed materials because of the wider temperatures variation that will be experienced by the airframe in normal operations. Although not as high as those routinely experienced by engine hot-section parts, portions of the HSCT airframe will be subjected to temperatures beyond all commercial transport airframe experience to this time (except, possibly, the Concorde). Because HSCT airframes will involve quantities so much larger than occur in engine applications, economics will be a key factor. Thus, innovative uses of advanced alloys of titanium, new classes of aluminum, and resin matrix composites that can withstand high temperature will be required if HSCT configurations are to be successful.

Engine Applications

New, high-temperature-capable materials needed for advanced engine developments are often cited as including metal matrix composites, ceramics, ceramic matrix composites, and intermetallics. All of these advanced materials hold considerable promise, despite their high costs, of jet engine nozzle applications—particularly in HSCT aircraft. Variable exit nozzle cross sections, required for propulsion efficiency over a wide speed range, for example, call for both stiffness and strength at high temperature. Furthermore, the likelihood of aft location makes nozzle weight a matter of importance for flight stability in all cases and for aeroelastic stability in configurations with wing-mounted engines.

The use of MMCs such as silicon carbide/titanium for reinforcing high-pressure stage disks in axial compressors appears to be promising as well. Stiffness and strength at moderate temperature are required to carry the heavy "hoop tension" created by centrifugal and thermal loads, and light weight is always particularly important in rotating machinery. All of the promising MMC applications, however, require that substantial structural design and manufacturing research go hand in hand with materials development.

The extent to which CMCs become available will depend on progress in two distinct types of research programs that can profitably be pursued in parallel: namely, fundamental materials research to increase the toughness of CMCs, and structural design and manufacturing research to find applications that take into account all the limitations of present-day CMCs. Such applications seem most likely in turbine engine combustors, first turbine stages, and nozzles.

Intermetallics represent a new and promising source of high-strength, high-temperature-capable structural materials. Bringing candidate intermetallics to the point of practical application, however, will require fundamental metallurgical research, especially to achieve acceptable levels of damage tolerance.

Exploitation of composite materials of virtually any kind will require new techniques of joining built-up rotor stages and joining rotor blades to disks. Competitive designs for advanced rotating parts will depend on such exploitation and on improved understanding of flutter and resonance stress problems and application of magnetic bearing technology.

Smart Structures and Active Control

The potential of active materials in smart structures (e.g., "shape memory" alloys, piezoelectrics, and thermally responsive composites) seems strong for achieving advanced methods of structural integrity diagnosis for safety improvement and maintenance cost reductions. Equally important is their promise for active control of internal noise and for reducing structural dynamic loads, stabilizing various aeroelastic phenomena having the potential for destructive instabilities, and improving crew and passenger comfort by reducing vibrations. Their impact, taken together with applications of automatic feedback control techniques, particularly in providing solutions to aeroelastic instability problems, will be continually increasing. Reduction in size, weight, and cost of the components constituting these systems, through fiber optics, microprocessors, and smart material sensors and actuators, will allow the redundancies necessary for operations in keeping with commercial transport safety standards.

It is noted, however, that before any diagnostic means for increasing structural integrity can be useful, the damage tolerance of composite materials needs to be increased substantially. Graphite/epoxy, for example, is a brittle material. Thus, hybrids that incorporate fibers with high failure strains should be pursued to achieve higher damage tolerance.

Acoustics

Acoustics issues are of sufficient importance to warrant basic research to improve fundamental understanding and accumulate the technical knowledge required for practical application of noise control methods of all kinds for rotorcraft, high-subsonic and short-haul transports, and GA aircraft. This will require analytical methods for predicting noise generation and propagation characteristics reliably, as well as research on human reaction to noise, including sonic boom. Increased information on the effectiveness of active noise control techniques is required to an extent sufficient to allow reliable trade-offs to be made, at the design stage, among active and passive treatment alternatives, cost, reliability, and range/payload. This applies to acoustic sources of all kinds—aerodynamic, propulsive, and those generated by dynamic system components—and to both interior and exterior noise.

Regulatory Aspects

The weight savings possible with composite structural materials are limited by inspection capabilities and damage design criteria. Both need additional emphasis. Differences in criteria should be addressed by NASA and the FAA to the extent that safety and reasonably competitive positions are ensured. Including the acquisition of comprehensive airworthiness data as an integral part of materials and structures research should pay great dividends in allowing early definition of realistic regulations and certification requirements, thus expediting application of new materials and structural concepts.