



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 01: Introduction: Fundamental concepts of quality, inspection and their role in manufacturing



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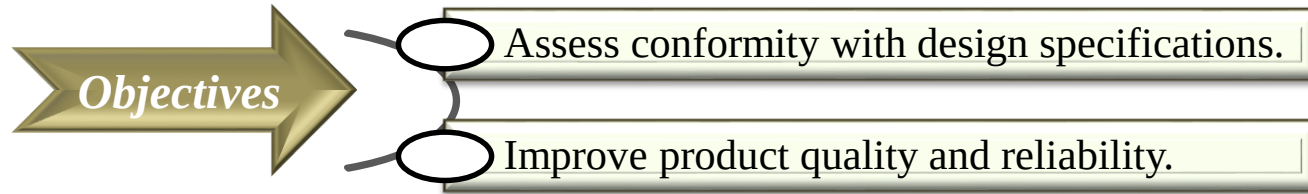
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What is Inspection?

Definition- “Measuring, examining, testing and gauging one or more characteristics of a product or service and comparing the results with specified requirements to determine whether conformity is achieved for each characteristic.” - ISO 2859



- Inspection can be performed at several places in production: from acceptance of the raw materials and parts from the suppliers to the shipping of the products to the customers.
- Inspected products can be the components used for production, work-in-process inventory, or finished goods.
- For manufacturing systems which are in continuous operation and subject to breakdown, inspection can be an appropriate maintenance strategy.

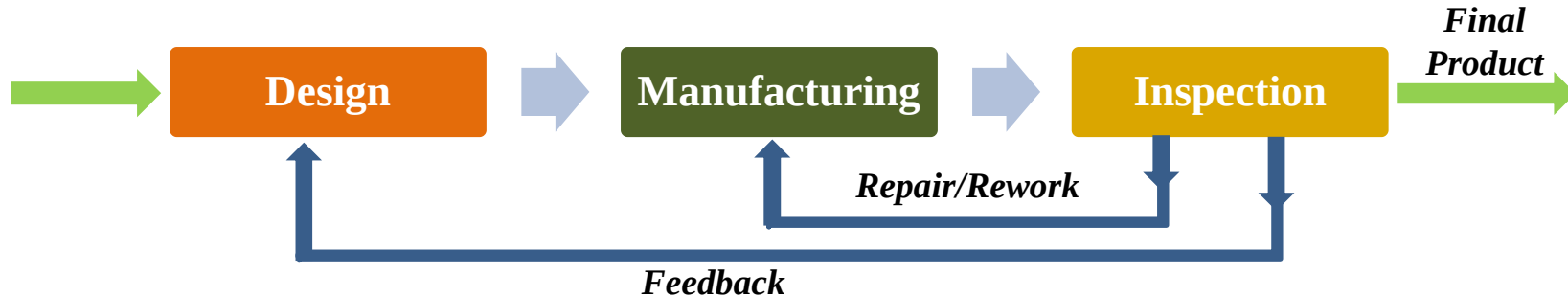
Role of Inspection in Manufacturing:

“Intellectuals solve problems, geniuses prevent them”



-Albert Einstein

- ❑ Inspection: *Watchdog* of a manufacturing process.



- ❑ Inspection is performed in an manufacturing industry to prevent the defects from passing further down the line and to make the product as per the required specifications.

- ❑ Inspection is done to minimize the **rework** and **scrap** costs in manufacturing.

- ❖ **Rework** – *The transformation of products not fulfilling the present specification into products that do, e.g. correcting of defective, failed, or non-conforming items, during or after inspection.*
- ❖ **Scrap** – *Waste that either has no economic value or only the value of its basic material content recoverable through recycling.*

- ❑ Scrap and rework are an incredible drain on company resources.
- ❑ Scrap and rework costs are incurred due to many reasons, for example:
 - When the wrong parts or raw materials are ordered.
 - Machine malfunction or human error.
 - When designs are not properly executed on the manufacturing line.
 - When engineering changes aren't effectively communicated.
 - Product damaged in transit.

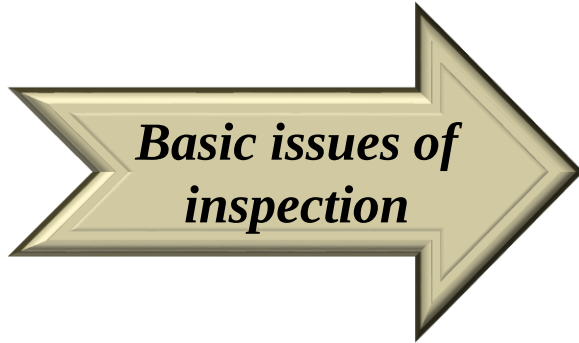
Functions of Inspection:

Inspection is normally carried out:

1. To find out **physical imperfections** (such as surface defects and internal defects etc.).
2. To check the **quantity** (such as numbers, volume, and weight etc.).
3. To check the **physical dimensions** (such as length, width, height, and thickness etc.).
4. To check the **nominal size** (usually done for the bulk raw materials).
5. To check the **physical appearance** (such as brightness, dullness, rusting, weathering, colour, solid, liquid etc.).
6. To check **the chemical composition**.
7. To check **physical, mechanical, and electrical properties** like density or specific gravity, dimensional tolerances, product shape, temperature, tensile strength, microstructure, fracture analysis etc.
8. To check many **other properties** which are specific to certain products such as **coating thickness** in case of coated products, refractoriness and apparent porosity etc.

