Ministry of Higher Education
Higher Institute For Engineering
And Modern Technology Marg

Diagnosis of mechanical failure
MED 441

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MED 441 Diagnosis of mechanical failure

3 Cr. hrs. = [2Let. + 2Tut + 1Lab]

Prerequisite: MED 351

Lntroduction to modes of surfaces failures, Welded, brazed and bonded joints, Elastic instability "Bucking", stress discontinuity,Creep and creep rupture, fracture mechanics and crack propagation, Fail –safe design, ldentification, detection and control of filures, Case studied and applications to some mechanical components, Fault Diagnosis using Vibration Measurements, measuring instruments, vibration international standards, machine diagnostics, method of analyzing vibration measurement results, common faults, Applications and course project.

مكص ٤٤١ تشخيص الأعطال الميكانيكية

مقدمة لا نماط الانهيارات الكلية والسطحية المختلفة، الانهيار فى المواصلات الملحومة، الانهيار المرن، الانبعاج، الانهيار اللدن، الانهيار التزحفى ، انهيار الشروخ وتوقع العمر الامن،تطبيقات على حالات انهيار الاجزاء الميكانيكية، تشخيص الاعطال باستخدام قياس الاهتزازات، توقع الانهيار عن طريق قياس الاهتزازات، اجهزة القياس، المواصفات الدولية للاهتزازات الآمنة ، تشخيص حالة المعدات، اساليب تحليل النتائج، الاعطال الشائعة، تطبيقات ومشروع مقرر.

Laboratory:

1 practice on Universal and Creep Testing Machines.

2 practice on simulation and animation of mechanisms and rotating machines using Working model, FE, Matlab, Lab view packages with practical examples.

3 practice on vibration measuring instruments.

4 Computer oriented Course project on practical case studies.

References:

• O- suk Yang, lntroduction of lntelligent Machine Fault Diagnosis& prognosis, nova science pub lnc, 2008.

• L.H.Chiang,E.L.Russell,R.D Braatz, Falt Diagnosis&Diagnoss in lndustrial systems springer, 1stEd., 2001.

CHAPTRR.1

1.1.Introduction to Modes of surface Failure

- Definitions:

  Failure

Deflection or fracture of the part interferes with proper function.

- Failure Mode is
  - The way in which the component, subassembly, product, input, or process could fail to perform its intended function
  - Failure modes may be the result of upstream operations or may cause downstream operations to fail
  - Things that could go wrong

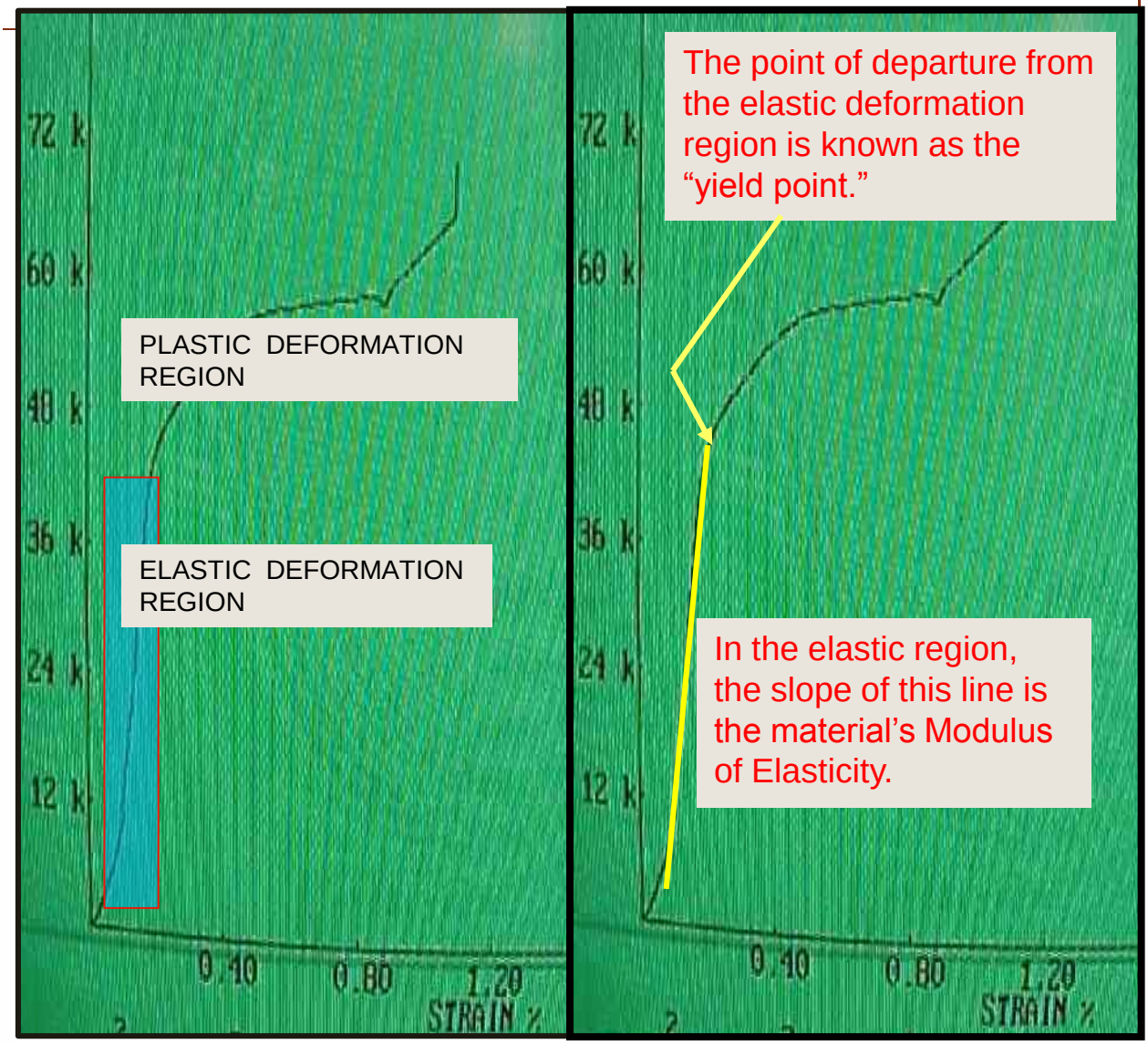
Modes of Mechanical Failure

Failure modes are the physical processes that take place or combine their effects to produce failure, as just discussed. The following list includes the failure modes most commonly observed in machines and machine parts.

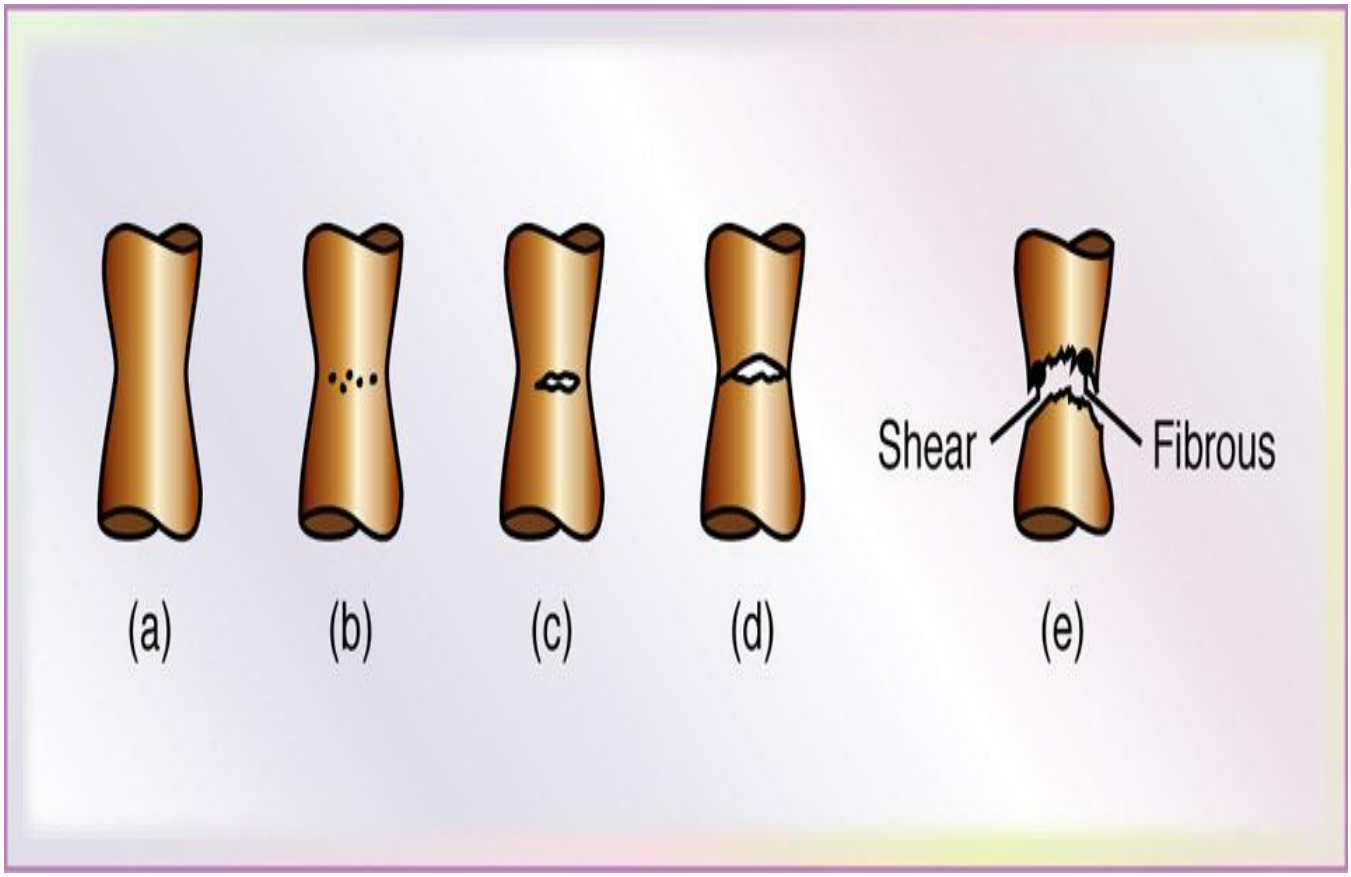
1. Force- and/or temperature-induced elastic deformation
2. Yielding
3. Brinnelling
4. Ductile rupture
5. Brittle fracture
6. Fatigue:
   a. High-cycle fatigue
   b. Low-cycle fatigue
   c. Thermal fatigue
   d. Surface fatigue
   e. Impact fatigue
   f. Corrosion fatigue
   g. Fretting fatigue
7. Corrosion:
   a. Direct chemical attack
   b. Galvanic corrosion
   c. Pitting corrosion
   d. Intergranular corrosion
   e. Selective leaching
   f. Erosion corrosion
   g. Cavitation corrosion
   h. Hydrogen damage
   i. Biological corrosion
   j. Stress corrosion
8. Wear:
   a. Adhesive wear
   b. Abrasive wear
   c. Corrosive wear
   d. Surface fatigue wear
   e. Deformation wear
   f. Impact wear
   g. Fretting wear
9. Impact:
   a. Impact fracture
   b. Impact deformation
   c. Impact wear
   d. Impact fretting
   e. Impact fatigue
10. Fretting:
    a. Fretting fatigue
    b. Fretting wear
    c. Fretting corrosion
11. Creep
12. Thermal relaxation
13. Stress rupture
14. Thermal shock
15. Galling and seizure
16. Spalling
17. Radiation damage
18. Buckling
19. Creep buckling
20. Stress corrosion
21. Corrosion wear
22. Corrosion fatigue
23. Combined creep and fatigue

Force- and/or temperature-induced elastic deformation failure occurs whenever the elastic (recoverable) deformation in a machine member, brought about by the imposed operational loads or temperatures, becomes great enough to interfere with the ability of the machine to satisfactorily perform its intended function.

Yielding failure occurs when the plastic (unrecoverable) deformation in a ductile machine member, brought about by the imposed operational loads or motions, becomes great enough to interfere with the ability of the machine to satisfactorily perform its intended function.

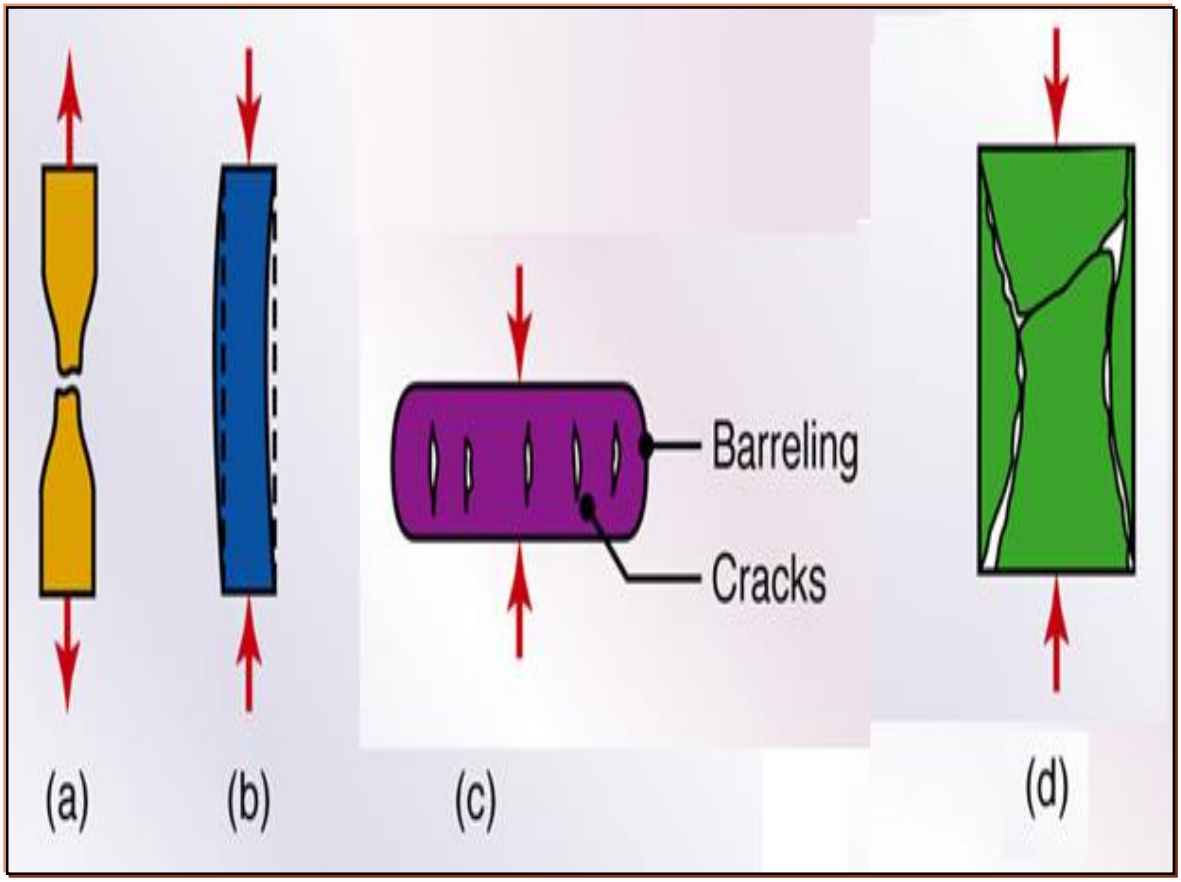


Progression of a Fracture



Sequence of events in the necking and fracture of a tensile-test specimen: (a) early stage of necking; (b) small voids begin to form within the necked region; (c) voids coalesce, producing an internal crack; (d) the rest of the cross-section begins to fail at the periphery, by shearing; (e) the final fracture surfaces, known as cup- (top fracture surface) and cone- (bottom surface) fracture.

Material Failures



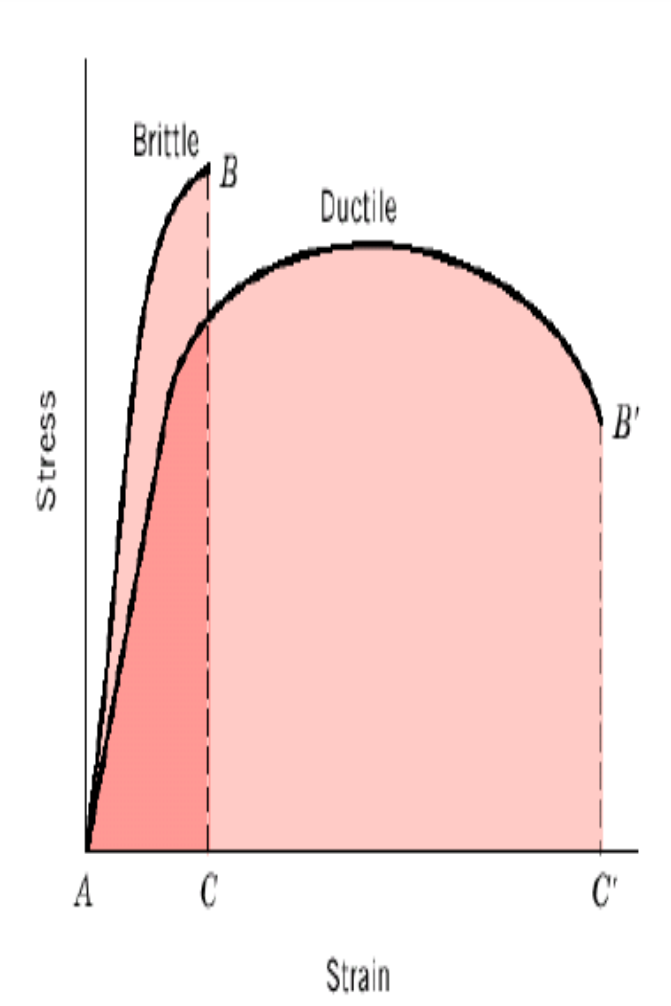
Schematic illustrations of types of failures in materials: (a) necking and fracture of ductile materials; (b) buckling of ductile materials under a compressive load; (c) cracking on the barreled surface of ductile materials in compression; (d) fracture of brittle materials in compression

Brinnelling failure occurs when the static forces between two curved surfaces in contact result in local yielding of one or both mating members to produce a permanent surface discontinuity of significant size. For example, if a ball bearing is statically loaded so that a ball is forced to permanently indent the race through local plastic flow, the race is brinnelled. Subsequent operation of the bearing might result in intolerably increased vibration, noise, and heating, and, therefore, failure would have occurred.

Ductile rupture failure occurs when the plastic deformation, in a machine part that exhibits ductile behavior, is carried to the extreme so that the member separates into two pieces. Initiation and coalescence of internal voids slowly propagate to failure, leaving a dull, fibrous rupture surface.

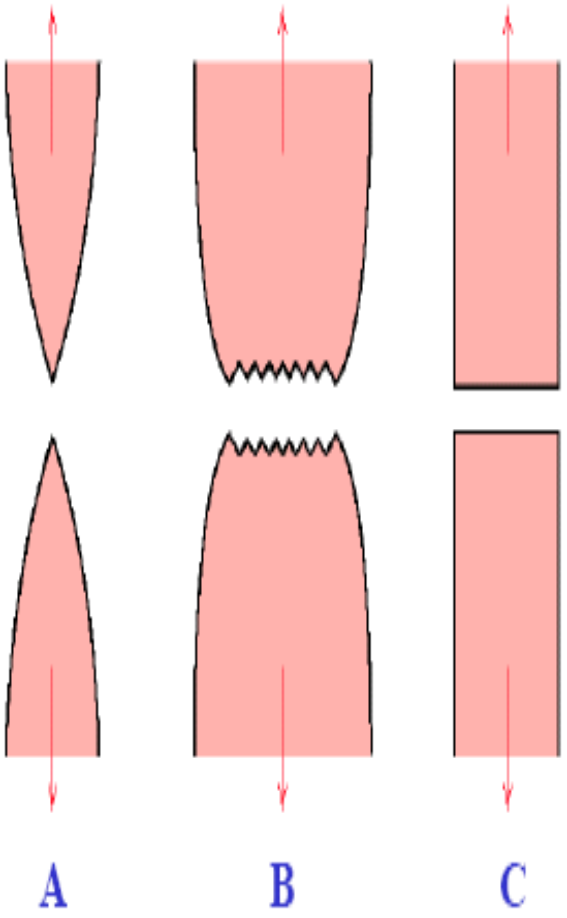
Brittle fracture failure occurs when the elastic deformation, in a machine part which exhibits brittle behavior, is carried to the extreme so that the primary interatomic bonds are broken and the member separates into two or more pieces. Preexisting flaws or growing cracks provide initiation sites for very rapid crack propagation to catastrophic failure, leaving a granular, multifaceted fracture surface.

Brittle vs. Ductile Fracture



- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture

Brittle vs. Ductile Fracture

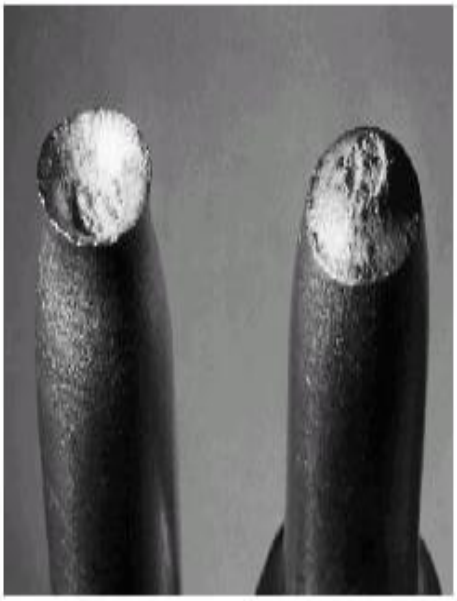


A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

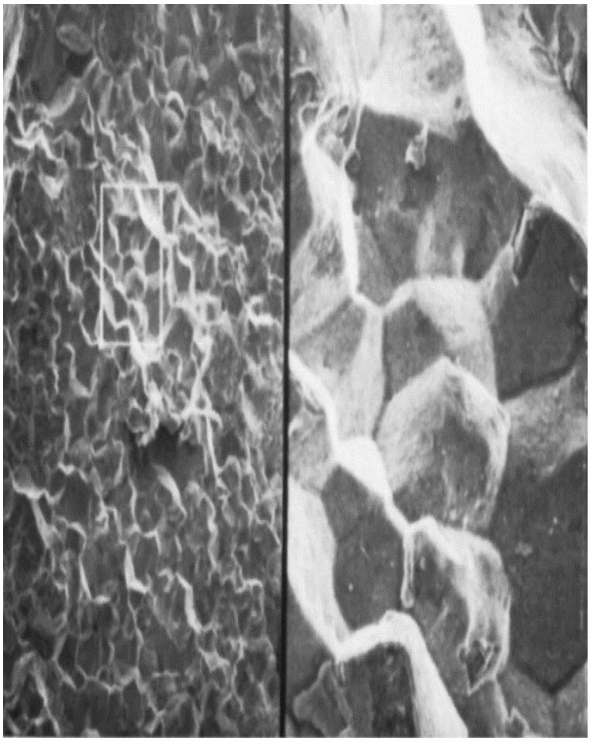
B. **Moderately ductile fracture**, typical for ductile metals

C. **Brittle fracture**, cold metals, ceramics.

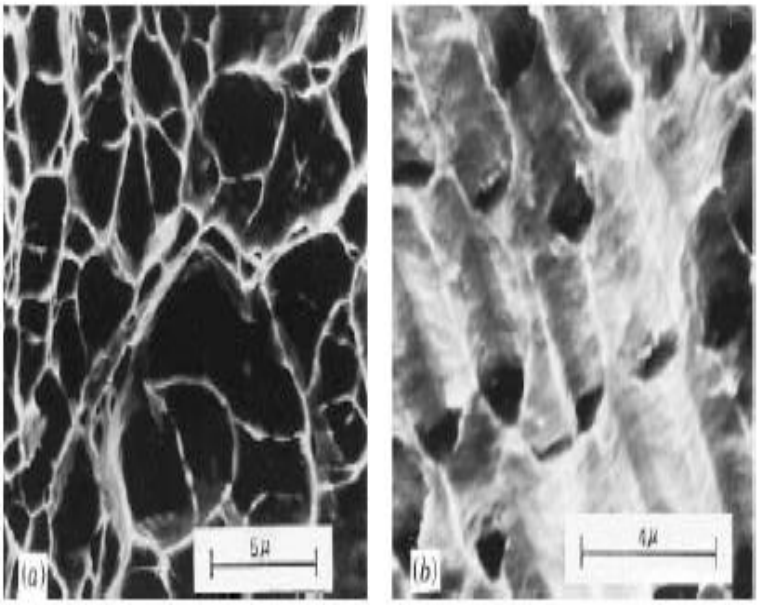
Ductile Fracture



(Cap-and-cone fracture in Al

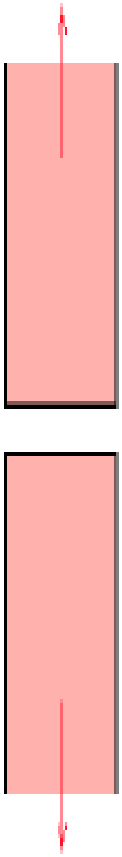


Intergranular fracture,. Grains and grain boundaries are clearly visible in this micrograph. The fracture path is along the grain boundaries. Magnification: left, 100x; right, 500x.



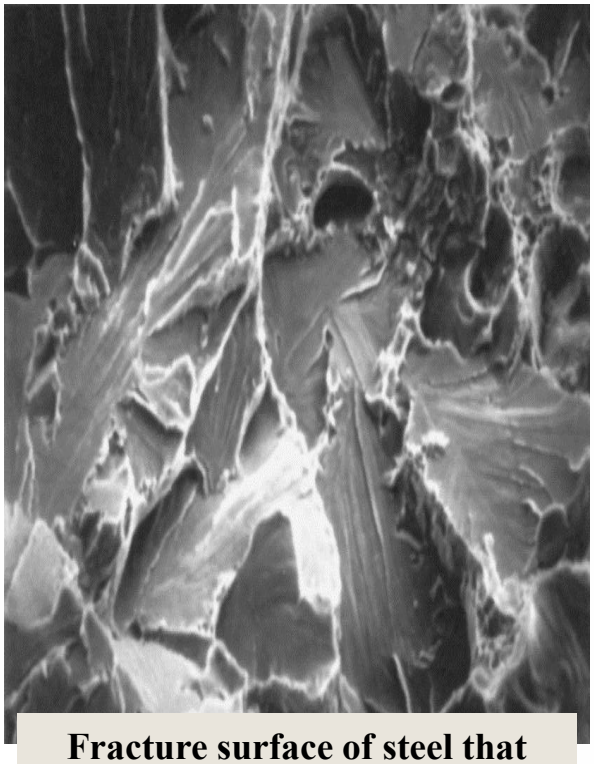
Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical "dimples" correspond to micro-cavities that initiate crack formation.

Brittle Fracture





Brittle fracture in a mild steel



Fracture surface of steel that has failed in a brittle manner. The fracture path is transgranular (through the grains). Magnification: 200x.

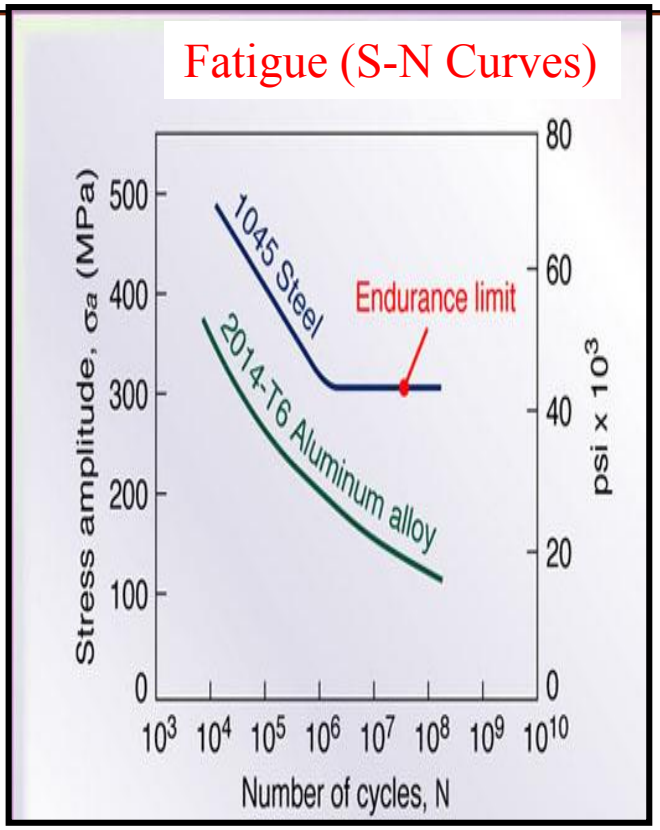
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).

Fatigue failure is a general term given to the sudden and catastrophic separation of a machine part into two or more pieces as a result of the application of fluctuating loads or deformations over a period of time.

Corrosion failure, a very broad term, implies that a machine part is rendered incapable of performing its intended function because of the undesired deterioration of the material as a result of chemical or electrochemical interaction with the environment.

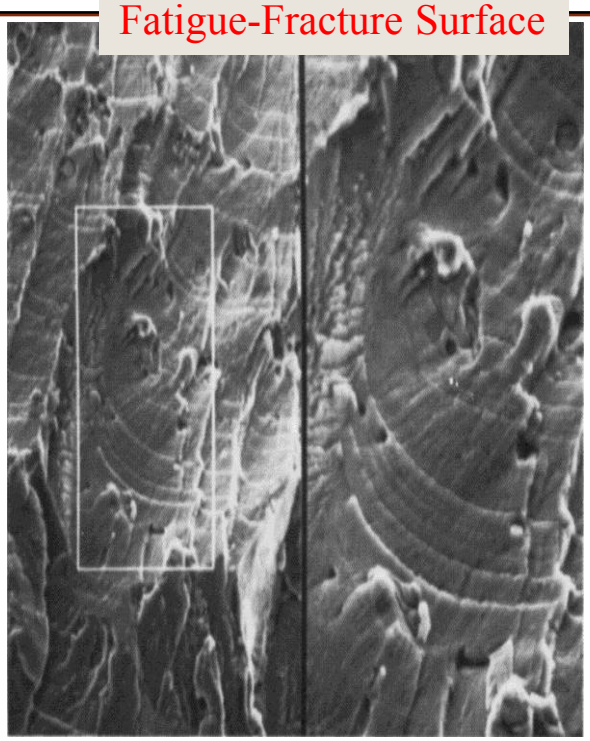
Wear is the undesired cumulative change in dimensions brought about by the gradual removal of discrete particles from contacting surfaces in motion, usually sliding, predominantly as a result of mechanical action.

Fatigue (S-N Curves)



Typical S-N curves for two metals. Note that, unlike steel, aluminum does not have an endurance limit.

Fatigue-Fracture Surface

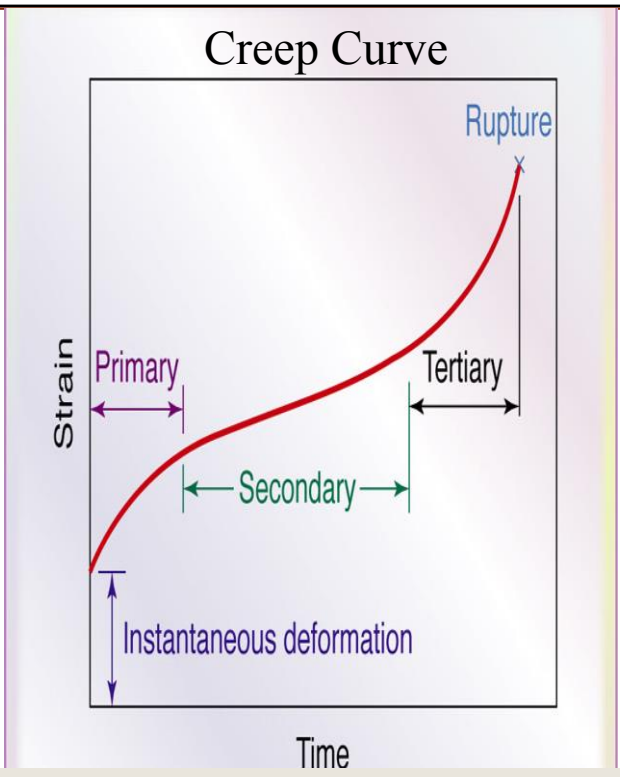


Typical fatigue-fracture surface on metals, showing beach marks. Magnification: left, 500x; right, 1000x..

Impact failure results when a machine member is subjected to nonstatic loads that produce in the part stresses or deformations of such magnitude that the member no longer is capable of performing its function.'

Fretting action may occur at the interface between any two solid bodies whenever they are pressed together by a normal force and subjected to small-amplitude cyclic relative motion with respect to each other.

Creep failure results whenever the plastic deformation in a machine member accrues over a period of time under the influence of stress and temperature until the accumulated dimensional changes interfere with the ability of the machine part to satisfactorily perform its intended function.



. The linear segment of the curve (secondary) is used in designing components for a specific creep life.



Typical creep-fracture surface on metals

Thermal relaxation or *stress relaxation* failure occurs when the dimensional changes due to the creep process result in the relaxation of a prestrained or prestressed member until it no longer is able to perform its intended function.

Stress rupture failure is intimately related to the creep process except that the combination of stress, time, and temperature is such that rupture into two parts is assured.

Thermal shock failure occurs when the thermal gradients generated in a machine part are so pronounced that differential thermal strains exceed the ability of the material to sustain them without yielding or fracture.

Galling failure occurs when two sliding surfaces are subjected to such a combination of loads, sliding velocities, temperatures, environments, and lubricants that massive surface destruction is caused by welding and tearing, plowing, gouging, significant plastic deformation of surface asperities, and metal transfer between the two surfaces.

Spalling failure occurs whenever a particle is spontaneously dislodged from the surface of a machine part so as to prevent the proper function of the member.

Radiation damage failure occurs when the changes in material properties induced by exposure to a nuclear radiation field are of such a type and magnitude that the machine part is no longer able to perform its intended function,

Creep buckling failure occurs when, after a period of time, the creep process results in an unstable combination of the loading and geometry of a machine part so that the critical buckling limit is exceeded and failure ensures.

Stress corrosion failure occurs when the applied stresses on a machine part in a corrosive environment generate a field of localized surface cracks,

Corrosion wear failure is a combination failure mode in which corrosion and wear combine their deleterious effects to incapacitate a machine part.

Corrosion fatigue is a combination failure mode in which corrosion and fatigue combine their deleterious effects to cause failure of a machine part.

Combined creep and fatigue failure is a combination failure mode in which all of the conditions for both creep failure and fatigue failure exist simultaneously, each process influencing the other to produce accelerated failure.



Failure Modes and Effects Analysis (FMEA)

- **Definition**

Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service.

Types of FMEA:

- System - focuses on global system functions
- Design - focuses on components and subsystems
- Process - focuses on manufacturing and assembly processes
- Service - focuses on service functions
- Software - focuses on software functions

Usage:

- provide the designer with tools and procedures that will lead to a systematic and thorough framework for design instead of **the use of the safety factors as a way of making sure that the design will work and protect the user against product or process failure**

FAILURE ANALYSIS OF WELDED COMPONENTS

INTRODUCTION

The welded joints are most critical places of steel structures due to:

1- high residual stresses and stress concentration (constructional and structural notches)

2- possible cracking originated from welding process.

3-In service, cracks can easily propagate, either suddenly (brittle fracture) or gradually (fatigue, creep or corrosion). It is very important to distinguish the crack types e.g. to eliminate hot cracking usually lower welding heat input is required, but this is unfavorable for cold cracking.

CRACK TYPES IN WELDED JOINTS

There are four basic crack types which occur in the welded joint :

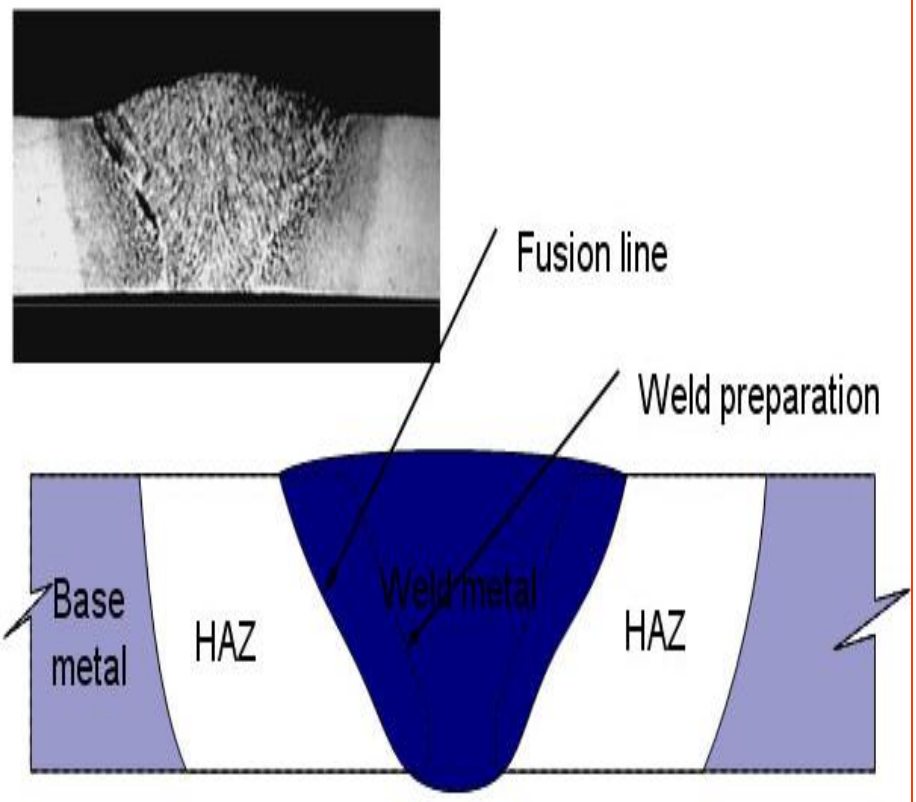
a-hot cracks,

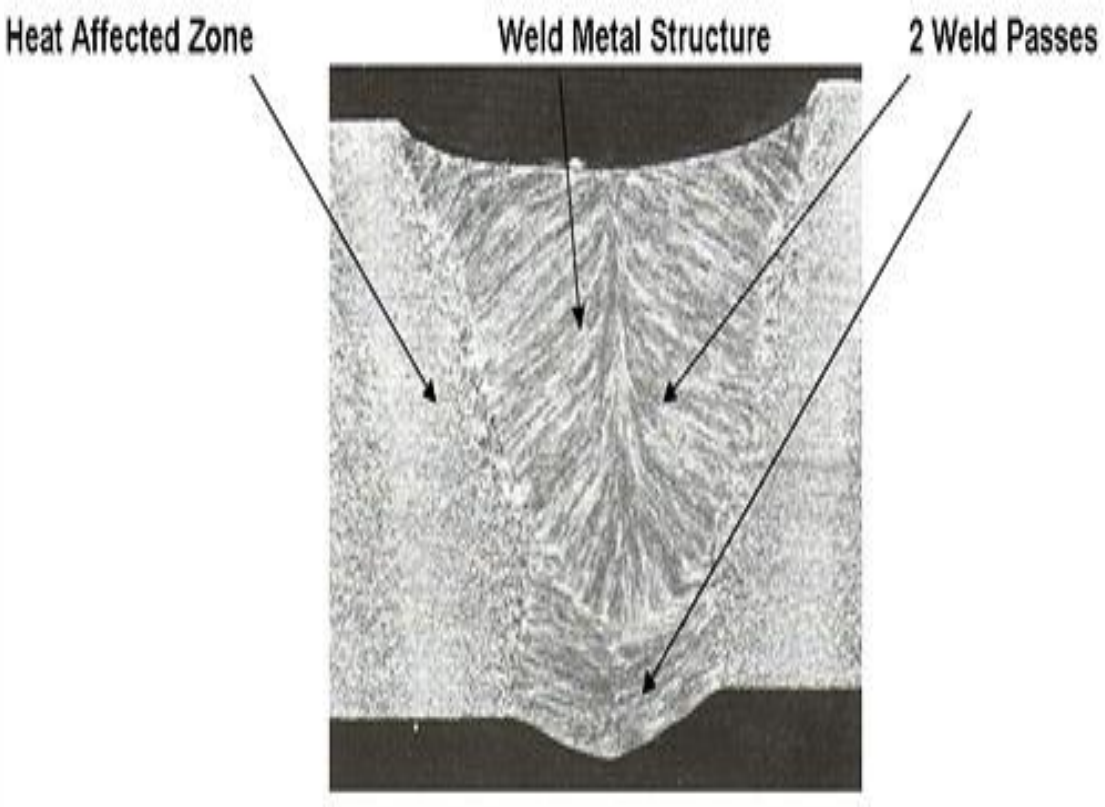
b-cold cracks,

c-lamellar tearing and

d- reheat cracks.

Fusion weld structure





POINTS OF CRACK INITIATION:

The cracks can be found in:

*the weld metal (WM) or

*in the heat affected zone (HAZ) from where they can propagate to parent metal or remain in the weld

• Even though there are some differences in the shape of the various cracks If the crack leads to fracture, its surface can be analyzed immediately.

•In the case of a shorter or an internal crack the section with a crack must be broken.

•Hot cracks

Three types of hot cracks occur in welded joints, namely:

1-solidification cracks, which are formed during solidification in the weld metal,

2-liquation cracks, which are formed in the underbead zone of the base metal, 3- polygonization cracks, which are formed in the lower temperature zone (800 – 1100°C), in the heat affected zone and the weld metal

Methods of detection:

open hot cracks (i. e. on the surface) can generally be distinguished from other types of cracks by:

1- Their oxidized black and brown tinged surface..

2-Hot cracks are usually shorter and more laminated than other types.

3-The liquation cracks have round grains with typical soliditied bridges between them.

4-The surfaces of polygonization cracks are pure.