Basic Issues of Inspection:

- The purpose of inspection is to provide information on the degree to which items conform to a standard.



At what points in the process inspection should occur?

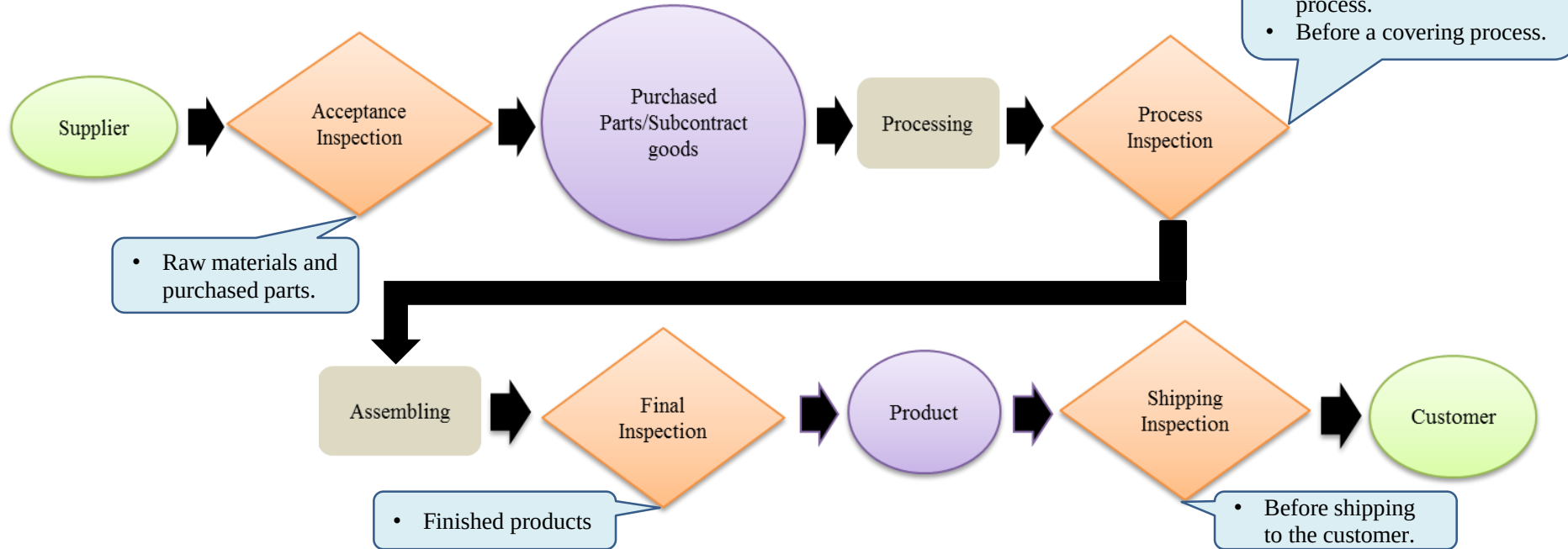
How much to inspect and how often?

Whether to inspect attributes (counts) or variables (measures)?

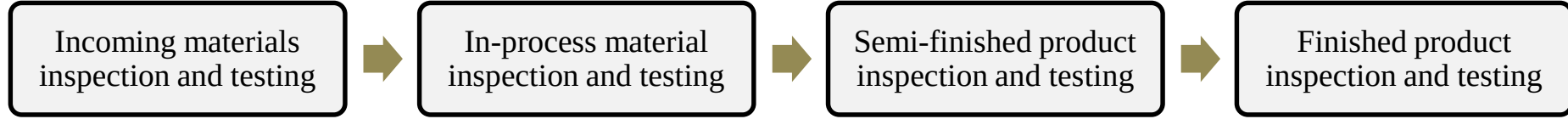
Whether to inspect in a centralized or on-site location?

1. Where to inspect?

- Inspection always adds to the cost of the product; therefore it is important to restrict inspection efforts to the points where they can give the more advantage.
- In manufacturing, some of the typical inspection points are:



Stages of Inspection and Testing:



I. Incoming Materials Inspection and Testing:

- Incoming Inspection is called as Raw Material Inspection and it is done for the purchase order.
- This procedure covers inspecting purchased supplier material i.e. raw material, purchased parts, subcontracted goods etc.

II. In-process Material Inspection and Testing:

- It is performed when the product is transferred from one process to the next.
- Its purpose is to prevent defected goods from entering the next process and producing further damage.

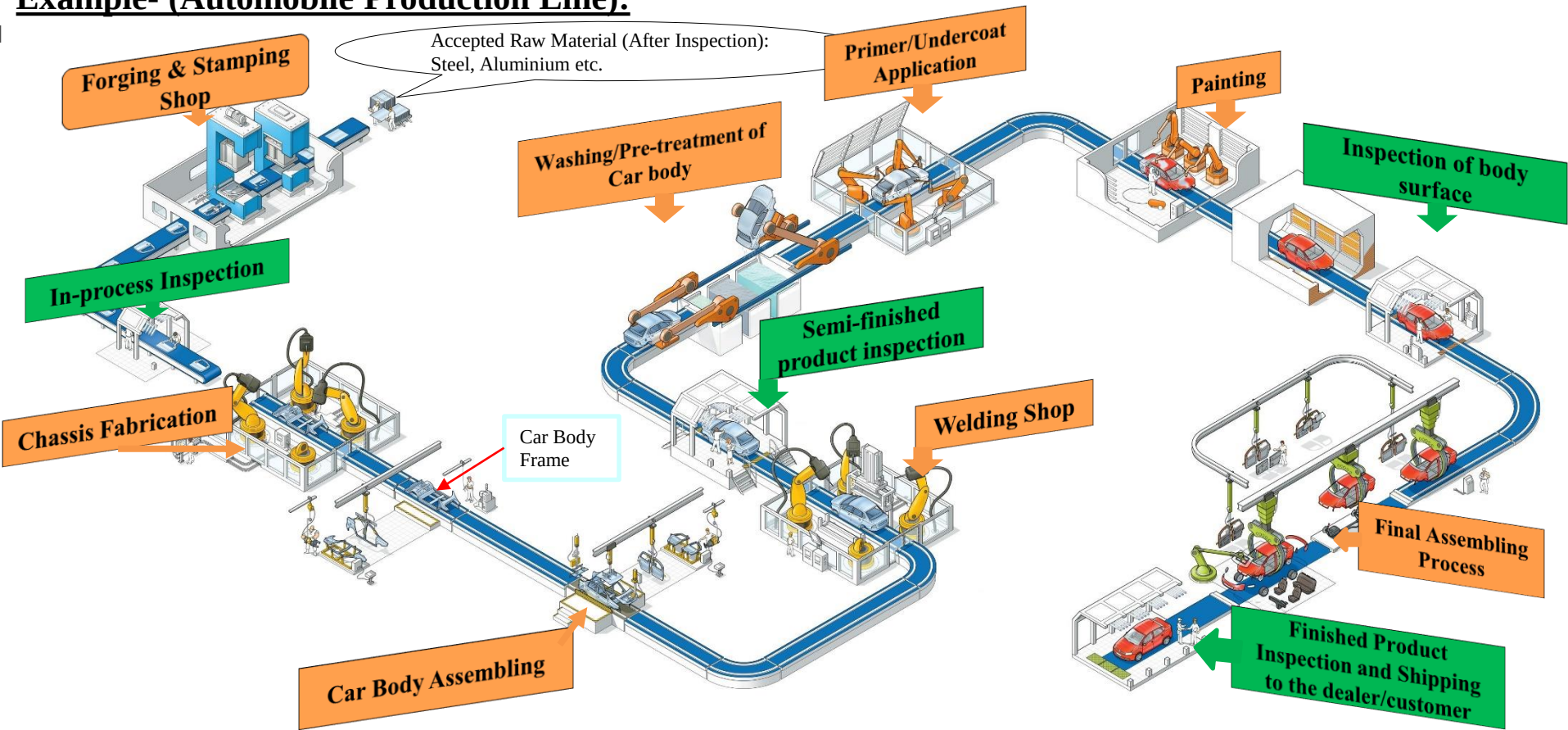
III. Semi-finished Product Inspection and Testing:

- It is performed for processed parts, and assemblies, and it does not include the completely finished goods.

IV. Finished Product Inspection and Testing:

- It is the inspection performed in the final stage of manufacturing process.
- In this test, whether the complete goods meet the requirements as a product or not is determined in order to prevent the loss in customer confidence, various problems, and damages in advance.

Example- (Automobile Production Line):



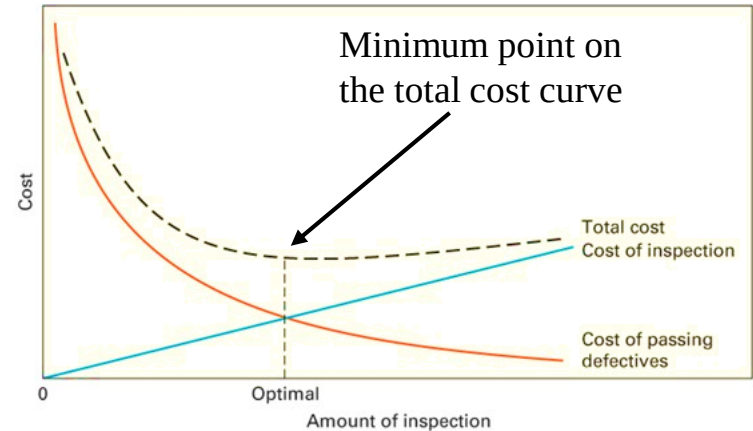
2. How much to inspect?