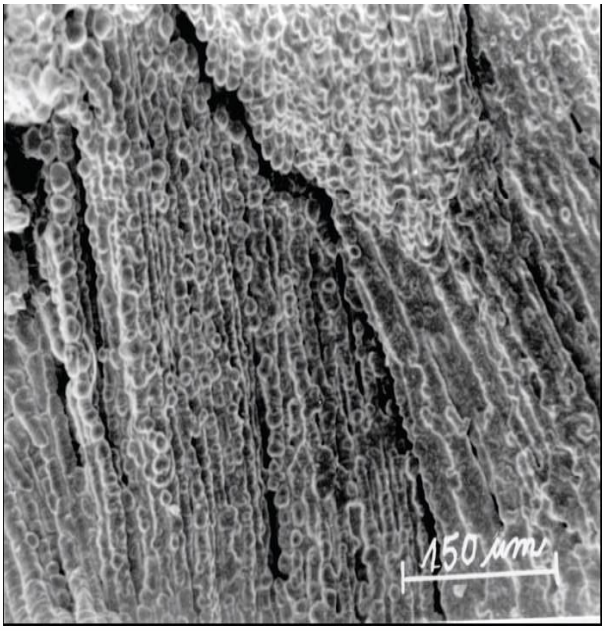


Figure 1 –solidification crack fracture surface

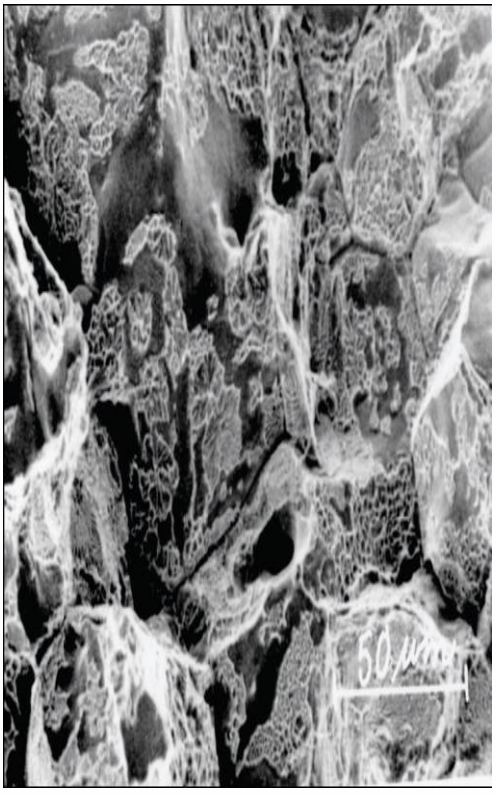


Figure ٢– kcarc noitauqil eht ecafrus erutcarf



Figure ٣– no segdirb deifidiloS kcarc noitauqil eht ecafrus

Cold cracks

1-Cold cracks (also called hydrogen-induced cracks) are longer, less laminated and generally more open than hot cracks . .

2-Their open surface is metallic lustrous or has a blue tinge.

3-The oxidation layer is comparatively thin

Lamellar cracks (tearing)

1-Lamellar cracks are typical defects in rolled steels

2-When the crack propagates, and cascade character

3-They are mainly formed in fillet welds and thick plates.

4-Crack propagation (joining) in the heat affected zone

Lamellar tearing



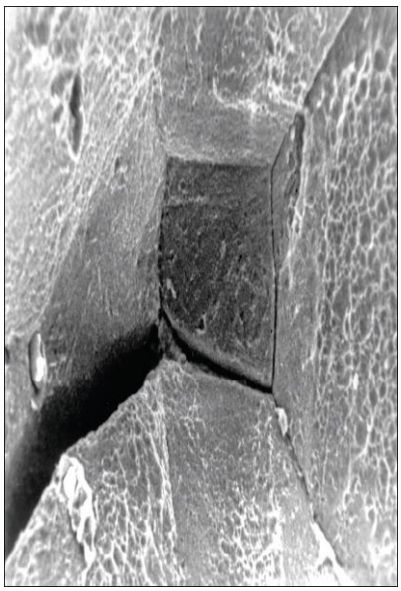
Reheat cracks

1-Reheat cracks are formed mainly during stress-relief annealing of welded joints.

2-They are a serious problem in the huge structures of low-alloyed Cr, Ni, Mo, V steels.

3-These are mostly microcracks situated in the coarse-grained of the heat affected zone.

4-Reheat cracks are of intercrystalline character with smooth and ductile facets



the reheat crack surface

PRINCIPLE OF BRAZING

1-In brazing joining of metal pieces is done with filler metal.

2-Filler metal is melted and distributed by capillary action between the faying surfaces .

3-In this case only filler metal melts.There is no melting of workpiece metal.

4-The filler metal (brazing metal) should have the melting point **more than** 450^{o} C.

5-Its melting point should be lesser than the melting point of workpiece metal.

PRINCIPLE OF SOLDERING

1-Soldering is very much similar to brazing and its principle is same as that of brazing.

2-The major difference lies with the filler metal:

3-the soldering filler metal used should have the melting temperature **lower than 450^{o}C.**

5-The surfaces to be soldered must be pre-cleaned so that these are faces of oxides, oils, etc.

6-An appropriate flux must be applied to the faying surfaces and then surfaces are heated.

7-Filler metal called solder is added to the joint, which distributes between the closely fitted surfaces.

8-Strength of soldered joint is much lesser than welded joint and less than a brazed joint

Comparison between Welding, Soldering and Brazing

No.	Welding	Soldering	Brazing
1.	These are the strongest joints used to bear the load. Strength of a welded joint may be more than the strength of base metal.	These are weakest joint out of three. Not meant to bear the load. Use to make electrical contacts generally.	These are stronger than soldering but weaker than welding. These can be used to bear the load upto some extent.
2.	Temperature required is upto 3800°C of welding zone.	Temperature requirement is upto 450°C.	It may go to 600°C in brazing.
3.	Workpiece to be joined need to be heated till their melting point.	No need to heat the workpieces.	Workpieces are heated but below their melting point.
4.	Mechanical properties of base metal may change at the joint due to heating and cooling.	No change in mechanical properties after joining.	May change in mechanical properties of joint but it is almost negligible.
5.	Heat cost is involved and high skill level is required.	Cost involved and skill requirements are very low.	Cost involved and sill required are in between others two.
6.	Heat treatment is generally required to eliminate undesirable effects of welding.	No heat treatment is required.	No heat treatment is required after brazing.
7.	No preheating of workpiece is required before welding as it is carried out at high temperature.	Preheating of workpieces before soldering is good for making good quality joint.	Preheating is desirable to make strong joint as brazing is carried out at relatively low temperature.

SOLDERING DEFECTS

Some of the common soldering defects are discussed below :

(a) Granular formation at the surface of the joint of solder .

(b) Formation of spheroids at the surface of soldering joint is also similar defect. This happen due to under heating or over heating of solder iron, insufficient use of flux. Formation of spheroids make the joint ugly and week in strength.

(c) Improper or uneven application of flux may make the joint of weaker strength.

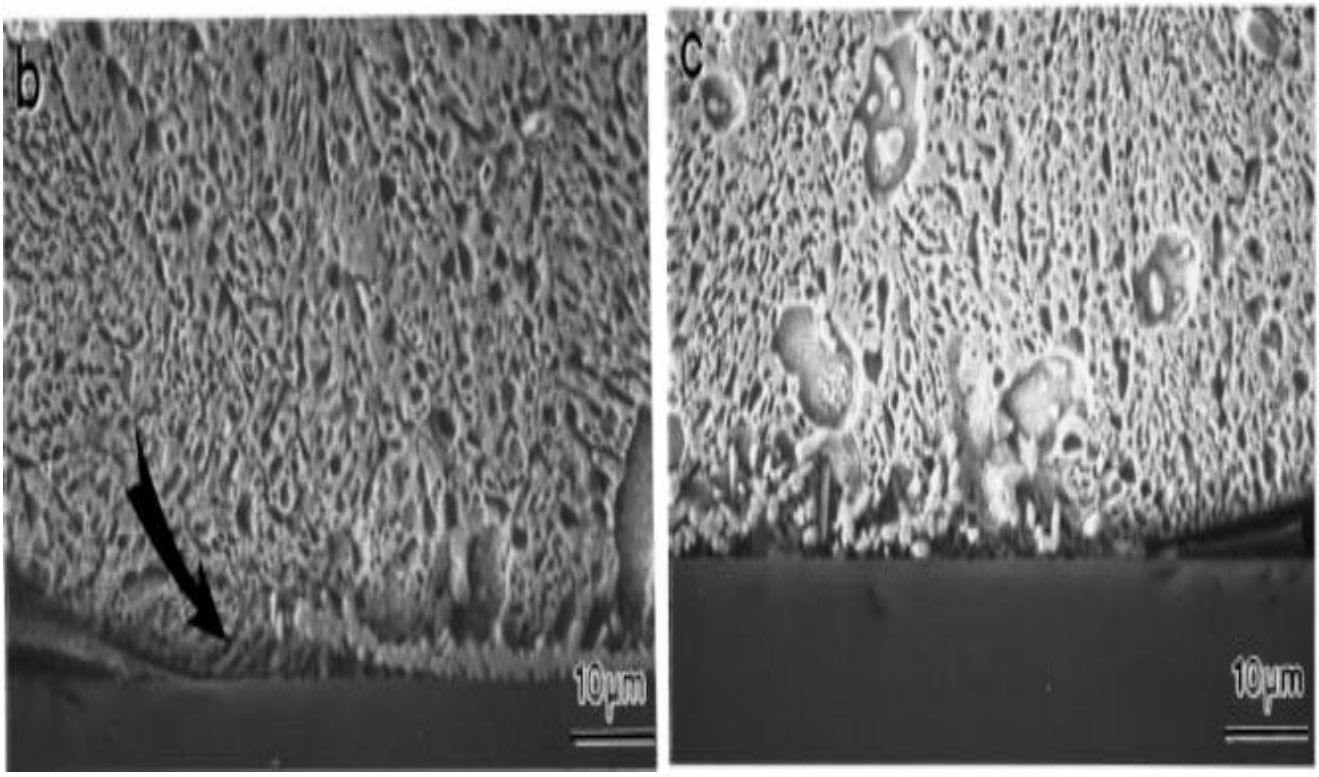
(d) Proper coordination between flux application and soldering makes the joint of good quality.

(e)the interface of solder/workpiece plays a critical role in the mechanical reliability of solder joint.

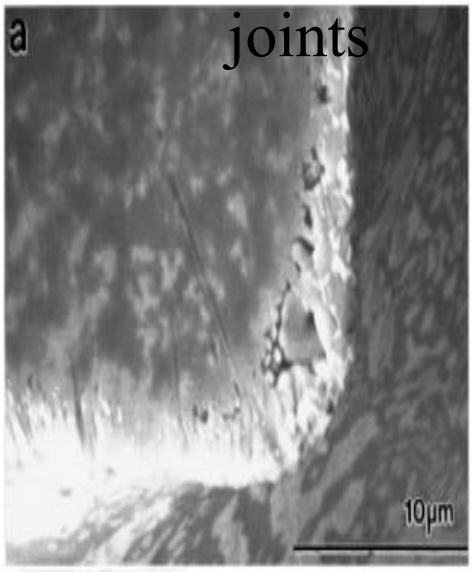
(f)Weak interfaces lead to brittle fracture mode of failure.Thus the crack formation at its corners and edges.

(g)We found that the failure mode is interfacial Fracture

(eh)The corners and edges are the most susceptible sites for failure due to stress concentration.



Cross sectional images of the edge area of solder joints



fractured surfaces of the corner area of solder joints

Bonded Joints

Adhesive-bonded joints are increasingly being used due to:

1- The ease with which they can be formed.

2-Issues in adhesive-bonded joints is the prediction of failure mechanisms.

3-Two major failure mechanisms widely reported in adhesive-bonded joints are :

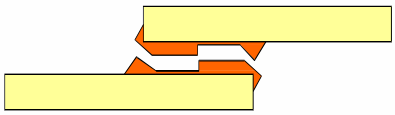
a-interfacial b-cohesive fractures

4-The interfacial fracture refers to the separation of the adhesive from the substrate at the interface between the two the adhesive and the substrate.

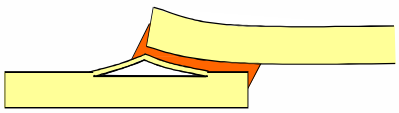
5-The cohesive failure refers to the failure of the adhesive at a point within the adhesive.

Either defects at the adhesive/substrate interface or poor bonding between the two materials or cracks initiating at the site of the stress singularity may result in the interfacial failure.

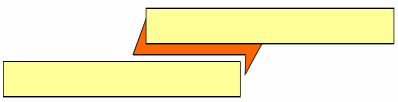
Adhesive failure modes in composite joints



Cohesive failure, wholly within the adhesive layer, - preferred



Failure due to induced through thickness stresses in the composite - very common, not ideal



Adhesive failure at interface - unpredictable must avoid

Recommended design practice

- ✓ Bondline thickness 0.1 to 0.5 mm
- ✓ Minimise peel loads & stresses Bond length < 30 mm
- ✓ Ultimate Load/unit width < 1 kN/mm
- ✓ Use stepped-lap joints for thick adherends
- ✓ Use internal end-chamfer & fillets

Use computer modelling to refine the geometry if needed

1.2.Buckling and Stress Discontinuity

Buckling

Introduction

–Buckling is a mode of failure generally resulting from structural instability due to *compressive* action on the structural member or element involved.

–Examples

- Overloaded metal building columns.
- Compressive members in bridges.
- Roof trusses.
- Hull of submarine.
- Metal skin on aircraft fuselages or wings with excessive torsional and/or compressive loading.
- Any thin-walled torque tube.

–In view of the above-mentioned examples, it is clear that buckling is a result of compressive action.

–Examples of buckling for commonly seen and used tools (components) are provided in the next few viewgraphs.

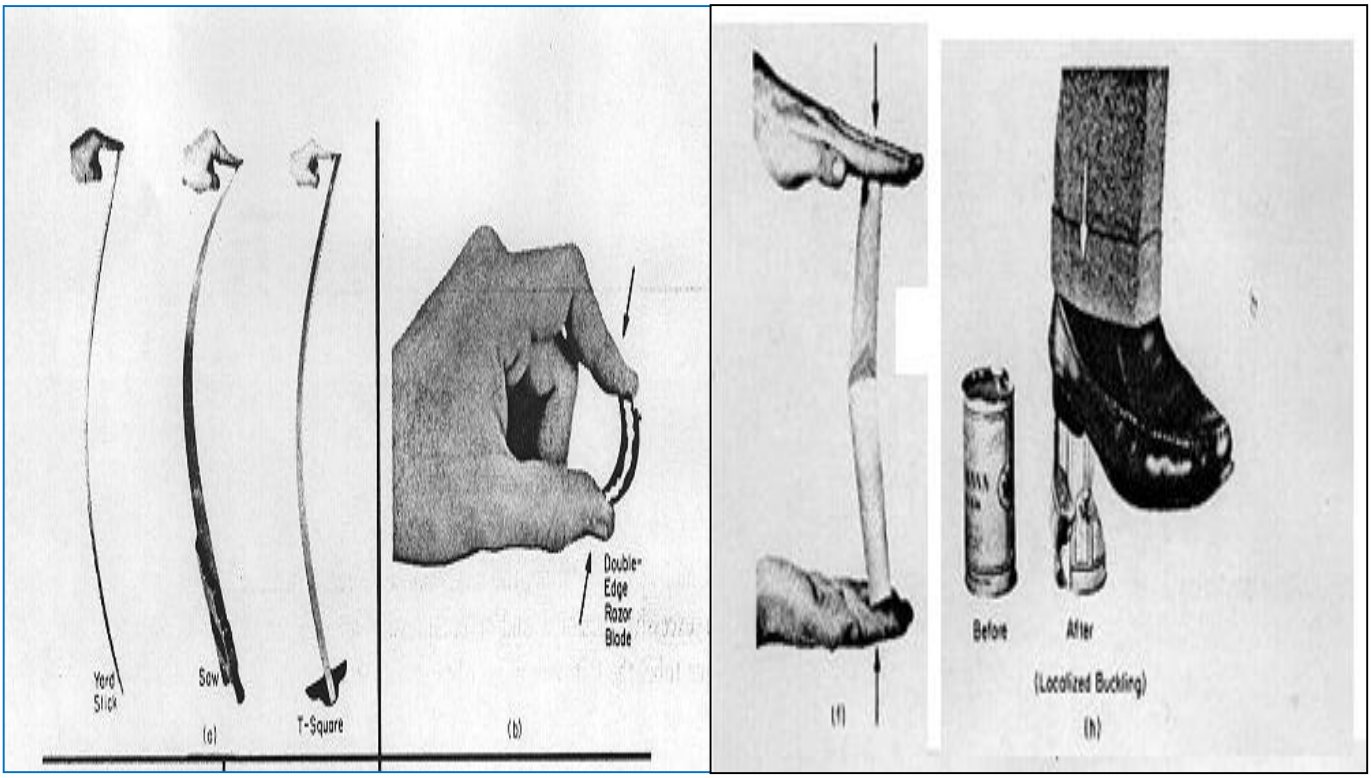


Fig. 1

–In Fig. 1, are examples of temporary or elastic buckling.

–in he same figure are examples of plastic buckling

–The distinctive feature of buckling is the *catastrophic* nature of failure.

–The collapse of a column supporting stands in a stadium or the roof of a building usually draws large headlines and cries of engineering negligence.

■ The Nature of Buckling

–Our usual approach of deriving a load-stress and load-deformation relations is the approach to find an expression for the buckling load P_{cr}.

–Buckling results from a state of unstable equilibrium.

Mechanisms of Buckling

- *1- Stable equilibrium*.

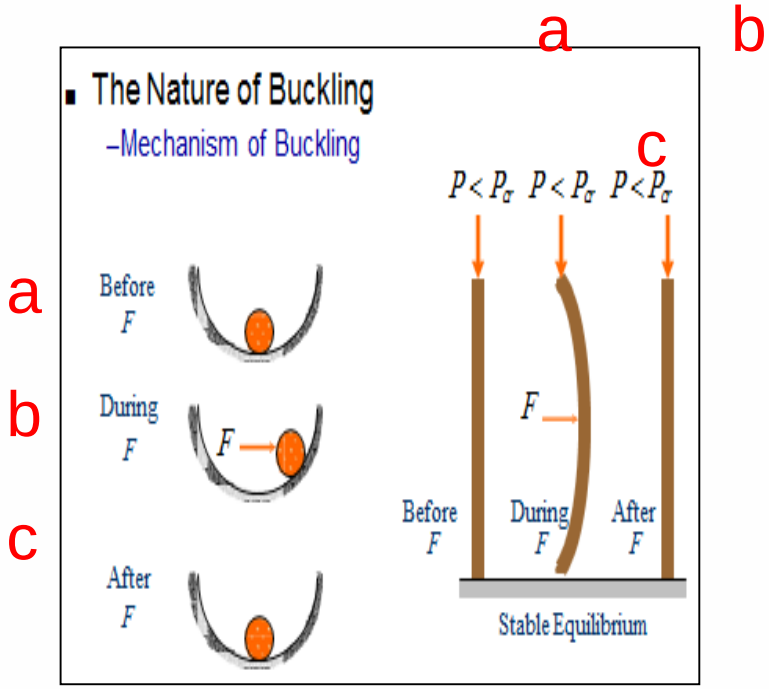
•In which the elasticity of the loaded element itself acts as restoring force and the element returns to its original shape after releasing the applied load.

• Let's consider the Figs., and study them very carefully.

•In the Fig.(a) some axial load *P* is applied to the column.

•In the Fig.(b) The column is then given a small deflection by applying the small lateral force *F.*

•In the Fig.(c) the load *P* is sufficiently small, when the force *F* is removed, the column will go back to its original straight condition.



•The column will go back to its original straight condition just as the ball returns to the bottom of the curved container.

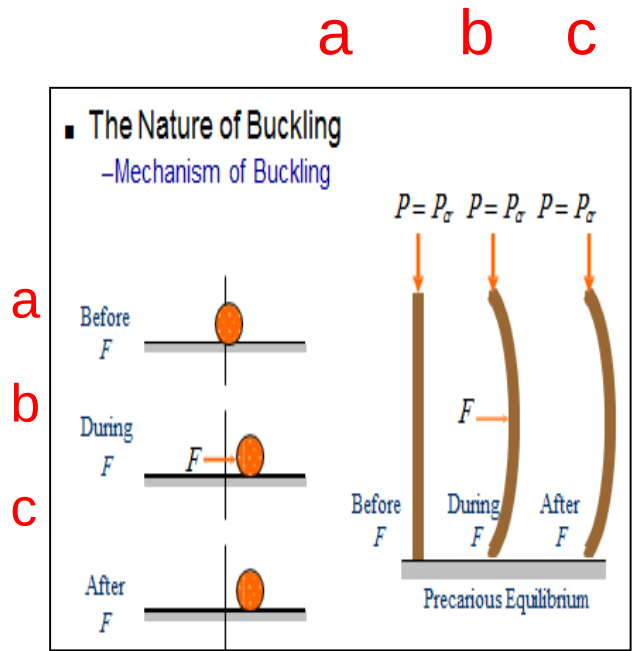
•In the Fig. the ball and the curved container, gravity tends to restore the ball to its original position, while for the column the elasticity of the column itself acts as restoring force.

•This action constitutes *stable equilibrium*.

•*2-Neutral or precarious equilibrium*.

•The elastic restoring force of the element is not sufficient to return it to its original straight condition, but is sufficient to prevent excessive deflection of it.

•The same procedure can be repeated for increased value of the load P until some critical value P_{cr} is reached, as shown in the Fig. below. When the element carries this load, and a lateral force F is applied and removed, the element will remain in the slightly deflected position.



•In the Fig. the ball and the flat surface, the amount of deflection will depend on the magnitude of the lateral force *F*.

•Hence, the element can be in equilibrium in an infinite number of slightly bent positions.