- The amount of inspection can range from no inspection to inspection of each item many times.
- **Low-cost, high volume items** such as paper clips and pencils often require little inspection because:
 - ✓ The cost associated with passing defective items is quite low.
 - ✓ The process that produces these items are usually highly reliable, so that defects are rare.
- **High-cost, low volume items** that have large cost associated with passing defective items often require more intensive inspection such as airplanes and spaceships.
- The majority of quality control applications ranges between these two extremes.
- The amount of inspection needed is governed by the cost of inspection and the expected cost of passing defective items.

Optimal Amount of Inspection

- The complete setup and execution of inspection activities increase total production cost.
- Total inspection cost is the sum of the fixed cost and the variable cost, in which the variable cost is related to the quantity inspected per day.
- The fixed cost includes the setup cost and salaried workers of the inspection area
- For calculating the optimal amount of inspection, the variable cost is taken into consideration.

$$\text{Total Cost} = \text{Cost of inspection} + \text{Cost of passing defectives}$$



3. Whether to Inspect Attributes (Counts) or Variables (Measures)?

- Basically, there are two types of data to collect as part of a inspection procedure:
 - a) Attribute (Discrete) Data:**
 - Quality characteristic for which a numerical value is not specified.
 - It is a qualitative data that can be counted for recording and analysis.
 - For example: taste, paint quality, quality of output, no. of defects, no. of defectives, no. of scrap items, etc.
 - b) Variable (Continuous) Data:**
 - It is a measurement information of the product.
 - For example: length, volume, time, etc.
- They are both important information, but variable data is generally more useful as it is more precise and contains more information.

Difference Between Attribute Data and Variable Data:

<u>Attribute Data</u>	<u>Variable Data</u>
Attribute data focuses on numbers or go/no-go information.	Variable data focuses on measurements on a continuous scale.
Attribute data simply classifies the output as defective or not defective.	Variable data tells that how bad each defective product is: 10% faulty, 20% faulty, and so on.
Attribute data is simpler to gather, so it's a good choice if we are looking at a binary condition, for example: • The product works or it doesn't work. • The parts fit the slot or not. • Students pass the test or they fail.	Variable data can tell us many things that attribute data can't. • With variable data trends are seen allowing for corrective action to be taken long before the product reaches the reject level.
Example:  On or Off?  Broken or Unbroken?	Example:  Size  Temperature

4. Whether to inspect in a centralized or on-site location?

- Based on the timing and place of the inspection procedure in relation to the manufacturing process, two alternative situations are possible:

I. Off-line or Centralized Inspection

II. On-site Inspection

❖ Off-line or Centralized Inspection:

- Off-line or centralized inspection is performed away from the manufacturing process, and there is generally a time delay between processing and inspection.
- Generally, in these inspection activities:
 - ✓ More specialized testing equipment are used.
 - ✓ More favourable testing environment is needed.

For example: Medical tests, analysing food samples, testing metals for hardness, running viscosity tests on lubricants etc.



❖ On-site Inspection:

- The alternative to off-line inspection is on-line inspection, in which the procedure is performed when parts are made.
- In this case, quicker decisions can be made and extraneous factors (e.g. surface scratches) can be avoided.

For example: Inspecting the hull of a ship for cracks, construction site inspection.

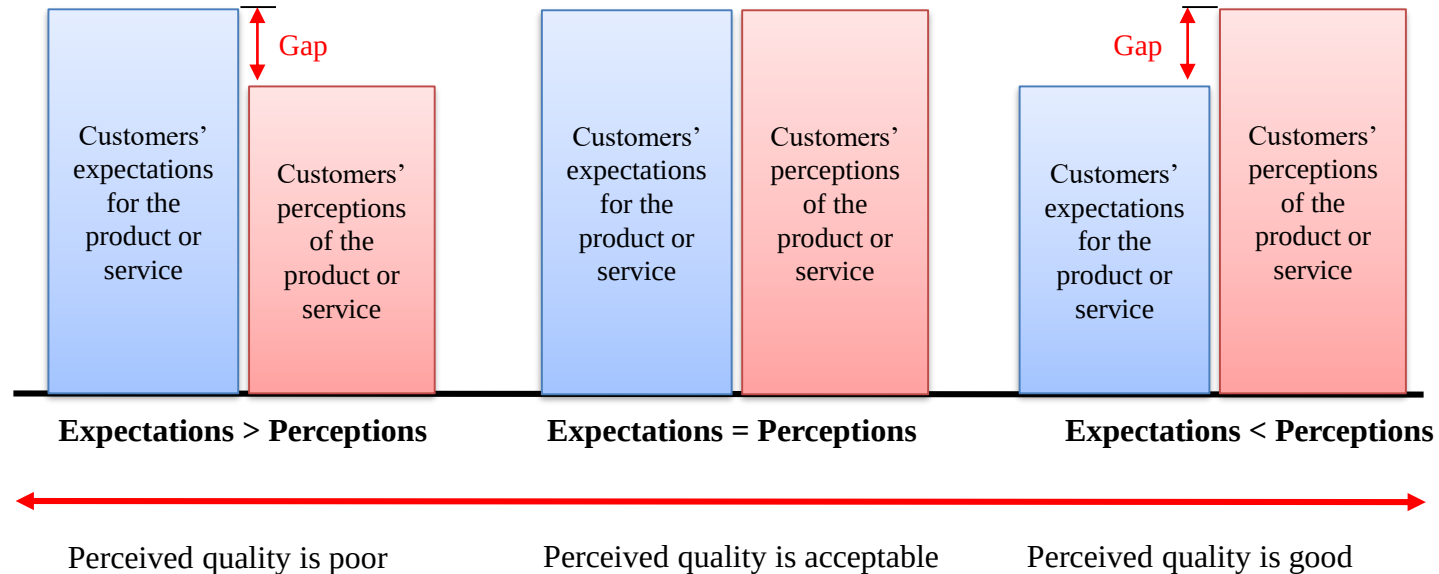
Centralized or on-site location?

- ❖ Effects on cost and level of disruption are major issues in selecting centralized vs on-site inspection.

What is Quality?

- ❖ Quality has no specific meaning unless related to a specific function and/or object.
- ❖ The definition of “quality” has changed over time, and their various interpretations are given below:
 - ✓ The totality of features and characteristics of a product or services that bear on its ability to satisfy stated or implied needs of the customers (ISO).
 - ✓ Quality of a product or service is the fitness of that product or service for meeting its intended use required by the customer (JOSEPH JURAN).
 - ✓ Quality is conformance to specifications (EDWARD DEMING).
 - ✓ Quality is conformance to requirements (PHILIP CROSBY).
 - ✓ Quality is what the customer says, it is (FEIGENBAUM).
- ❖ The common element of the above definitions is that the quality of a product or service refers to the perception of the degree to which the product or service meets the customer's expectations.

- ❖ Perceived quality is governed by the gap between customers' expectations and their perceptions of the product or service.



Dimensions of Product Quality:

As prescribed by Garvin, the eight dimensions of quality are:

1. **Performance** (will the product do the intended job?)
2. **Conformance** (does the product meets the specifications?)
3. **Reliability** (how often the product fails?)
4. **Durability** (how long the product lasts?)
5. **Serviceability** (how easy is to repair the product?)
6. **Aesthetics** (what does the product looks, feels, sounds, smells, or tastes?)
7. **Features** (what does the product do? For example extra features added to basic features.)
8. **Perceived quality** (what is the reputation of a company?)



What is Quality Control?

- **Definition:** Inspection, analysis and action applied to a portion of the product in a manufacturing operation to estimate overall quality of the product and determine what, if any, changes must be made to achieve or maintain the required level of quality.

- It involves inspection and testing of units and determining if they are within the specifications for the final product.
- The purpose of the testing is to determine any needs for corrective actions in the manufacturing process.

Quality control of a product can be viewed as a system which ensures:

Proper Planning

Right Design

Proper equipment

Proper Inspection

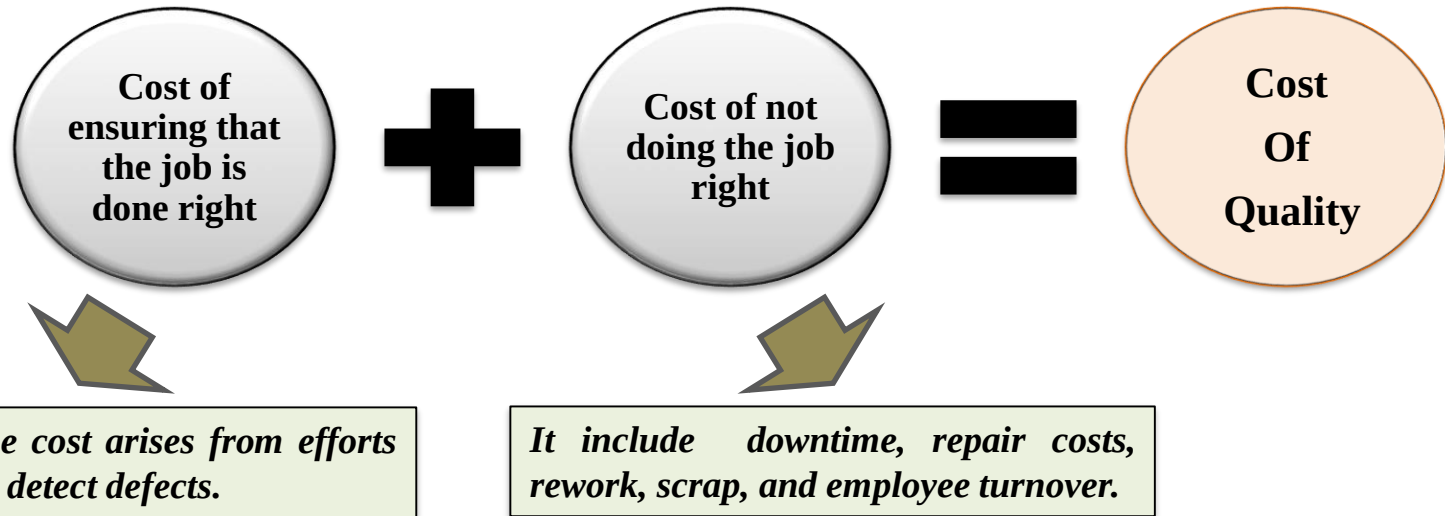
Corrective action

Benefits of Quality Control:

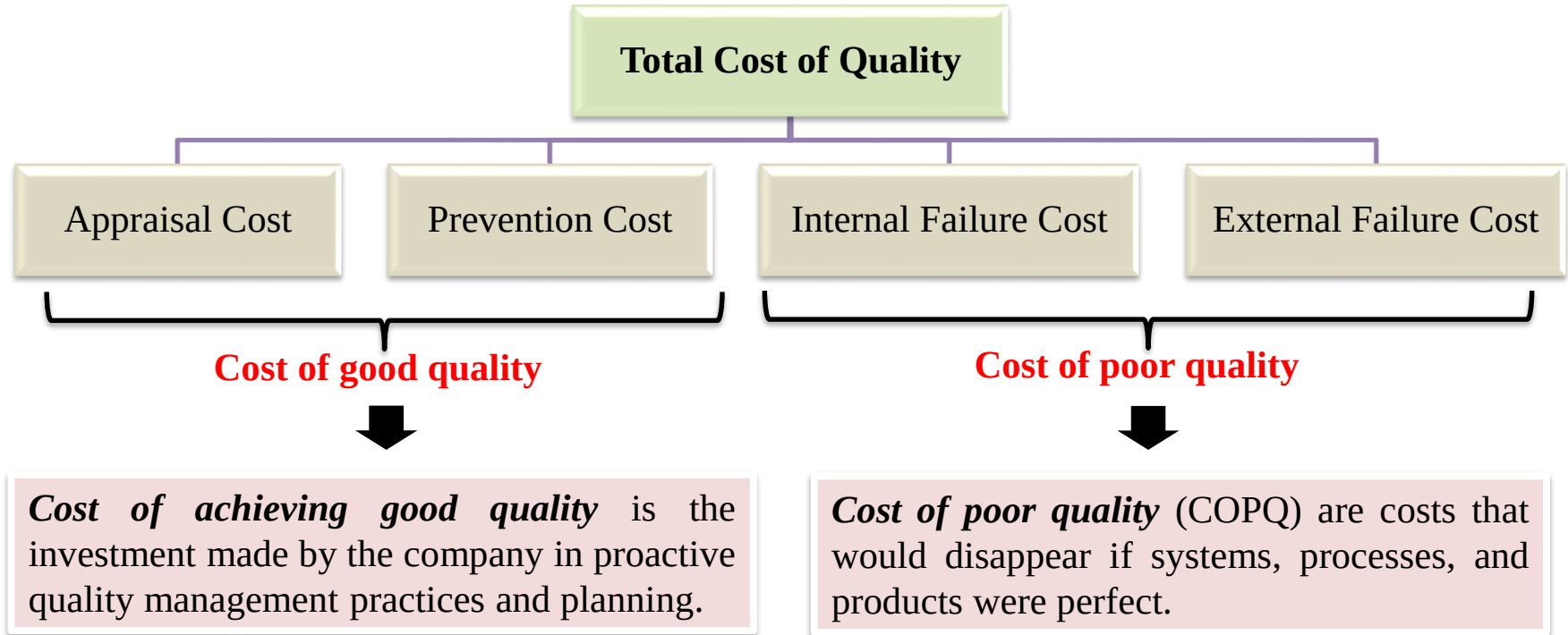
- ❑ Quality is vital in all areas of business, including the product development and production functions.
- ❑ A well established, committed quality system in an organization will render the following benefits:
 - ✓ Defect reduction
 - ✓ Higher productivity
 - ✓ Cost reduction
 - ✓ Continuous improvement in quality of product
 - ✓ Customer satisfaction

Cost of Quality:

- Money spent beyond expected production costs (labour, materials, equipment) to ensure that the product the customer receives is a quality (defect free) product.
- It quantifies the total cost of quality-related efforts and deficiencies in manufacturing a product.



Four Cost Categories Related to Quality



❑ Prevention Cost

- Cost of planning and executing a project so it is error free or within an acceptable error range.
- ❖ **Example:** Cost of training and performing acceptance sampling of raw materials, SQC, Six Sigma, and other techniques.

❑ Appraisal Cost

- Cost of evaluating process and their outputs to ensure quality.
- ❖ **Example:** Cost of detecting defects in the final product i.e. outgoing inspection of products before being shipped to customers

❑ Internal Failure Cost

- Cost incurred to correct an identified defect before the customer receives the product.
- ❖ **Example:** Cost of scrap and rework of defective products- This includes the extra paper work, delays, rescheduling required, etc.

❑ External Failure Cost

- Cost that relates to all errors not detected and corrected before delivery to the customer.
- ❖ **Example:** Cost of Warranty Claims- This also includes the loss of goodwill on the part of customers.