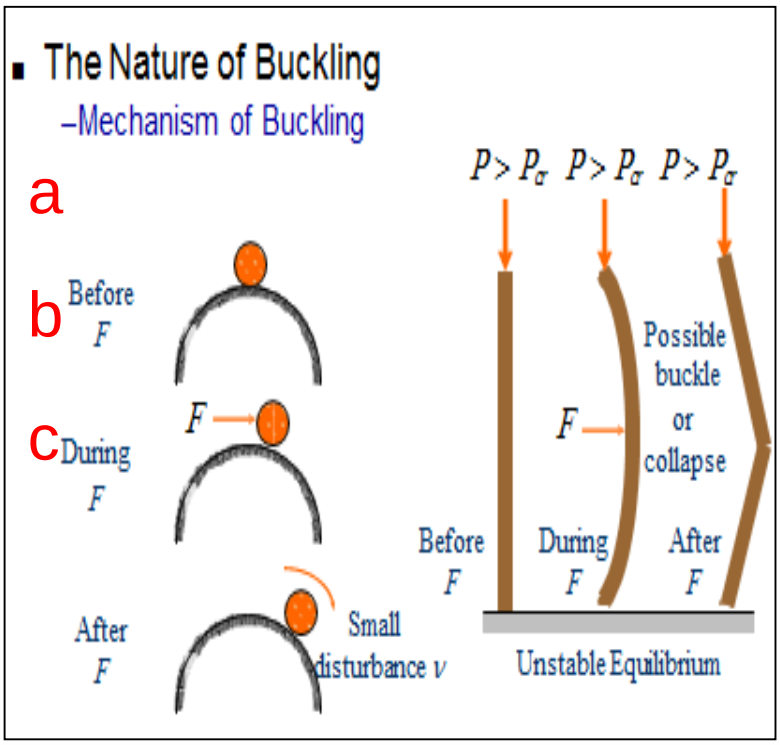
•This action constitutes *neutral or precarious equilibrium*.

3- Unstable equilibrium

In which the elastic restoring force of the element is not sufficient to prevent a small disturbance from growing into an excessively large deflection

•If the element is subjected to an axial compressive load P that exceeds $P_{cr,}$ as shown in Fig. blow , and a lateral force F is applied and removed, the column will bend considerably.

a b c



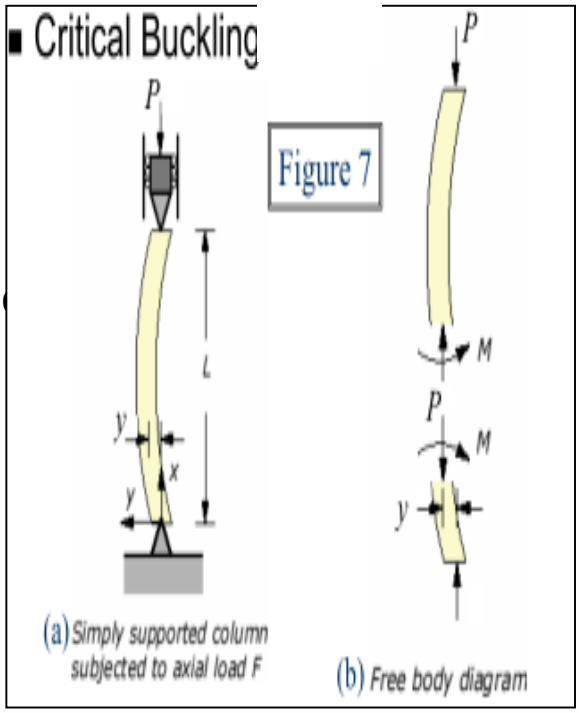
- Depending on the magnitude of P, the element either will remain in the bent position or will completely collapse and fracture, just as the ball will roll off the curved surface
- This type of behavior indicates that for axial loads greater than Pcr, the straight position of a column is one of unstable equilibrium in that a small disturbance will tend to grow into an excessive deformation. on

- Critical Buckling Load
- The purpose of this analysis is to determine the minimum axial compressive load for which a column will experience lateral deflection. δ

Governing Differential Equation:

- Consider a buckled simply-supported column of length L under an external axial compression force P, as shown in the left schematic Fig.

The transverse displacement **of** the buckled (δy).



–Governing Differential Equation:

•The right schematic of Fig. shows the forces and moments acting on a cross-section in the buckled column. Moment equilibrium on the lower free body yields a solution for the internal bending moment *M*,

$$Py + M = 0 \qquad Py = -M \qquad (1)$$

Recall the relationship between the moment M and the transverse displacement y for the elastic curve

Eliminating M from Eqs. 1 and 2 results in the governing equation for the buckled slender column,

$$EI\frac{d^2y}{dx^2} = M \qquad (2)$$

– Governing Differential Equation

:

$$\frac{d^2y}{dx^2} + \frac{P}{EI}y = 0 \qquad (3)$$

– Buckling Solution:

• The governing equation is a second order homogeneous ordinary differential equation with constant coefficients and can be solved by the method of characteristic equations. The solution is found to be,

$$y(x) = A\sin px + B\cos px \qquad (4)$$

Critical Buckling Load, P_{cr}

The critical buckling load (Euler Buckling) for a long column is given by

$$P_{cr} = \frac{\pi^2 EI}{L^2} \qquad (9)$$

where

E = modulus of elasticity of the material

I = moment of inertia of the cross section

L = length of column

Shape function:

- Substituting the expression of P in Eq. 9, into Eq. 4, and noting that $B = 0$, the shape function for the buckled shape $y(x)$ is mathematically called an eigenfunction, and is given by:

$$y(x) = A\sin\left(\frac{n\pi x}{L}\right) \qquad (10)$$

The critical buckling normal stress

The critical buckling normal stress σ_n is found as follows:

Buckling of Long Straight Columns

The critical buckling normal stress is given by

$$\sigma_{cr} = \frac{\pi^2 E}{(L/r)^2} \qquad (12)$$

Where

r = radius of gyration $= \sqrt{\frac{I}{A}}$

(L/r) = slenderness ratio of column

–Many columns lie between these extremes in which neither solution is applicable.

–These intermediate-length columns are analyzed by using empirical formulas to be described later.

–*When calculating the critical buckling for columns, I (or r) should be obtained about the weakest axis.*

1.3.Stress Discontinuity

Discontinuity: is defined as an imperfection or interruption in the normal physical characteristics or structure of an object (*crack, porosity, inhomogeneity, etc.*).

Discontinuities are categorized in four groups which are:

1-Inherent discontinuities

2-Primary processing discontinuities

3-Secondary procession discontinuities

4-Service discontinuities

Inherent discontinuities

This group refers to the discontinuities that originate during the initial casting process (when the metal is casted into ingots for further processing as:

-Blowholes and Porosity

Blowholes and porosity are small rounded cavities found at the surface or near surface of castings and they are caused by the entrapped gasses that could not escape during solidific



Nonmetallic Inclusions

Nonmetallic (or slag) inclusions are usually oxides, su silicates

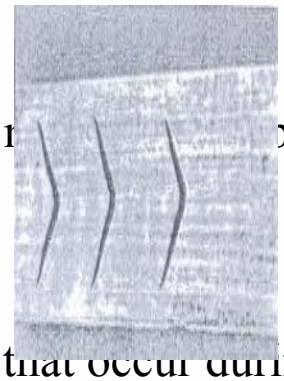
that remained with the molten metal during original c



2-Primary processing discontinuities

This group refers to the discontinuities that originate during hot or cold forming processes (extrusion, forging, rolling, drawing, welding, etc.) as:.

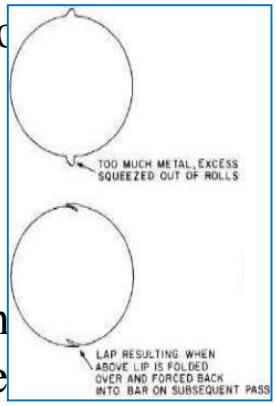
Cupping



Cupping is a subsurface discontinuity that r bars during extrusion or sever cold drawing.

Forging and Rolling Laps

Laps are elongated surface discontinuities that occur during rolling or forging operations due to the presence o excessive material (fin)



that is folded over

3-Secondary processing discontinuities

This group refers to the discontinuities that origin grinding, machining, heat treating, plating and re finishing operations.

Grinding Cracks

Grinding cracks develop at locations where there is a localized heating of the base metal ***Pickling Cracks***

Pickling is chemical surface cleaning operation (using acids) used to remove unwanted scale.

4-Service discontinuities

This group refers to the discontinuities that originate or develop while the component is in service.

The service conditions (loading, mechanical and chemical environment, maintenance) of a component affect its expected life.

Fatigue Cracks

When a component is subjected to fatigue stress (cyclically applied stress), fatigue cracks can develop and grow and that will eventually lead to failure (even if the magnitude of the stress is smaller than the ultimate strength of the material).

Creep and Creep rupture

Creep in Metals

The mechanical strength of metals decreases with increasing temperature and the properties become much more time dependent.

Effects of high temperature on metals are:

- Lower strength.

- Greater atomic and dislocation mobility.

- Higher equilibrium concentration of vacancies.

- New deformation mechanisms, such as grain boundary sliding.

- Recrystallisation and grain growth.

- Age hardened alloys will overage by particle coarsening and lose strength.

- Oxidation and intergranular penetration.

Tests required to evaluate high temperature properties:

(i) High Temperature Tensile Test:

Similar to a short term room temperature test, i.e completed in a few minutes and producing stress versus strain curves at specific temperatures.

Its result:

Provides useful data for short term applications such as rocket parts.

(ii) Creep Test:

Measures dimensional changes accurately at constant high temperature and constant load or stress.

Its result:

Useful for long term applications which are strain limited, such as turbine blades.

(iii) Stress Rupture Test (Creep rupture test):

Measures time to failure at specified stress and temperature.

Its result:

It is carried out at a constant load. Useful for applications where some strain can be tolerated but failure must be avoided, such as large furnace housings.

Definitions:

Creep :

1-It is the tendency of a solid material to slowly deform permanently under the influence of stresses.

2- It occurs as a result of long term exposure to levels of stress that are below the yield strength of the material.

3-Creep is more severe in materials that are subjected to heat for long periods, and near the melting point.

4-Creep always increases with temperature.

Factors affect creep:

The rate of this deformation is a function of:

- the material properties, exposure time, exposure temperature and the applied load.

Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function

creep

Creep occurs when a metal is subjected to a constant tensile load at an elevated temperature.

Undergo a time-dependent increase in length.

temperature At which material will creep:

•Since materials have its own different melting point, each will creep when the homologous temperature > .٠,٥

$$\text{Homologous temp} = \frac{\text{Testing temperature}}{\text{Melting temperature}} > 0.5$$

Creep Properties

Creep is a time-dependent deformation of a material while under an applied load that is below its yield strength.
It is most often occurs at elevated temperature, but some materials creep at room temperature.

Creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature. Results of tests are usually plotted as strain versus time up to rupture

Creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature. Results of tests are usually plotted as strain versus time up to rupture.

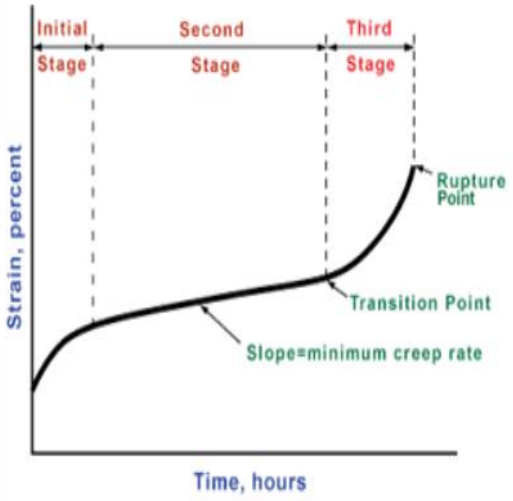
As indicated in the image, creep often takes place in three stages. In the initial stage, strain occurs at a relatively rapid rate but the rate gradually decreases until it becomes approximately constant during the second stage.

This constant creep rate is called the minimum creep rate or steady-state creep rate since it is the slowest creep rate during the test.

In the third stage, the strain rate increases until failure occurs

While most materials are subject to creep, the creep mechanisms is often different between metals,

plastics, rubber, concrete.

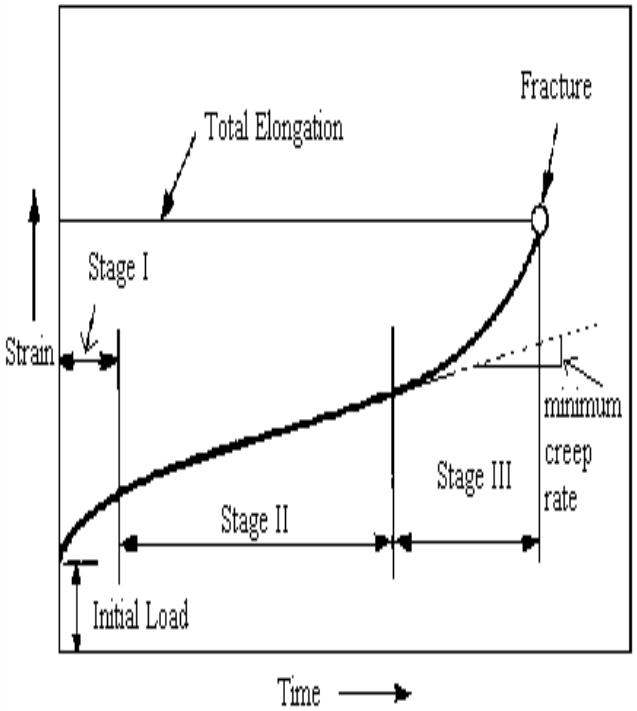


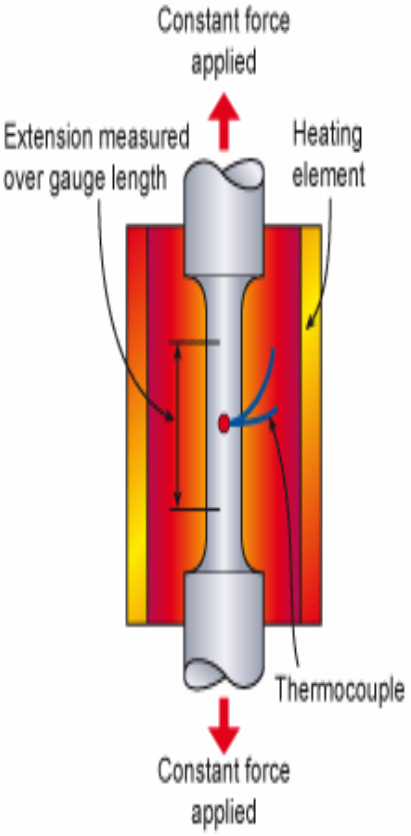
Creep test



The creep test is carried out by applying a constant load to a tensile specimen maintained at a constant temperature.

Typical creep curve



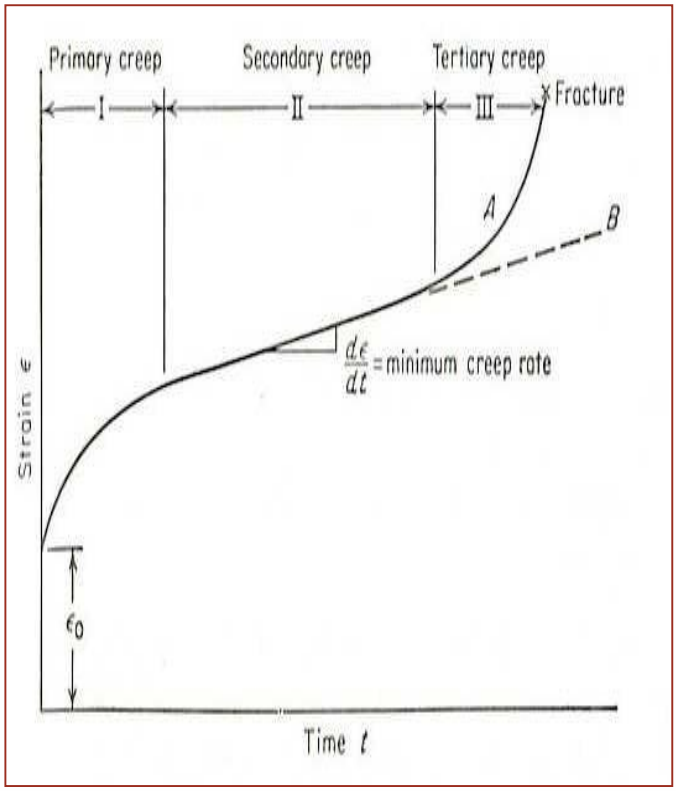


Schematic creep test

The creep test : **measure the *dimensional changes* which occur when subjected to high temperature.**

The rupture test : **measures the effect of temperature on the long- time load bearing characteristics.**

The creep curve



A typical creep curve

shows three distinct stages with different creep rates.

After an initial rapid elongation ε_o esaerced etar peerc eht ، eht gnihcaer litnu emit htiw .etats ydaets

Primary creep

provides decreasing creep rate.

Secondary creep

gives the representing constant creep rate.

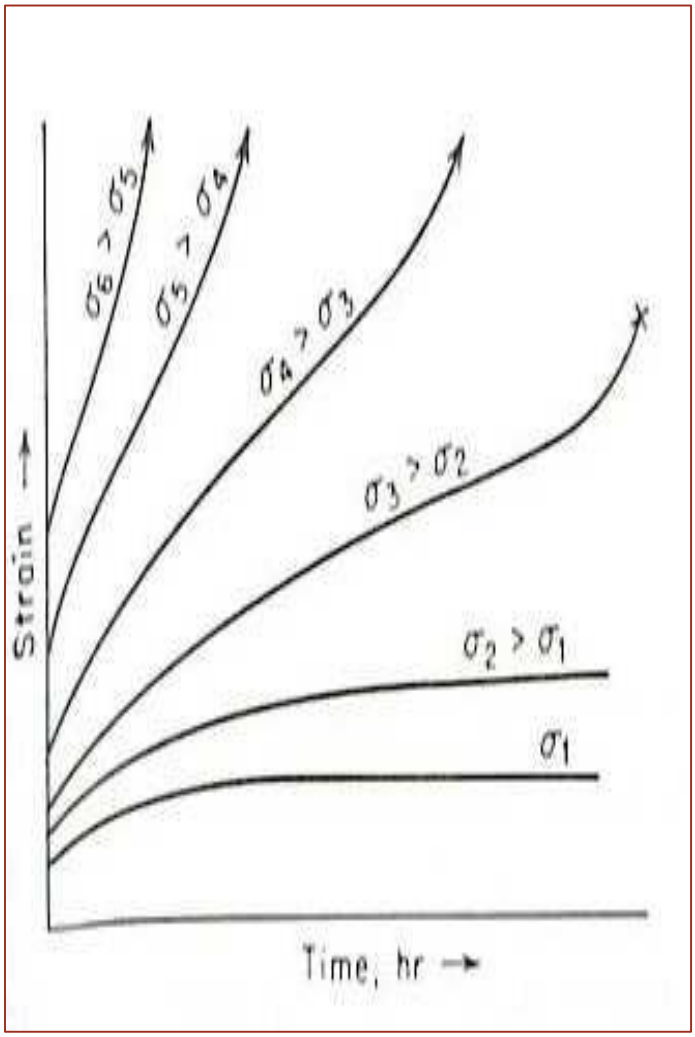
Tertiary creep

yields a rapid creep rate till failure.

Notes: B curve is obtained when the stress rather than the load is maintained.

ε_o is instantaneous strain on loading which is partly *recoverable* with time (anelastic) and partly *nonrecoverable* with time (plastic)

Effect of stress on creep curves at constant temperature



The shape of creep curve will slightly change according to the *applied stress* at a constant temperature.

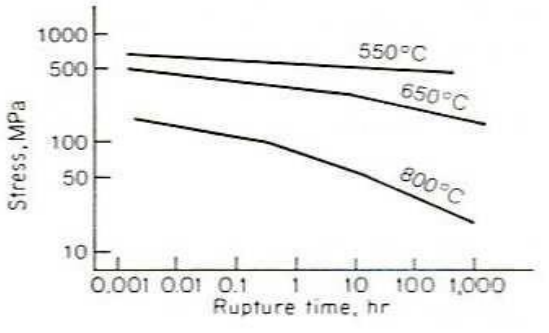
Applied stress ↑ → Strain ↑

Temp ↑ → Creep rate ↑

The Creep rupture test

	Creep test	Creep rupture test
Load **Creep rate**	**Low load minimum creep rate**	**high load high creep rate**
Test period	2000-10000 h	1000 h
Total strain	0.5%	50%
Strain gauge	Good strain measuring devices	Simpler strain measuring devices

The *rupture test* is carried out in a similar manner to the *creep test* but at a *higher stress level* until the specimen fails and the *time at failure* is measured.



Stress rupture- time data on log-log scale

Rupture strength and *failure time* are plotted, normally showing a *straight line*.

Changing of the slope indicates *structural changes in the material* ralunargsnart ‹.e.i ‹ intergranular fracture, oxidation, recrystallisation, grain growth, spheroidization, precipitation.

•Direct application in *design*.

Stress Rupture Properties:

1-Stress rupture testing is similar to creep testing except that the stresses are higher than those used in a creep testing.

2-Stress rupture tests are used to determine the time necessary to produce failure so stress rupture testing is always done until failure.

3-Data is plotted log-log as in the chart above.