Activities Associated with Different Cost Categories:

Prevention

- Design and development of equipment.
- Quality review.
- Maintenance and calibration of production and inspection equipment.
- Supplier quality audits.
- Quality training (seminars, workshops/lectures).
- Quality improvement programs.

Appraisal

- Receiving inspection.
- Laboratory inspection and testing.
- In-process inspection.
- Final inspection.
- Field testing (performance test and status reporting).
- Inspection and test equipment.

Internal Failure

- Scrap.
- Rework and repair.
- Rescheduling due to downtime.
- Overtime to cover production losses.
- Downgrading.
- Failure Analysis- To establish the causes of internal product or service failure.

External Failure

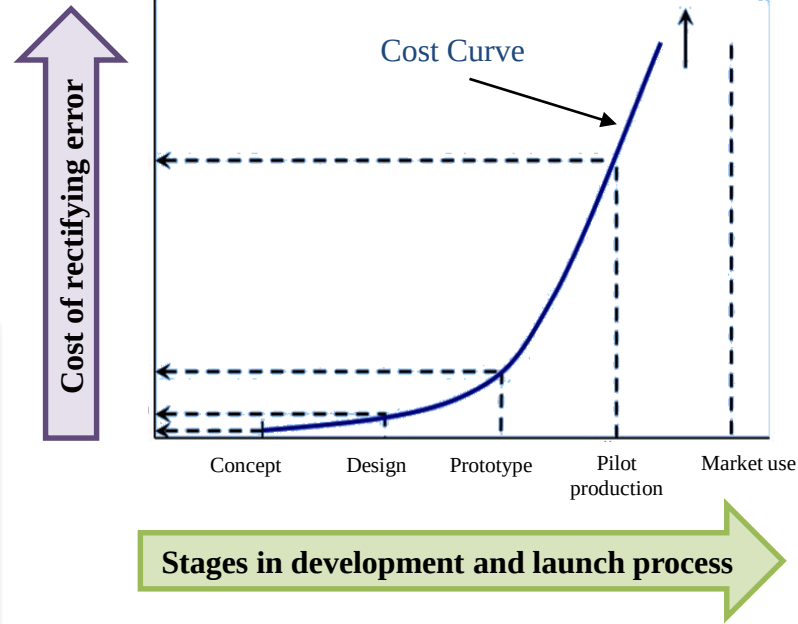
- Lost profit/sales.
- Repair/replacement of sold goods.
- Warranty claims.
- Product recalls.
- Allowances.
- Complaint adjustment.
- Cost of support operations.

Cost of rectifying error over the product development stages:

- The cost of rectifying errors increases more rapidly the longer they remain uncorrected in the development and launch process.
- The sooner, the better: the sooner we find the error, the cheaper the cost will be.

Criticality of failure of a part at different stages:

- I. Failure at supplier's site (bad)
- II. Failure at manufacturer's site (worse)
- III. Failure at customers' site (worst)

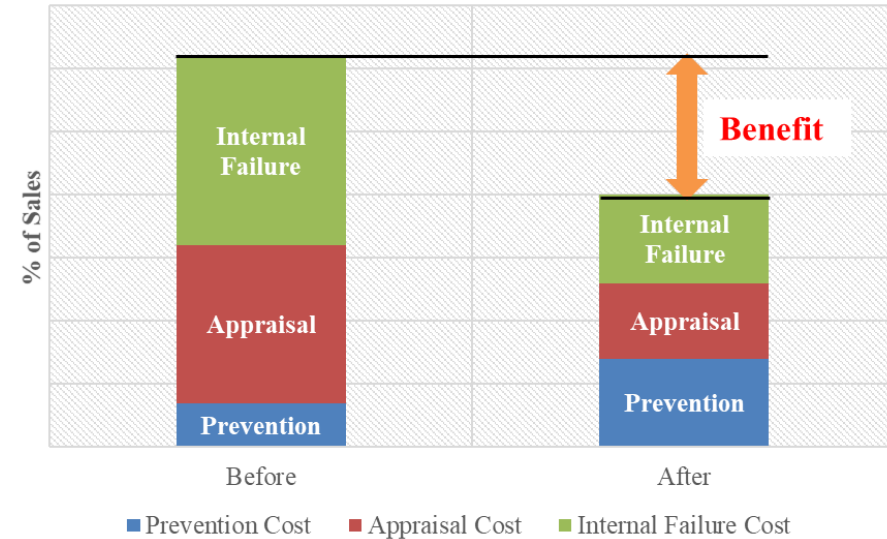


Impact of Quality Management on Costs:

- Total cost of quality is ultimately reduced by investing money up front in quality design and development.
- Increasing the effort spent on preventing errors occurring in the first place brings a more than equivalent reduction in other cost categories.

Example:

If we design the product right first time, build it right first time - we save all the costs of redesign, rework, scrap, resetting, repair, warranty work etc.