4-A straight line or best fit curve is usually obtained at each temperature of interest.

5-This information can then be used to extrapolate time to failure for longer times

Fracture at elevated temperature

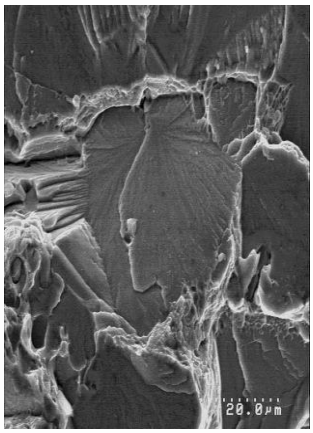
Temp

Transgranular fracture

Slip planes are weaker than grain boundaries

Intergranular fracture

Grain boundaries are weaker than slip planes.

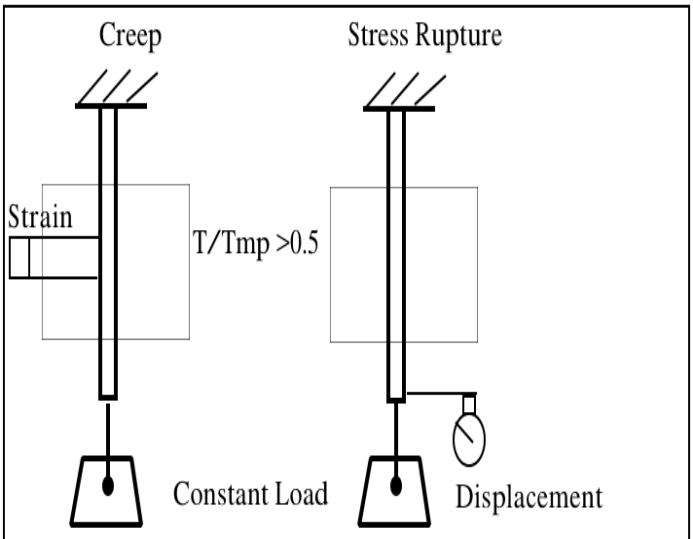




Grain boundary fracture

Comparison of Creep and Stress Rupture Tests.

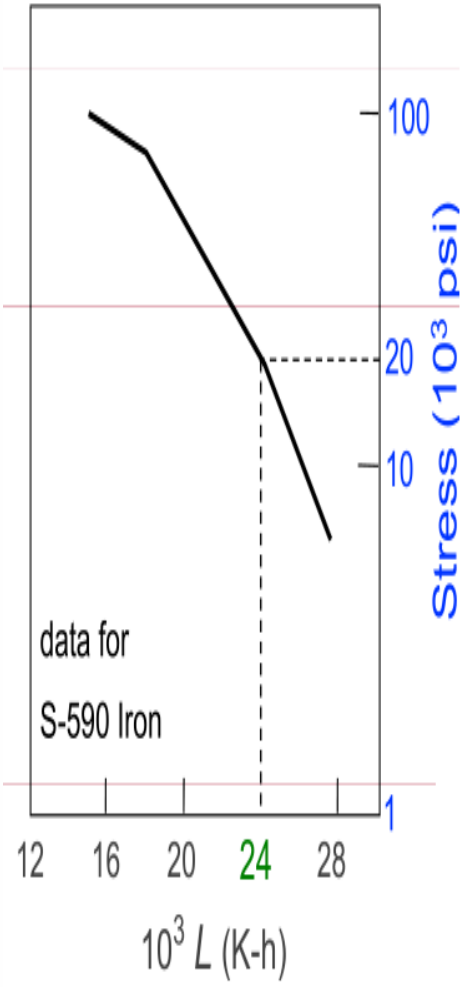
Creep Test	Stress Rupture Test
Measures strain versus time at constant temperature and load or **stress**	Measures stress versus time to rupture at constant temperature.
Relatively low loads and creep rates.	Higher loads and creep rates.
Long duration, 2,000 to 10,000 hours. Not always to fracture.	Shorter duration, less than 1,000 hours typically. Always to fracture.
Strain measured accurately using sensitive equipment (inductance gauges) to determine creep rate. Strains typically less than 0.5%.	Simpler less sensitive strain measuring equipment (dial gauges). Time and strain to fracture measured. Strains typically up to 50%.



- Low Loads	- High Loads
- Precision Strain Measurement (ε_f<0.5%)	- Gross Strain Measurement (ε_f up to 50%)
- Long term (2000-10,000 h)	- Short term (<1000 h)
- Expensive equipment	- Less expensive equipment
Emphasis on minimum strain rate at stress and temperature	Emphasis on time to failure at at stress and temperature

Prediction of Creep Rupture Lifetime

Estimate rupture time for S-590 Iron, $T = 800°C$, $\sigma = 20{,}000$ psi



Time to rupture, t_r

$$T(20 + \log t_r) = L$$

temperature

time to failure (rupture)

function of applied stress

$$(1073\,\text{K})(20 + \log t_r) = 24 \times 10^3$$

Ans: t_r = 233 hr

CHAPTRR.2

Fracture mechanics and crack propagation

FRACTURE

- Fracture mechanics
- Crack propagation

Fracture mechanics:

Definition:

It is the subject that study the attempts to characterize a material's resistance to fracture and its "toughness."

Goals of fracture mechanics:

- One of the goals of fracture mechanics is to derive a material property (the fracture toughness), which can characterize the mechanical behavior of a material with flaws (cracks) in it.
- One of the important goals of material/component design is to avoid catastrophic failure. Determine minimum detectable crack length (how small of crack can nondestructive testing detect)
- Determine critical crack length for the maximum load
- Create a crack growth curve showing crack length as a function of number of cyclic loads
- Determine how much time is required from the crack to grow from the minimum detectable length to critical length

Cracks

Types of cracks:

1-steady (i.e. slowly increasing crack length with time or load). If crack propagation is steady, then we can practice preventive maintenance (i.e. replace the component after certain hours of service) → this cannot be done in the case of catastrophic failure.

2-catastrophic (unsteady crack propagation, leading to sudden failure of the material)

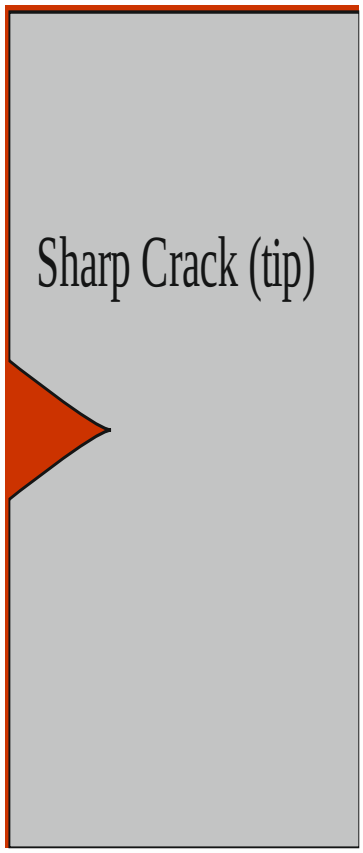
❑Mechanism of cracking:

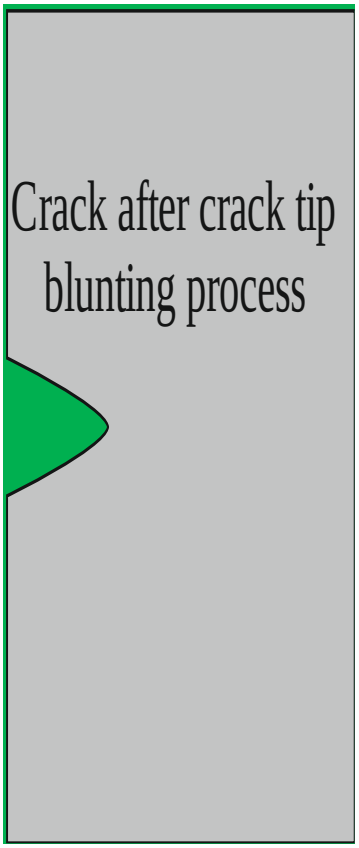
❑Under tensile loading if the stress exceeds the yield strength , the material begins to plastically deform.

❑The area under the stress-strain curve is designated as the *toughness* in uniaxial tension. Toughness relates to the energy absorbed to fracture.

❑ Similarly, in the presence of cracks we arrive at a *material parameter*, called the **fracture toughness**.

❑In *most* materials the crack tip is not 'infinitely' sharp, but is *blunted* a little. This further avoids the stress singularity at the crack tip .

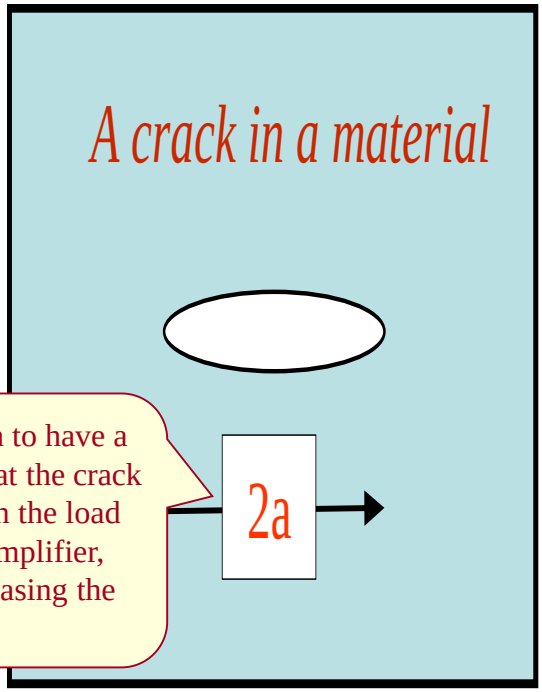

Sharp Crack (tip)


Crack after crack tip
blunting process

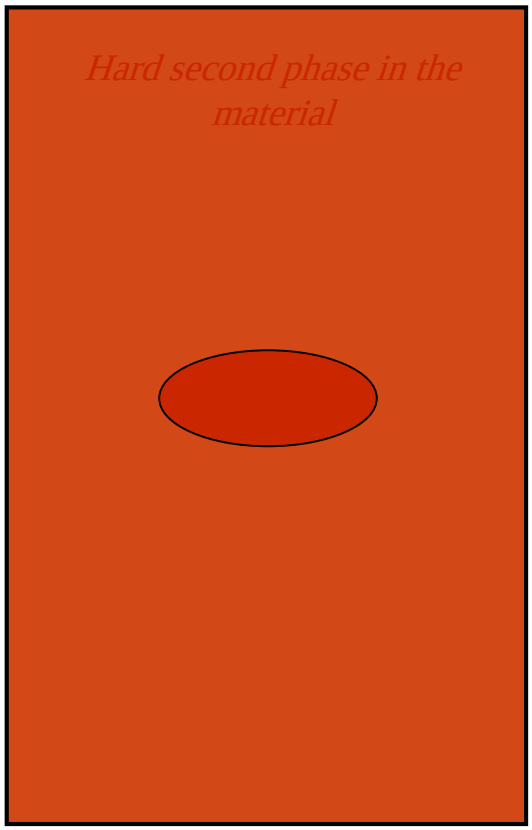
Crack propagation

Reasons of crack propagation:

- The sharper the crack-tip, the higher will be the stresses at the crack-tip.
- It is a region where atoms are 'debonded' and an internal surface exists (this internal surface may be connected to the external surface).).
- Even void or a through hole in the material can be considered a crack.
- The crack is considered to be a discontinuity in the material with a 'sharp' feature .
- Material nonhomogeneity
- A crack reduces the stiffness of the structure *(though this may often be ignored).*



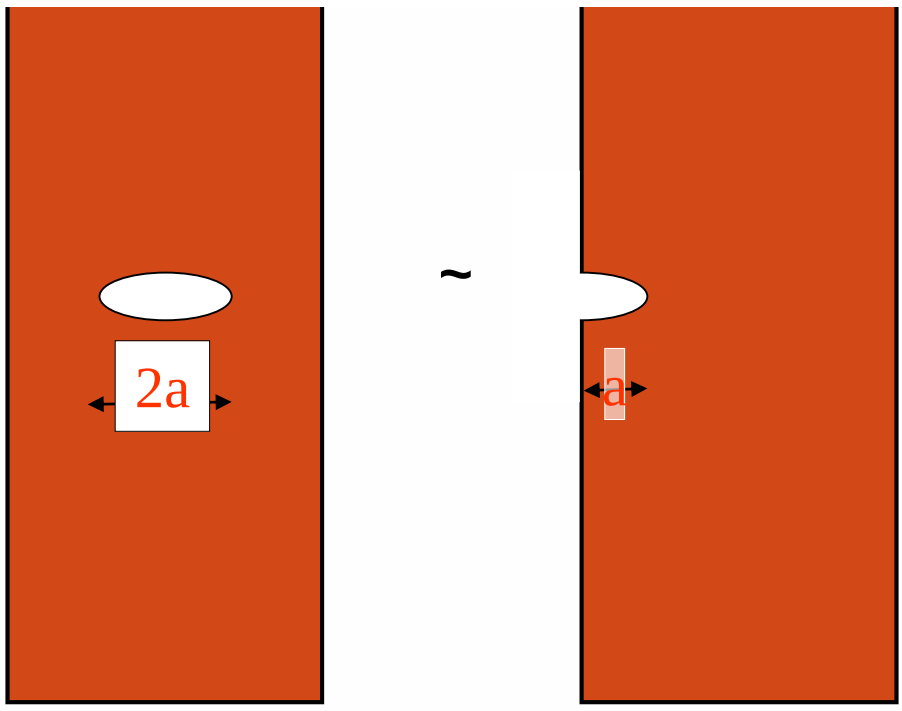
Though often in figures the crack is shown to have a large lateral extent, it is usually assumed that the crack does not lead to an appreciable decrease in the load bearing area [i.e. crack is a local stress amplifier, rather than a ‘global’ weakener– by decreasing the load bearing area].



Characterization of Cracks

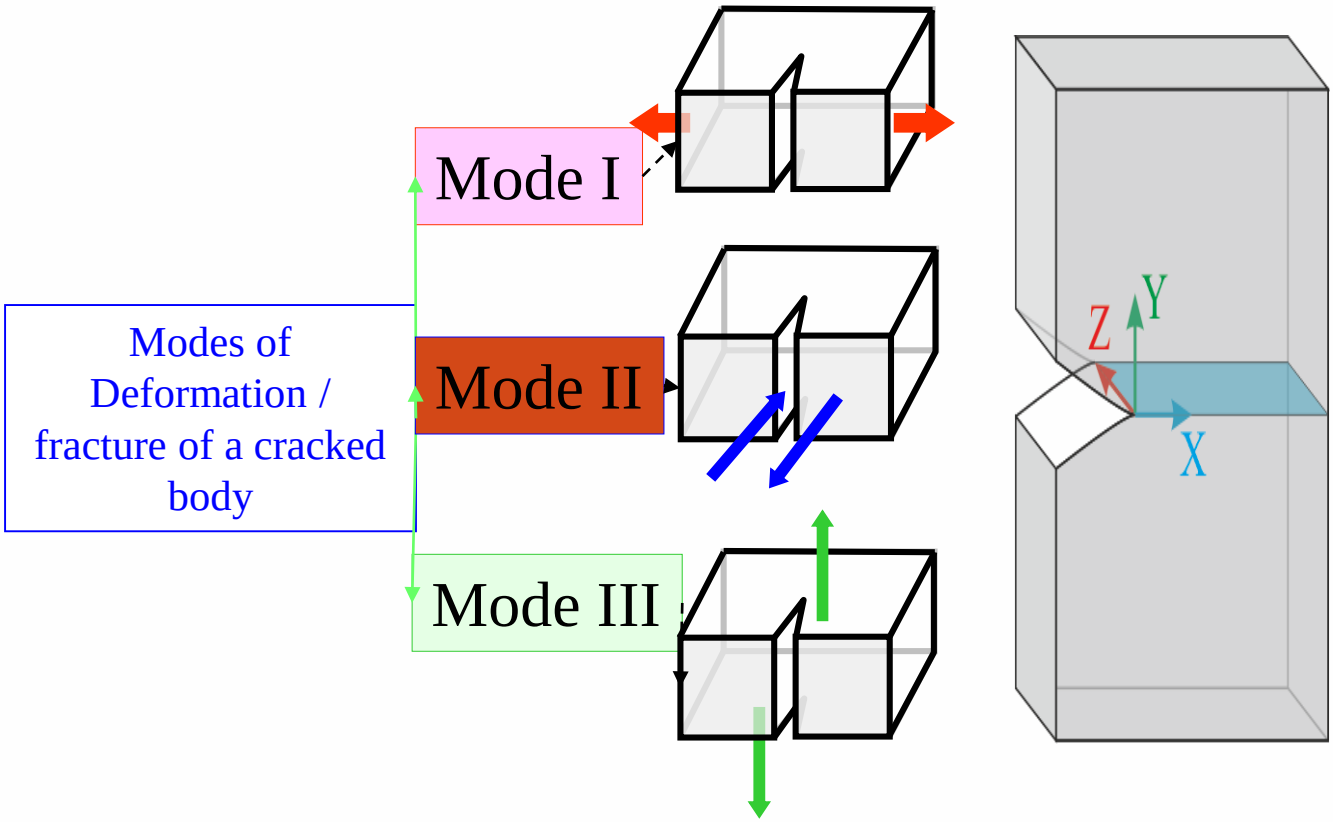
Cracks can be characterized looking into the following aspects.

- Its connection with the external free surface: (i) completely internal, (ii) internal cracks with connections to the outer surfaces, (iii) Surface cracks.
- Cracks with some contact with external surfaces are exposed to outer media and hence may be prone to oxidation and corrosion (cracking).
- Crack length (the deleterious effect of a crack further depends on the type of crack (i, ii or iii as above).
- Crack tip radius (the sharper the crack, the more deleterious it is). Crack tip radius is dependent of the type of loading and the ductility of the material.
- Crack orientation with respect to geometry and loading.



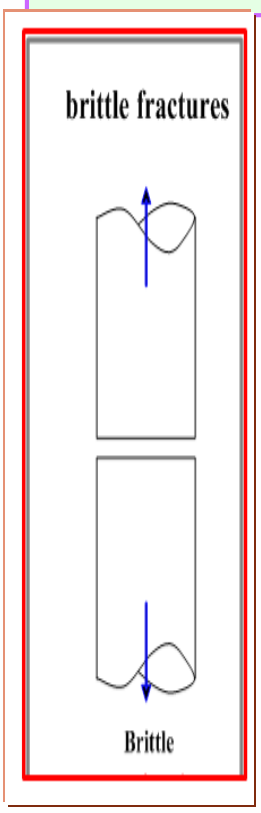
Modes of deformation of a cracked body (m

- Three ideal cases of modes of deformation:
  - Mode I: Opening mode
  - Mode II: Sliding mode
  - Mode III: Tearing mode
- In the general case the mode is not pure (i.e. is mixed mode).



Three factors influence the nature of fracture:

- (i) Temperature : Materials which behave in a brittle fashion at low temperature may become ductile at high temperatures.
- (ii) Strain rate When strain rate is increased (by a few orders of magnitude) a ductile material may start to behave in a brittle fashion.
- (iii) The state of stress



Factors affecting (the nature of) fracture

- Temperature
- Strain rate
- State of stress

Fracture

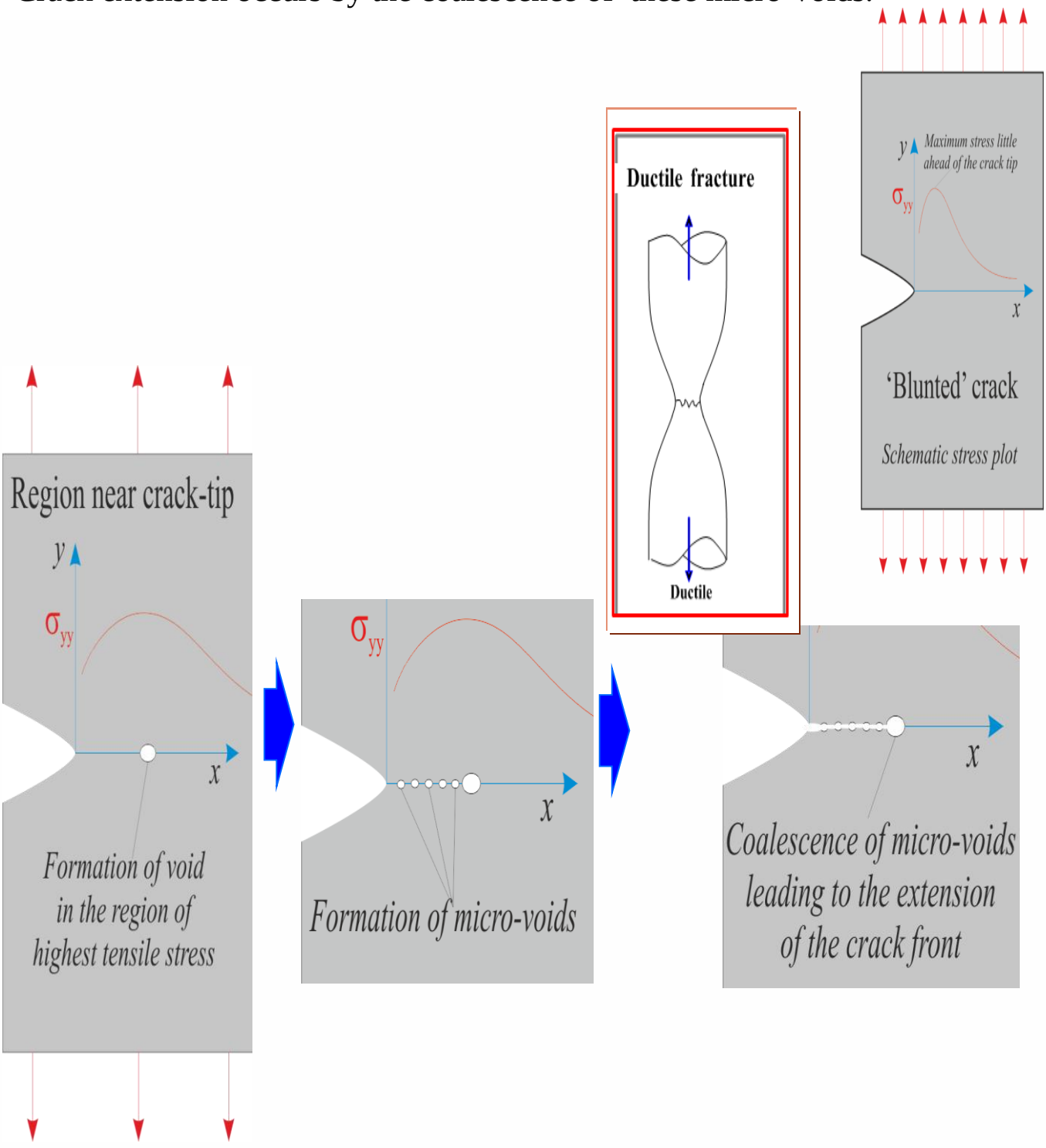
- Ductile
- Brittle

Promoted by

- Low Temperature
- High Strain rate
- Triaxial state of str

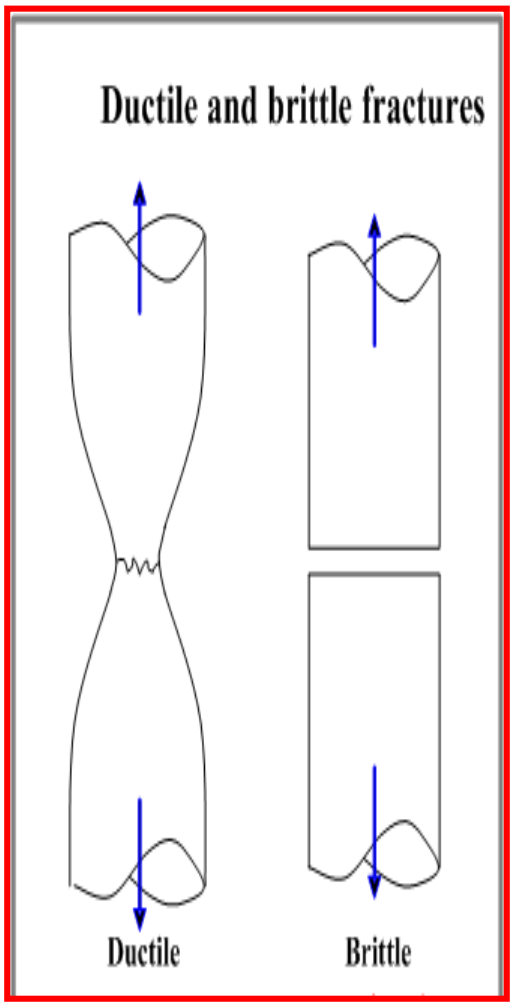
The mechanism of Crack propagation in ductile materials

- the maximum crack opening stress (mode-I) is at the crack tip and hence crack propagation involves breaking of bonds at the crack tip.
- the maximum stress lies a little ahead of the crack tip.
- Void(s) nucleate in the region of highest stress (usually at some heterogeneity).
- Crack extension occurs by the coalescence of these micro-voids.



The mechanisms of Crack propagation in brittle fracture

- Cracks are sharp & no crack tip blunting.
- No energy spent in plastic deformation at the crack tip.
- Fracture surfaces are flat.



Fail-Safe Designs identification ,detection and control of failure

Fail-Safe design

Definitions:

1-Fail-safe designs :

Are designs that incorporate various techniques to mitigate losses due to system or component failures.

The design assumption is that failure will eventually occur but when it does the device, system or process will fail in a safe manner.

Benefits of fail-safe designs include:

1-Being able to manage the unexpected and mitigating damage if failure occurs.

2-Safe-Life:

Safe-life assumes that the component or system is designed to not fail within a certain, defined period.

-It is assumed that testing and analysis can provide an adequate estimate for the expected lifetime of the component or system.

-At the end of this expected life, the part is removed from service.

The benefit of safe-life designs includes:

1- Reducing the likelihood of unplanned maintenance .

2-Reducing the likelihood of any failure.

-There is no method to help determine which if either of these philosophies should be employed.

-Engineers must use their judgment on a case-by-case basis.

-The decision to use either of these philosophies is justified whenever the “cost” and likelihood of failure .

"Cost" of failure may include:

1-Physical harm to people or the environment

2-Loss or destruction of system or equipment

3-Loss of productivity or use of the failed "system" or device

4-Damaged reputation

Likelihood of failure

1-The engineer should always consider how likely a certain failure will be. 2-In so doing, it is important to consider all potential loading conditions even abusive loads.

"Cost" of implementing can include:

1-Increased expense and time for design and testing

2-Increased production costs

3-Decrease in product performance

There are no formulas to help determine when fail-safe or safe-life designs should be employed.

Techniques for Safe-Life Design

1-Extensive testing and analysis is required. Since it is imperative that the component or system not fail within the predicted life time,

2-Estimation how long the component can be in service before it will likely fail.

3-Using of a generous factor of safety should be included to prevent catastrophic failure ,since no amount of analysis and testing can assure how long a particular part will perform without failure,.

4-The product should be designed so that it can be easily inspected in service.

Early Detection

When a structure is designed such that cracks will easily be detected before they reach critical length, it may be considered a fail-safe design.

A critical element of this is the detection of the crack before it reaches critical length. It is very important that proper materials (high fracture toughness) be selected that can withstand large cracks before fracturing.

2.2.Identification , detection and control of failure

Failure Identification:

Failure Mode features

- **The way failure occurs**
- **Can cause a failure mode in another item**
- **Engineer must Identify and list possible failure modes .**
- **Examples –**

  . Wrong type of oil or No oil added in the system

Failure Effects

- Immediate consequence of a failure
- Effects can range from very small to major disasters.
- Examples –

  Engine wear or Engine Failure
- **Severity**
- **Worst consequence of a failure**
- **it determined by Standard scale from 1 (no danger) to 10 (very severe)**
- **Prioritize the failures modes and their effects**

Failure Cause

- **Design weakness includes :-**

-manner of failure occurrence.

-List of technical terms and documentations

- **Examples –**

  1. Improper uses and maintenance

- **Occurrence**
- **Probability of the cause occurring**
- **Look for similar products or processes**
- **Probability number scale from 1 (not likely) to 10 (inevitable)**
- **Current Controls**
- **Current controls that prevent the failure cause (before causing effects)**
- **Examples –**

  1. improve quality ,design .....

CHAPTRR.3

Fault Diagnosis by Vibration Measurements

Measurement types for mechanical vibrations

- **Vibration displacement „s“** — in µm or mil
  = deviation of measured point from rest position
- **Vibration velocity „v“** — in mm/s or ips
  = velocity with which measured point moves about rest position
- **Vibration acceleration „a“** — in m/s^2 or g
  = acceleration with which measured point moves about rest position

Selecting the measurement type

- **Vibration displacement:**
  - Machines with speeds under approx. 600 rpm (10 Hz)

    Structural vibrations or
  - Relative motions (shaft vibrations) in journal bearing machines of any speed
- **Vibration velocity:**
  - Vibrations in machines with speeds above 600 rpm (10 ... 1,000 Hz)
- **Vibration acceleration:**
  - Vibrations with frequencies of interest above 2,000 Hz

Factors affecting the type of the used vibration measuring instrument :

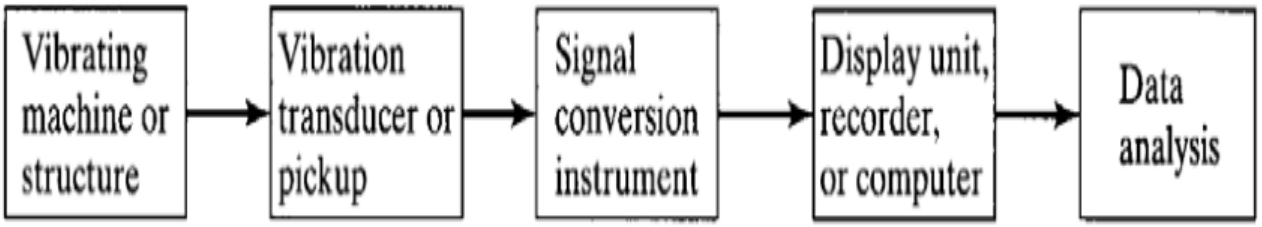
– Expected range of frequencies and amplitudes

– Size of machine/structure involved

– Conditions of operation of the machine/structure

– Type of data processing used

Scheme of vibration measuring instrument :



Selection of a transducer

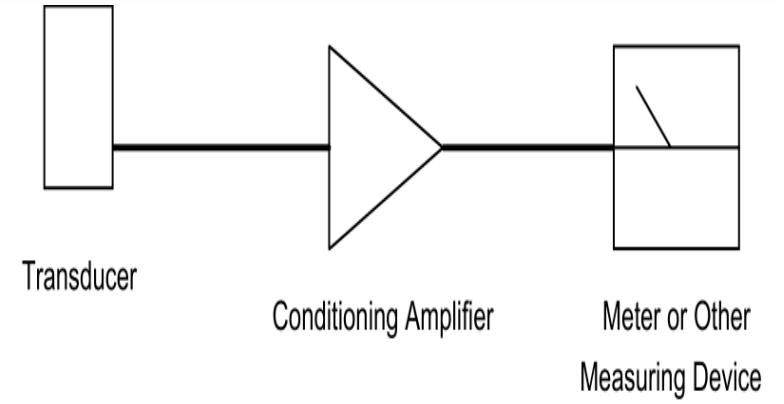
Frequency response data is needed to select the transducer and may be quite different for different transducer designs.

Transducer Mounting:

the transducer should be connected well to the item being measured and any brackets used for mounting should be very stiff.

Use Of Conditioning Amplifiers:

The conditioning amplifier is essential for piezo electric transducers, due to the very small signal level generated by these devices.



Conditioning Amplifier and Transducer

Vibration analysis uses:

1-Vibration analysis has been used as a predictive maintenance procedure.

2- Used as a support for machinery maintenance decisions.

3-As general rule, machines don't breakdown or fail without some form of warning, which is indicated by an increased vibration level.

3-By measuring and analyzing the machine's vibration, it is possible to determine both :

a-the nature and severity of the defect, and b-predict the machine's failure.

Vibration Measuring Device

1-The accelerometer :is used to measure the acceleration, velocity and displacement as

vibration amplitude.

Since the majority of general rotating machinery operates in the range of 10–1000 Hz, velocity is commonly used for vibration measurement and analysis .

2-The dynamometer :its vibration amplitude has been measured as a unit of velocity in mm/s, root mean square value (rms).

3-The sensor :is connected to analyzer and data collector Fig..

4.Transducers

a-A transducer is a device that converts a small amount of the energy of the quantity to be measured into another form of energy, usually electrical.

b-In vibration measurement, we may wish to measure the vibration displacement, velocity or acceleration

c.Because of this choice we have transducers suitable for measuring each quantity.

The transducers may make use of the following techniques for energy conversion:

a.piezo - electric effect

b.piezo - resistive effect (silicon strain gauge)

c.inductance

d.capacitance

e.resistance

f.optical



vibration device and sensor

Application of Some Intentional Faults

The system vibration has been measured at three different positions on the dynamometer,
namely horizontal, vertical and axial positions as shown in Fig.The intentional faults are, namely(unbalance, looseness and misalignment)
.

The sequence of measurements:

It is as following:
a- First, the system vibration has been measured at normal operation without loading at
different speeds rpm (Hz)
b- Measurements have been taken after loading the dynamometer with torque load for the speeds (Hz).
c- Repeating (a) after applying intentional faults, namely(unbalance, looseness and misalignment)
d- Repeating (b) after applying looseness fault
e-Recording the results
f-Analyzing the rdecorded data
g-Determination of the fault.



Horizontal, vertical and axial positions for vibration measurement

Data Analysis Instrumentation:

The type of equipment needed to carry out these analyses will now be described.

1 Vibration Meter:

This type of device gives an overall reading of the vibration level, usually an RMS value.

2. Frequency Analysers

Much use is made in vibration analysis of frequency analyzers.

3. Weighting Curves:

Weighting curves are used primarily in vibration analysis for the assessment of human effects of vibration.

DIN ISO 10816 Part 3, Group 2

Medium-sized machines with nominal power from 15 kW to 300 kW;
Electrical machines with shaft height 160 mm ≤ H >315 mm

Sub-structure	Assessment zones	Displacement µm (rms)	Velocity mm/s (rms)
Rigid	A	22	1.4
	B	45	2.8
	C	71	4.5
	D		
Flexible	A	37	2.3
	B	71	4.5
	C	113	7.1
	D		

Assessment zones

Assessment zones according to DIN ISO 10816:

- **Zone A:**
  Vibration in newly-installed machines
- **Zone B:**
  Machines may be operated for an unlimited time without restriction
- **Zone C:**
  Machines may be operated for a limited time
- **Zone D:**
  Vibrations are at a dangerous level and may cause damage to the machines

1. Time Based Vibration Analysis Techniques

Time-based analysis techniques currently available will be used for faults detection and diagnostic.

All the analysis techniques used for faults detection and diagnostic are applied on the acquired acceleration of the vibration signal.

a.RMS Level Measurements

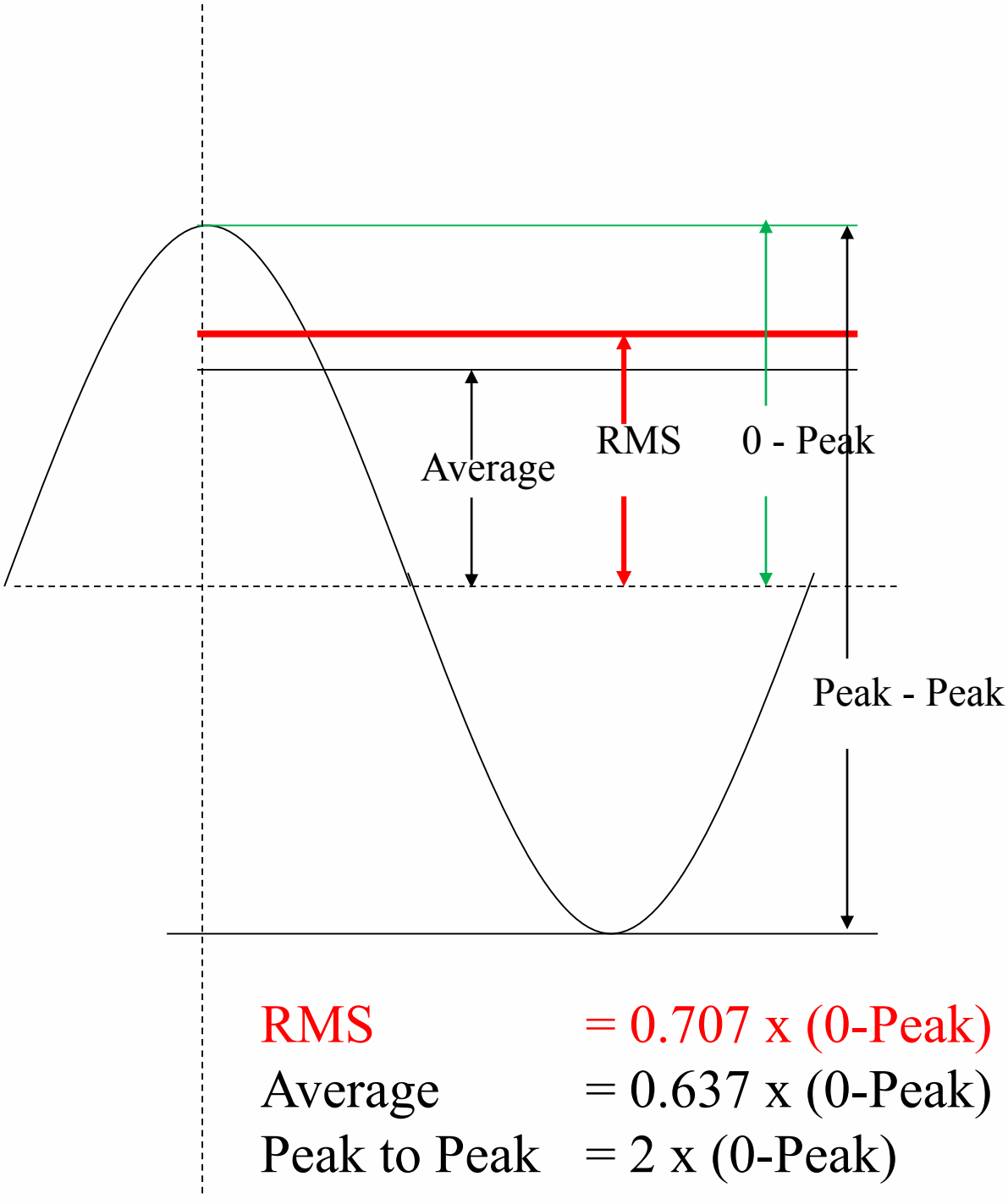
Overall level measurements using the root mean square (RMS) are the most common vibration measurement in use. the ISO "International Standards Organization" vibration severity level standardized charts (Figure)

R.m.s. vibration velocity mm/sec	up to 15 kW Class I	15 to 75 kW Class II	> 75 kW (rigid) Class III	> 75 kW (soft) Class IV
0,28 (89 dB)	A	A	A	A
0,45 (93 dB)				
0,71 (97 dB)				
1,12 (101 dB)	B			
1,8 (105 dB)		B		
2,8 (109 dB)	C		B	
4,5 (113 dB)		C		B
7,1 (117 dB)	D		C	
11,2 (121 dB)		D		C
18 (125 dB)			D	
28 (129 dB)				D
45 (133 dB)				

Criteria zone vibration magnitude for different type of machines

Note that zone A, B, C and D refer to good, allowable, just tolerable and not permissible zones respectively.

UNITS OF VIBRATION



RMS = 0.707 x (0-Peak)

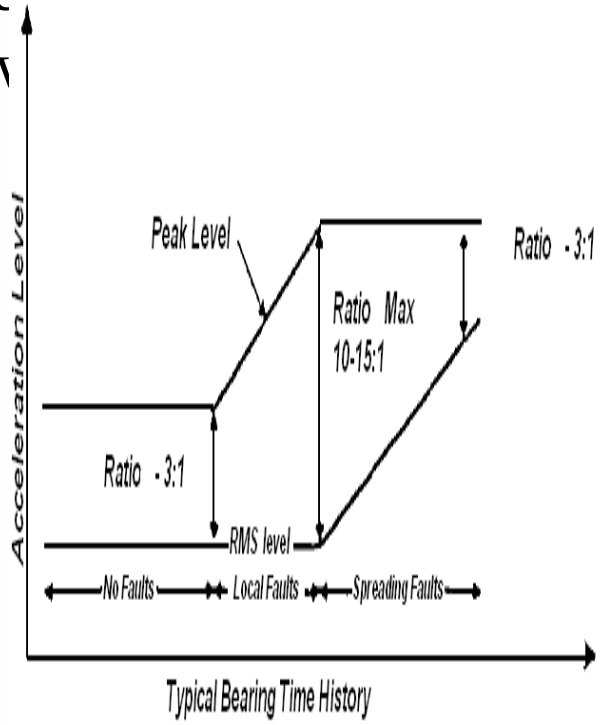
Average = 0.637 x (0-Peak)

Peak to Peak = 2 x (0-Peak)

b. Peak Level Measurements

As an alternative to overall level, the peak level of the acceleration signal can be used .

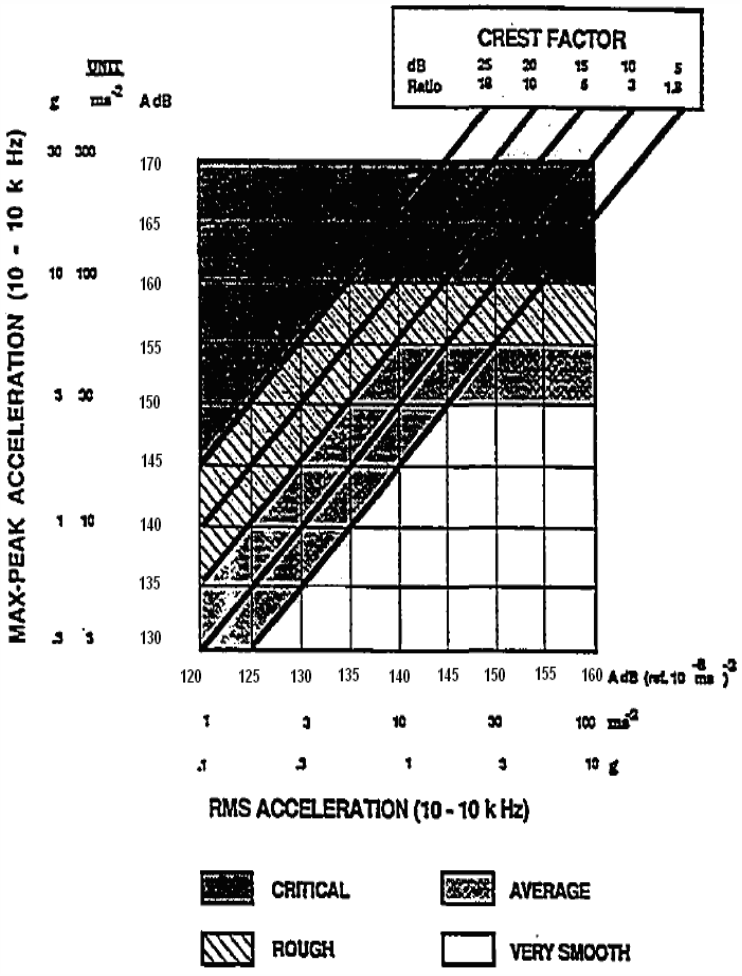
it is a useful technique to identify bearing faults, the data is shov



Trending Overall and Peak Level Acceleration for Bearing Fault Detection

c. Crest Factor

As bearing damage increases, the waveform becomes far more impulsive, with higher peak levels. The crest factor (CF) is the ratio of the peak level to the RMS level. A useful chart for showing



Bearing severity chart

d.Time Waveform

1-Most of the defects encountered in the rotating machinery give (vibration signature) and

hence most faults can be identified using vibration signature analysis techniques.

.2- The frequency components of the fault can be determined from (f=1/T).

3-The formula to calculate the sampled time period is:

$$T_s[s] = \frac{60 \times N}{RPM}.$$

Where $T_s$the total sample period in second, N is generally between 6 to 10 revolutions ,

RPM is the number of revolutions per minute of the shaft.

This method has been found to be a reliable technique for identifying bearing faults .

Time waveform can be used effectively to enhance spectral information in the following applications:

- Low speed applications (less than 100 RPM).
- Indication of true amplitude in situations where impacts occur such as assessment of rolling element bearing defect severity.
- Different faults will cause high vibrations at the same frequency.
- Lot of noise is present in the signal.

Time waveform can be used especially to detect bearings and gearbox faults, but does not give accurate result for unbalance and misalignment anomalies.

e. Kurtosis

Kurtosis is a statistical parameter,

. The kurtosis technique has the major advantage that the calculated value is independent of load or speed variations.

The kurtosis analysis is a good parameter for faults and transient effect detection

The kurtosis will be equal to 3 for healthy machine and greater than 3 if the machine presents some faults. The general definition of the kurtosis is:

$$Kurtosis = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^4}{(n-1)\times\sigma^2}.$$

Where $X_1, X_2 .. X_n$ are the population data of the signal, x is the mean of x, and σ is the variance of x. n is the number of samples.

2. Frequency-Based Vibration Analysis Techniques

The following is a description of frequency based vibration analysis techniques available for fault detection and diagnostic. Typical frequencies associated with common faults are shown in Table .

This technique is very accurate if the rpm of the shaft does not change over time .

Common faults with their corresponding frequencies

Forcing Frequency	Fault
1 x RPM	Imbalance-Misalignment-Bent shaft
2 x RPM	Misalignment-Bent shaft
Harmonics of RPM	Loose bearing caps
Non-integer multiples of RPM	Rolling bearings-Gears
Number of teeth time RPM and harmonics	Gear faults

a .Power Spectrum and Constant Percentage Band Analysis (CPB)

Given the running speed of the machine is directly proportional to the frequency measured,

the power spectrum will be normalized with respect to this fundamental frequency (measured by the encoder)

Frequency Range	Low	Medium	High
Faults to be detected	Unbalance, Misalignment, bent of the shaft 2	Wear faults in gears 1 and 2	Unbalance, Misalignment, bent of the shaft 1 (Rolling element bearings faults)

Wide vibration frequency range is required to detect all types of faults.

3. Time-Frequency "Short Time Fourier Transform" Based Vibration Analysis Techniques

When the rpm of the shaft is changing over time due to short transient effects or due to variances in load, the frequency changes means that the shaft begins to develop a fault,

Data Analysis

The common vibration faults such as unbalance and misalignment of the shaft and gears faults maybe detected on the prototype (dynamometer) if they exist.

Also the values of the kurtosis and crest factor should be acquired and compared to their expected values in normal operating conditions of the system

1.Theoretical Forcing Frequencies

The theoretical forcing frequencies are stored in a spreadsheet as a function of rotational speed. Table 5 shows the forcing frequencies measured at 44rpm. The governing equations are:

$$f_{gmf} = n_t \times \frac{rpm}{60}.$$

$$f_{or} = \frac{n_r}{2}\left[1 - \frac{D}{d}\right] \times s.$$

$$f_{cage} = \frac{n_r}{2}\left[1 - \frac{D}{d}\right].$$

$$f_{rol} = \frac{n_r}{2}\left[1 - \left(\frac{D}{d}\right)^2\right] \times \frac{d}{D}.$$

Where n_t is the number of teeth, D is the roller diameter, d is the pitch diameter, n_r is the number of rolling elements and s is the shaft speed (Hz).

3.3.COMMON FAULTS AND APPLICATIONS

Machinery fault diagnosis using vibration analysis

1. INTRODUCTION

Present day requirements for enhanced reliability of rotating equipment are more critical than ever before, and the demands continue to grow constantly. Advances are constantly made in this area, largely due to the consistent demand from the hydrocarbon, power generation, processes and transportation industries. Using vibration analysis, the condition of a machine can be constantly monitored. In this chapter, further attention is given to the method of correlating rotating machine defects to vibrations collected and displayed by the various types of analyzers.

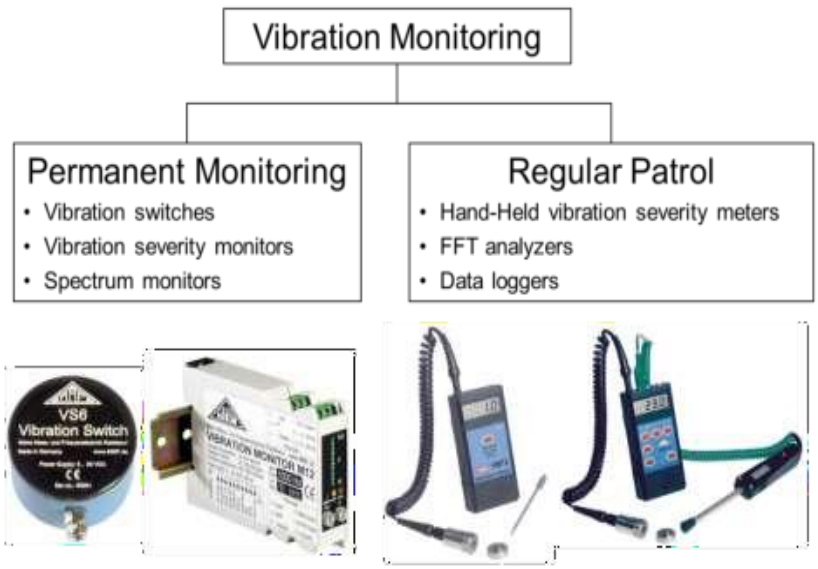
2. Vibration Condition Monitoring Devices

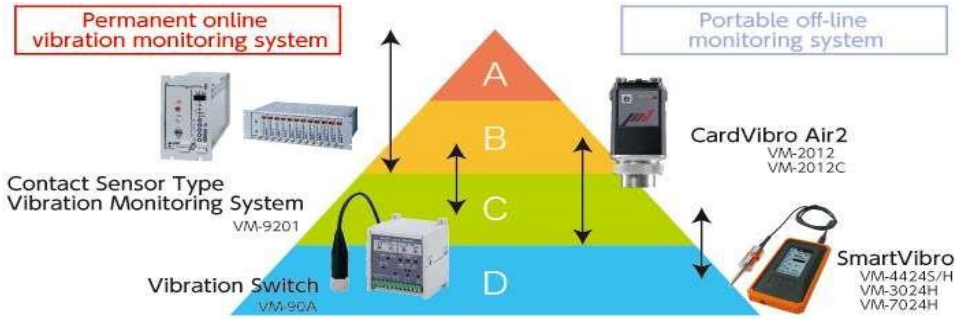
Measurement method

There are two types of vibration measurement methods "Permanent online vibration monitoring system" and "Portable off-line monitoring system".Either one is selected generally depending on importance rank of equipment.

The vibration monitoring system mainly depend on two types:

- Continuous or On-line Monitoring involves permanently installed sensors. Portable or hand held data collector.





- **A**：**High value machinery**
  （**Private power generator, High pressure compressor etc.**）

Mechanical failure is directly linked to stop of operation

- **B**：**Important machinery**
  （**Boiler, Pump,Compressor etc.**）

Mechanical failure may cause a decrease of production

- **C**：**Ordinary machinery**
  （**Intake or exhaust fan etc.**）

Mechanical failure may cause inconvenient for operation

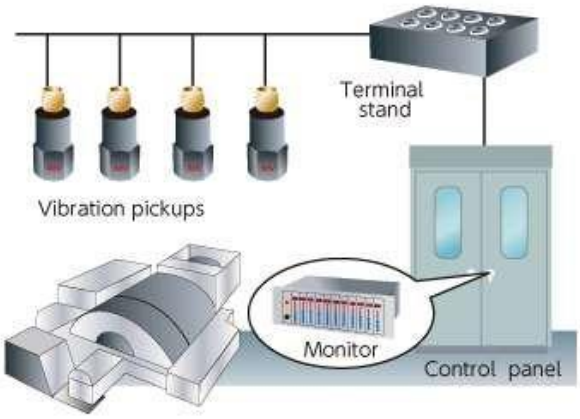
- **D**：**Low value machinery**
  (Small general purpose motor etc.）

Mechanical failure is not linked to operation and repair/replacement is much cheaper

2.1 Permanent condition monitoring

Online or permanent vibration condition monitoring designed on the basis of monitoring the machines at any times. So that the sensors and transducers are permanent mounted on the machine parts. For permanently installed systems, the transducers, cabling, and associated signal processing and analyzing equipment are permanently installed with data collected continuously or periodically. Typical installations are on complex machinery, critical machinery or both such as for dynamic positioning or main propulsion. In portable measuring equipment, machinery data are collected manually on a periodic basis on pre-selected permanently marked or affixed locations.

Online monitoring allows to customers with shortcomings in skills or available personnel to properly monitor your equipment efficiently and accurately without require fully trained skill personnel to use.





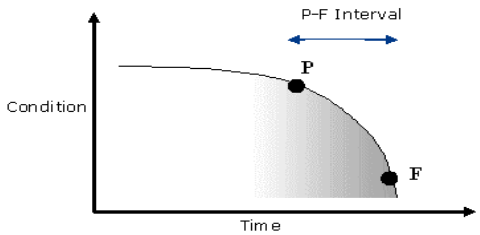
2.2 Portable vibration data collector

The portable approach is commonly used for equipment with longer PF intervals" ***The time, or cycles, from when a "Potential Failure" ("P") is first detected on an asset, or component, until the asset or component has reached "Functional Failure" ("F").***" and permanently installed systems used for equipment with shorter PF intervals.

Portable. There are many types of handheld vibrometrs or data collector as shown in figure (7.1).

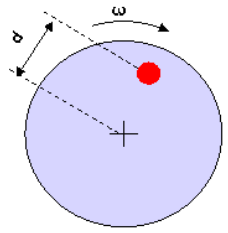
With portable measuring systems, some of types the collected data are transferred to other

hardware (i.e., PC) for analysis and data storage, and in some cases distribution to a shore side database.



Some of the machinery defects detected using vibration analysis are listed below:

- Unbalance
- Bent shaft
- Eccentricity
- Misalignment
- Looseness
- Belt drive problems
- Gear defects
- Bearing defects
- Oil whip/whirl
- Electrical faults
- Cavitation
- Shaft cracks
- Rotor rubs
- Resonance
- Hydraulic and aerodynamic forces.



$$F_{unalance} = m\ d\ \omega^2$$

We will now look at each one of the above cases in detail and see how they manifest in vibration analysis.

.3.1 Unbalance

Vibration due to unbalance of a rotor is probably the most common machinery defect. It is luckily also very easy to detect and rectify. The International Standards Organization (ISO) define unbalance as:

That condition, which exists in a rotor when vibratory, force or motion is imparted to its bearings as a result of centrifugal forces. It may also be defined as: The uneven distribution of mass about a rotor's rotating centerline. There are two new terminologies used: one is rotating centerline and the other is geometric centerline. The rotating centerline is defined as the axis about which the rotor would rotate if not constrained by its bearings (also called the principle inertia axis or PIA).The geometric centerline (GCL) is the physical centerline of the rotor. When the two centerlines are coincident, then the rotor will be in a state of balance. When they are apart, the rotor will be unbalanced. There are three types of unbalance that can be encountered on machines, and these are:

1.Static unbalance (PIA and GCL are parallel)

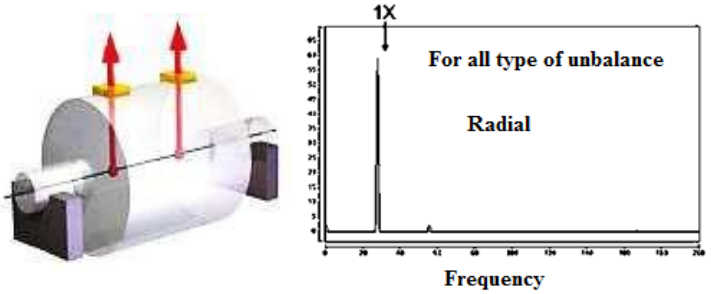
2.Couple unbalance (PIA and GCL intersect in the center)

3.Dynamic unbalance (PIA and GCL do not touch or coincide).

Static unbalance

For all types of unbalance, the FFT spectrum will show a predominant 1. rpm frequency of vibration. ***Vibration amplitude at the 1.*** rpm frequency will vary proportional to the square of the rotational speed. It is always present and normally dominates the vibration spectrum (Figure 7.2).

Fig.7: 2 FFT analysis – unbala in radial position

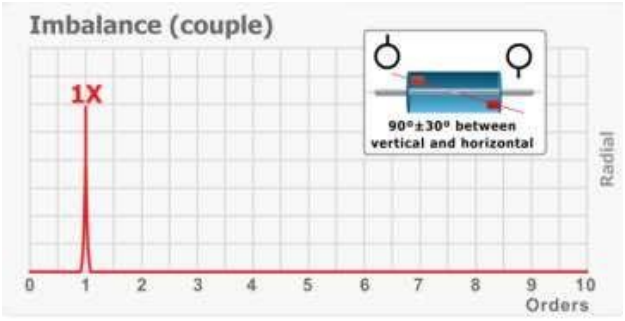


Correction method

- Balance weight in one plane at rotor center of gravity (CG).

Couple unbalance

In a couple unbalance (Figure 7.3) the FFT spectrum again displays a single 1. rpm frequency peak. The amplitude at the 1. varies proportional to the square of speed. This defect may cause high axial and radial vibrations. Couple unbalance tends to be 180° out of phase on the same shaft. Note that almost a 180° phase difference exists between two bearings in the horizontal plane. The same is observed in the vertical plane.



methods

Fig.7:3 Phase relationship – couple unbalance

Correction

Balance requires correction in two planes at 180°.

Dynamic unbalance

Is the most common type of unbalance and is essentially a combination of static and couple unbalances. It occurs when the principal axis of inertia and the axis of rotation are skew lines. This unbalance can be understood as two different masses mn1 and mn2, placed arbitrary on the rotor .Two centrifugal forces D1 and D2 arise due to these masses during rotation see figure (7.4).

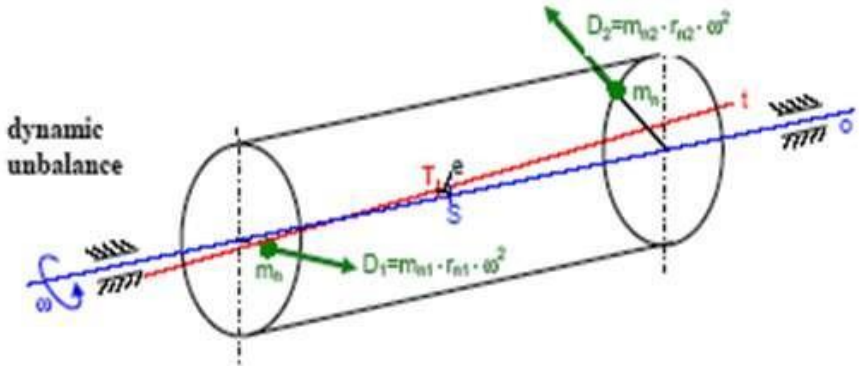


Fig.7: 4 Dynamic balance illustration

Correction method

Their effect can be compensated by two weights that are added or removed in two trim planes.

Unbalance – Overhung Rotors

The axial phase on the two bearings will seem to be in phase whereas the radial phase tends to be unsteady. A special case of dynamic unbalance can be found in overhung rotors see figure (7.5). Dynamic unbalance in overhung rotors causes high 1X levels in radial and axial direction due to bending of the shaft. The axial bearing signals in phase may confirm this unbalance.

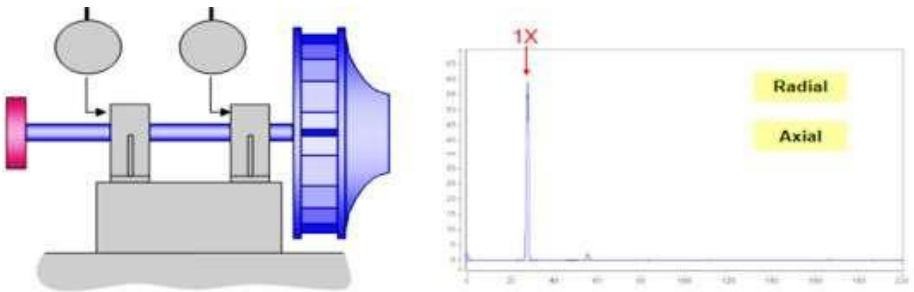


Fig.7:5 Overhung rotor unbalance

Unbalance location

At the radial or vertical position on bearings. For pumps, disks and fans check the bearing which just before the unbalance position as shown in figure (7.6)

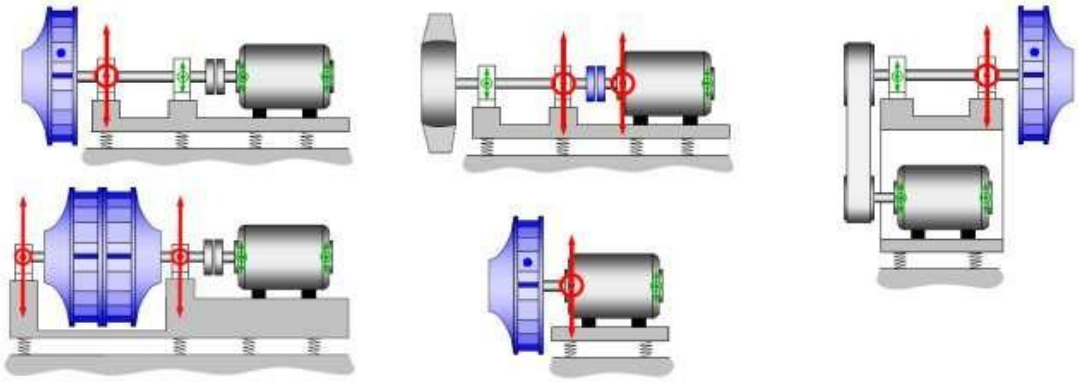


Fig.7: 6 Unbalance measurment position

In industry, unbalance can be due to poor manufacturing; for example, in large discs, the presence of casting defects can lead to an uneven distribution of the rotating mass and lead to unbalance. Many times, in chemical processing plants, the chemical slurry gets stuck to the rotating agitator, stirrer, or fan, and if neglected, leads to unbalance and to shearing of the fan blades or damage of the bearings.

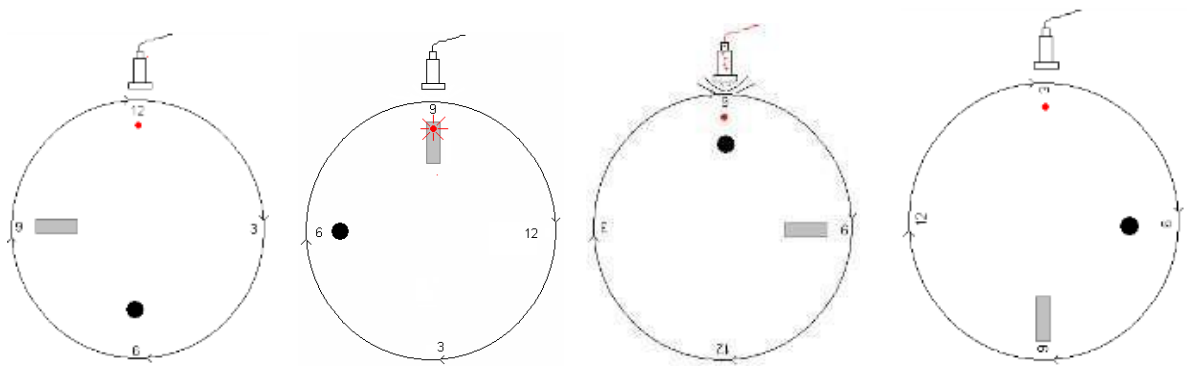
Fundamentals of Balancing

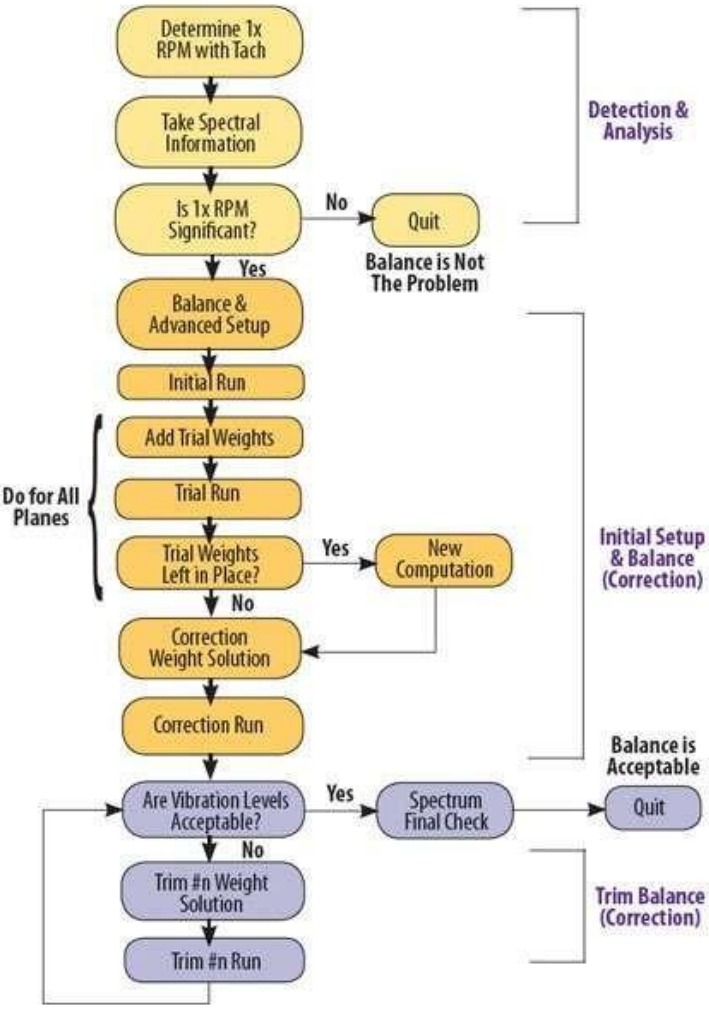
Data Collection and Processing

- The vibration sensor is installed on the engine as near the front bearing as possible. The Phototach is mounted on the cowling, behind the propeller. The reflective tape is applied to the back side of the target propeller blade in line with the Phototach beam.
- The mass is located by the relative occurrence of tach trigger and mass passage at the radial sensor location.
- As the heavy spot on the propeller passes the

location of the vibration sensor, the sensor generates and sends an electrical pulse to the analyzer.

- The Reflective tape triggers a response as it passes the Phototach, which then sends an electrical signal to the analyzer.
- In this illustration, the vibration sensor and Phototach beam are co-located at the 12:00 or 0 degree position. Rotation is clock-wise from the viewers position. This is our starting point, elapsed time = 0, **#[1]**
- The speed is 1 RPM. Fifteen seconds (90 degrees) of travel has occurred. In this sequence, the reflective tape has just entered the Phototach beam to trigger the tach event. Elapsed time = 15 seconds, **# [2]**
- In this sequence, the mass (heavy spot) is passing the accelerometer position, 15 seconds (90 degrees) after the tape passed the Phototach beam. Elapsed time = 15 seconds (90 degrees of travel, **# [3].**
- The tape and mass have both passed the 0 degree location. The unit now waits for the exact sequence to repeat for averaging, **#[4].**
- **Solution would be to add weight at 270 degrees.**





A safe speed can be chosen below the actual running speed, all the way down to about 500 RPM. Unbalance forces are not linear with speed; they are proportional to the square of the running speed. Hence, an unbalanced rotor at one speed will have four times the unbalance force when the speed is doubled! Keep this factor in mind for safety.

After making the initial run and deciding to perform a balancing correction, the next step is to place a known trial (calibration) weight on the rotor at a known location and make another set of amplitude and phase readings. This step is used to determine the rotor characteristics, locate the heavy spot and calculate the corrective weight to minimize the original unbalance force. This weight location will always be 180 degrees opposite of the heavy spot on the rotor. It is important to note here that we are typically dealing with

displacement as our measurement of vibration. We are not measuring the heavy spot, but we are seeing the high spot. However, for a rigid rotor running at 70% below critical, the high spot and the heavy spot are one and the same.

It is also important to note that we will see linearity in our placement of weight with a rigid rotor. As we place a weight at a known angle location, we will see a linear corresponding change in phase reading in the opposite direction. For example, if displacement phase is reading 165 degrees with a weight placement at 135 degrees, then moving that same weight to 180 degrees will result in a new phase reading at 120. The trial weight (or calibration) step is where we determine the so-called "influence coefficients" of the rotor. The next step is to make some correction callouts. There are five critical parameters here that must be adhered to for effective field balancing:

The exact same speed must be used on each run. The same radius must be used each time.

Direction of placement must be consistent (against rotation-AR or with rotation-WR).

Magnitude of readings must be stable within 5%.

Phase readings must be stable within three to five degrees.

If any of these conditions show variation, then the system is not linear or there are outside influences, and any attempts to balance will be futile. Sometimes, this will appear to be a "chasing your tail" exercise, where things just don't seem to make any sense!

Once a correction is made, then the resulting vibration reading must be compared to an acceptable standard for the class of machine. It could be that the exact weight or position could not be met, so a trim run might be necessary. Each subsequent run should get to a convergence, i.e., where weight callouts are getting smaller and smaller and vibration levels are decreasing as well. If excessive weights are being called out and unbalance is getting worse with each run - the so-called "chasing your tail" scenario - it is time to stop and look for other machine conditions that are not associated with unbalance. Oftentimes, major outside influences like looseness, resonance and misalignment can impede the process.

So far, we have been dealing with a simple single-plane balance. Performing a procedure like this in two planes becomes an iterative process in determining the influence coefficients. It involves a couple of extra steps. First, we perform an initial run with two simultaneous unbalance readings - one in each plane. Next, we place a known trial weight at a known location in one plane and read its influence on the two planes. We remove that weight and place it (or a similar weight) at a known position in the second plane and read its influence on the two planes. At this point, we are done with calibrating and determining

influence coefficients. The next steps follow recommended correction and trim weights in the two planes with weight callouts and locations. The same five rules stated earlier apply to step-by-step consistency and the stability of readings.

There are truly some elements of art and science involved in performing successful field balancing work. While microprocessor-based instruments with built-in software perform the required vector mathematics and geometry calculations, it really helps with the process to have a basic understanding of the tools and techniques involved. It also helps to benefit from others' field experiences in performing some tricks in arriving at an acceptable solution in a reasonable amount of time and number of trials.

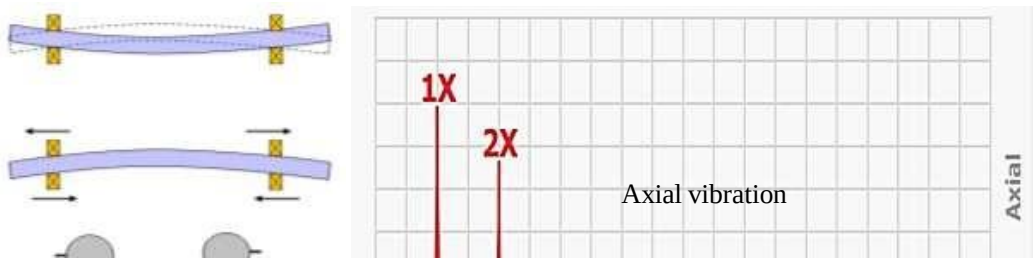
Fundamental requirements for field balancing include three key elements: linear response in the system, accurate/repeatable test measurements and consistent weight placement. These might sound like simple assumptions, but any variations on these can produce significant problems in getting to an acceptable residual unbalance level on a machine component.

2. Bent shaft

A bent shaft and bowed rotor are actually the same phenomena. The bent shaft is measurable outside the machine housing while the bowed rotor is the same condition inside. These defects sometimes develop on a motor that has been allowed to sit stationary for a long time. When sitting stationary, the weight of the rotor causes the shaft to deflect. After a period of time (about 6 months), the deflection takes a permanent set. When running, the vibration spectrum appears identical to imbalance, and in fact it is an imbalance condition. If a perfectly balanced rotor (such as a fan impeller) is attached to a bent shaft, it will run out of balance. It can be balanced back to a smooth-running condition. But then this rotor and this shaft are matched. Any other rotor on this shaft (even a new, well-balanced one) will run out of balance.

When a bent shaft is encountered, the vibrations in the radial as well as in the axial direction will be high. Axial vibrations may be higher than the radial vibrations. The FFT will normally have 1. and 2. components. If the:

- Amplitude of 1. rpm is dominant then the bend is near the shaft center Figure(7.7).
- Amplitude of 2. rpm is dominant then the bend is near the shaft end.



.3.3 Eccentric rotor

Eccentricity occurs when the center of rotation is at an offset from the geometric centerline of a sheave, gear, bearing, motor armature or any other rotor. The maximum amplitude occurs at 1. rpm of the eccentric component in a direction through the centers of the two rotors. The amplitude varies with the load even at constant speeds Figure (7.8).

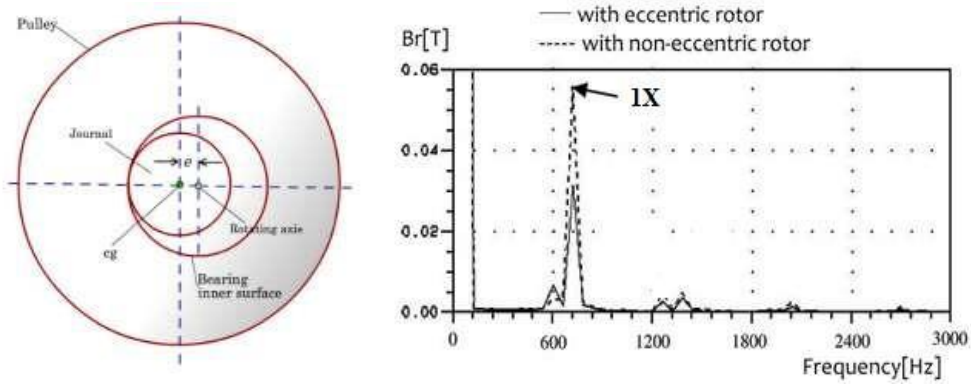


Fig.7: 7 Bent shaft schematic diagram with an FFT of a bent shaft with bend near the shaft center

Fig.7: 8 FFT spectrum for Eccentricity effect

.3.4 Misalignment

Misalignment, just like unbalance, is a major cause of machinery vibration. Some machines have been incorporated with self-aligning bearings and flexible couplings that can take quite a bit of misalignment. However, despite these, it is not uncommon to come across high vibrations due to misalignment. There are basically two types of misalignment (see figure (7.9)):

1. Angular misalignment: the shaft centerline of the two shafts meets at angle with each other.

2.Parallel misalignment: the shaft centerline of the two machines is parallel to each other and have an offset.

3.Combination of parallel and angular misalignments: the shaft center line of the two machines have the two previo

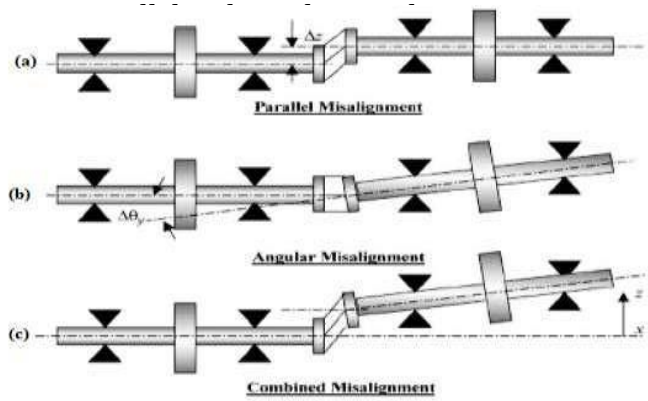


Fig.7:9 Shaft misalignment: (a) parallel, (b) angular and (c) combined.

Parallel misalignment

Parallel misalignment results in 2 *hits* per cycle and therefore a 2. rpm vibration in the radial direction. Parallel misalignment has similar vibration symptoms compared to angular misalignment, but shows high radial vibration that approaches a 180° phase difference across the coupling. Thus, we will see both the 1. and 2. peaks. When the parallel misalignment is predominant, 2. is often larger than 1., but its amplitude relative to 1. may often be dictated by the coupling type and its construction. Coupling construction will often significantly influence the shape of the spectrum if misalignment is severe (see Figure (7.10)).

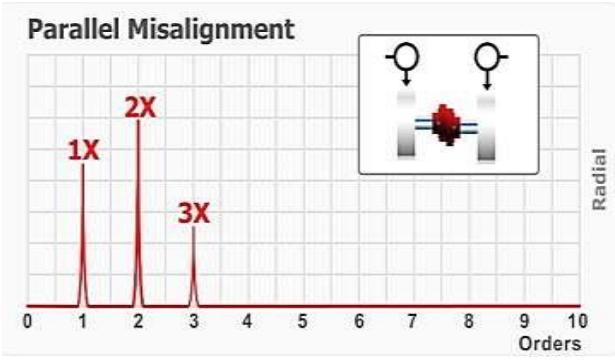




Fig.7: 10 FFT of parallel misalignment

Angular misalignment

As shown in Figure (7.11), angular misalignment primarily subjects the driver and driven machine shafts to axial vibrations at the 1. rpm frequency. The figure is an exaggerated and simplistic single-pin representation, but a pure angular misalignment on a machine is rare. Thus, misalignment is rarely seen just as 1. rpm peak. Typically, there will be high axial vibration with both 1. and 2. rpm. However, it is not unusual for 1., 2. or 3. to dominate.

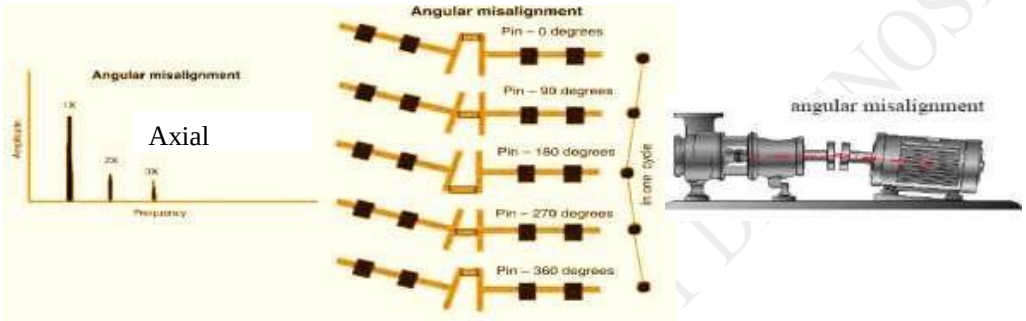


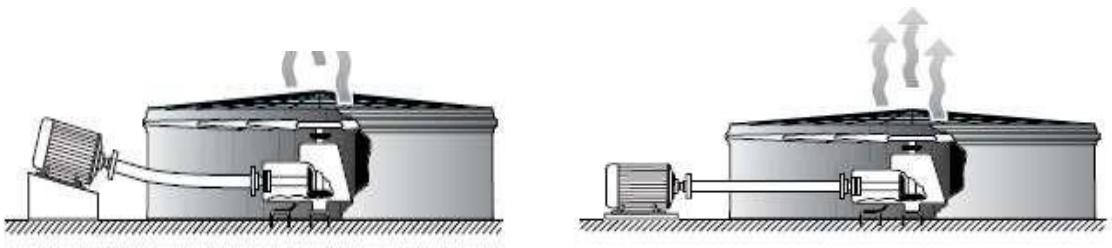
Fig.7:11 FFT of angular misalignment

What is shaft alignment

For the vast majority of close coupled rotating machines this catenary bow is negligible, and therefore for practical purposes can be ignored. On long drive machine trains, e.g. turbine generators in power generation plants or machines with long spacer shafts e.g. cooling tower fans or gas turbines, the catenary curve must be taken into consideration.

Operation above critical speed

When a very long, flexible shaft begins to rotate, the bow of the shaft tries to straighten out, but will never become a perfectly straight line. It is important to understand that the axis of rotation
of a shaft could very possibly run on a curved axis of rotation. In situations where two or more pieces of machinery are coupled together with one or more shaft rotating around a catenary
shaped axis of rotation, it is important to align the shafts so that they maintain the curved center-line of rotation.



5. Looseness

Mechanical looseness or the improper clearance between component parts, is generally characterized by a long string of harmonics of running frequency with abnormally high amplitudes. In some machines vibration levels may be excessive as a consequence of components being assembled too loosely, for example in the case of a bearing, which is not properly secured. Mechanical looseness can be classified for three categories:

1) Internal assembly looseness.
2) Looseness at machine to base plate interface.
3) Structure looseness.

Internal assembly looseness

This category of looseness could be between a bearing liner in its cap, a sleeve or rolling element bearing, or an impeller on a shaft. It is normally caused by an improper fit between component parts, which will produce many harmonics in the FFT due to the nonlinear response of the loose parts to the exciting forces from the rotor. A truncation of the time waveform occurs, causing harmonics. The phase is often unstable and can vary broadly from one measurement to the next, particularly if the rotor alters its position on the shaft from one start-up to the next.

Mechanical looseness is often highly directional and may cause noticeably different readings when they are taken at 30° increments in the radial direction all around the bearing housing. Also note that looseness will often cause sub-harmonic multiples at exactly ½. or ⅓ rpm (e.g. ½., 1½., 2½. and further) as shown Figures (7.13).

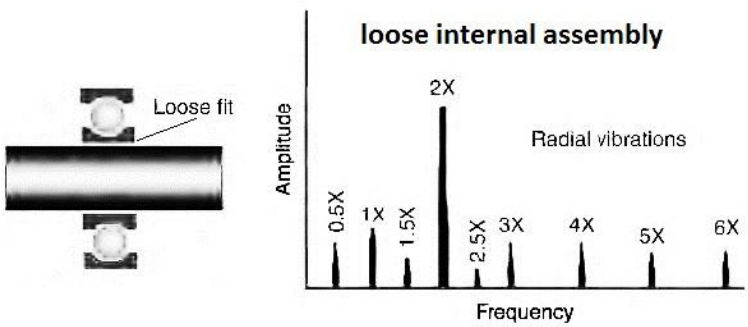


Fig.7:13 FFT spectrum for loose internal assembly graph

Looseness between machine to base plate

This problem is associated with loose pillow-block bolts, cracks in the frame structure or the bearing pedestal. Figures (7.14) make it evident how higher harmonics are generated due to the rocking motion of the pillow block with loose bolts.

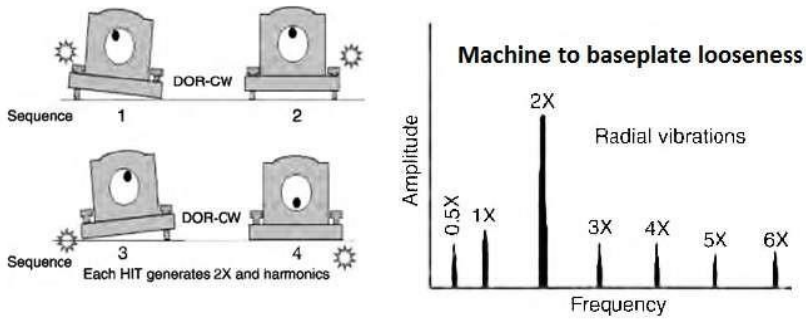


Fig.7:14 Mechanical looseness ilutration with FFT spectrum

Structure looseness

This type of looseness is caused by structural looseness or weaknesses in the machine's feet, baseplate or foundation. It can also be caused by deteriorated grouting, loose hold down bolts at the base and distortion of the frame or base (***known as 'soft foot'***) as it will be discuss in the next session. Phase analysis may reveal approximately 180° phase shift between vertical measurements on the machine's foot, baseplate and base itself (Figure 7.15). When the soft foot condition is suspected, an easy test to confirm for it is to loosen each bolt, one at a time, and see if this brings about significant changes in the vibration. In this case, it might be necessary to re- machine the base or install shims to eliminate the distortion when the mounting bolts are tightened again.

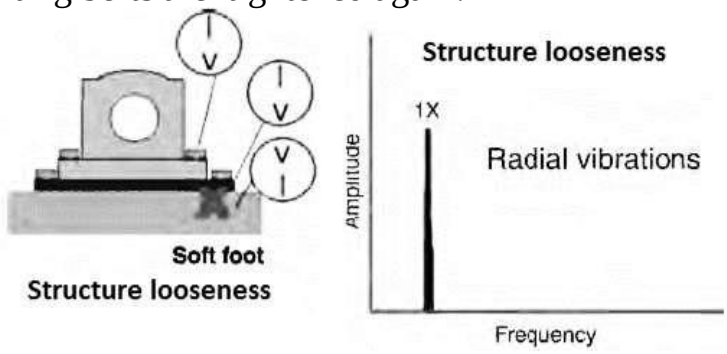


Fig.7: 15 Structure looseness graph with FFT spectrum