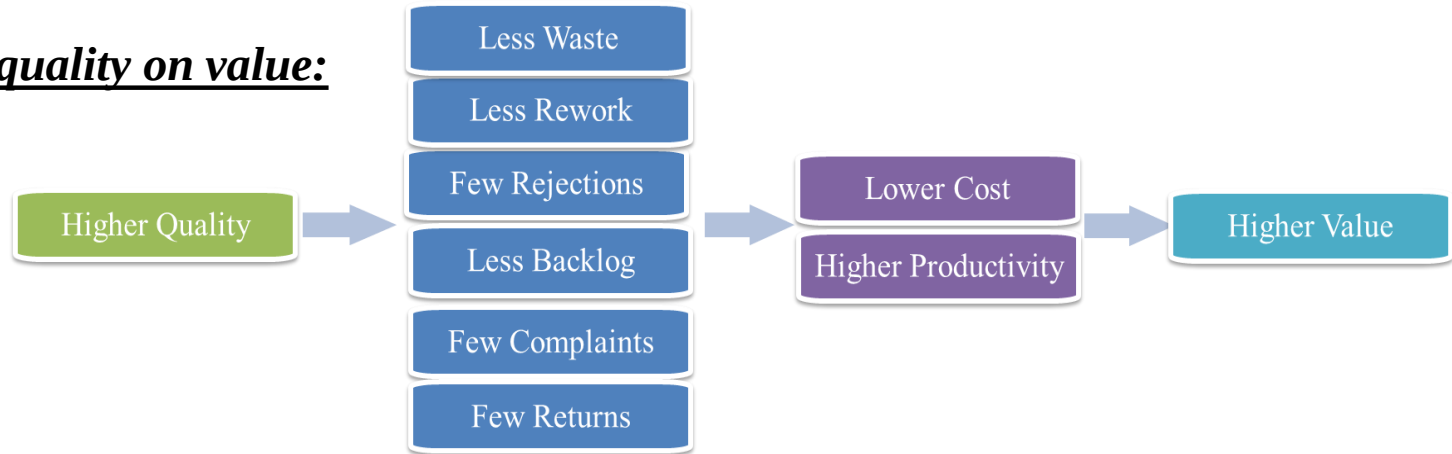


Impact of Higher Quality on Value:

What is value?

- Value is “the amount buyers are willing to pay for what a firm provides them. Value is generally measured by the total revenue of the company”.
- A firm’s value goes beyond its financial performance and it includes social impact and strategic importance to the regional and national economy.

Effect of higher quality on value:



Summary:

- Inspection is performed to assess the conformity with design specification and to improve the product quality and reliability.
- Basic issues related to the inspection in manufacturing have been discussed.
- Quality control involves inspection and testing of units and helps in determining the needs of corrective action during manufacturing.
- A proper inspection and quality control system ultimately reduces the total cost by minimizing the scrap and rework losses.

THANK YOU





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Lecture 02: Need of Inspection: Types and Principles



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Need of Inspection:

- Inspection is an indispensable tool of modern manufacturing process.
 - It helps to control quality, reduces manufacturing costs, eliminate scrap losses and assignable causes of defective work.
 - It has mainly two uses:
 1. **Quality Control** - before the component is used in service.
 2. **Maintenance and Health Monitoring** - while the component is in service.
-
- Inspection is the most common method of attaining standardization, uniformity and quality of workmanship.
 - It is the art of controlling the product quality after comparison with the established standards and specifications.
 - If the said item does not fall within the zone of acceptability it will be rejected and corrective measure will be applied to see that the items in future confirm to specified standards.

- Defects in manufactured parts, if remain undetected may result to failure of the product.

Example:

Crash of United Flight 232

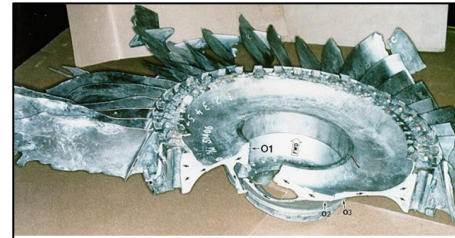
Place: Sioux City, Iowa; Date: July 19, 1989

Fatalities: 111; Injuries: 172

- ❑ The NTSB (National Transportation Safety Board) Accident Report cited the initial problem in the manufacturing of the fan rotor by General Electric Aircraft Engines (GEAE).
- ❑ During the purification of titanium-alloy rotor, a “hard α inclusion” (a microstructural defect that occurs from an inadequate vacuum during melt processing) formed within a cavity in the rotor.
- ❑ The rotor left the foundry with the defect unnoticed after its initial certification process.
- ❑ During the rotor’s normal use, one, if not more, fatigue cracks initiated from this defect area and grew (through sub-critical crack growth) until finally the rotor failed.



Tail Section of the crashed airliner



Fracture of engine disk

Purpose of Inspection:

The purpose of inspection is:

- To distinguish good lots from bad lots.
- To distinguish good pieces from bad pieces.
- To determine if the process is changing.
- To determine if the process is approaching the specification limits.
- To rate quality of product.
- To rate accuracy of inspectors.
- To measure the precision of the measuring instrument.
- To secure products – design information.
- To measure process capability.

Design for Inspection:

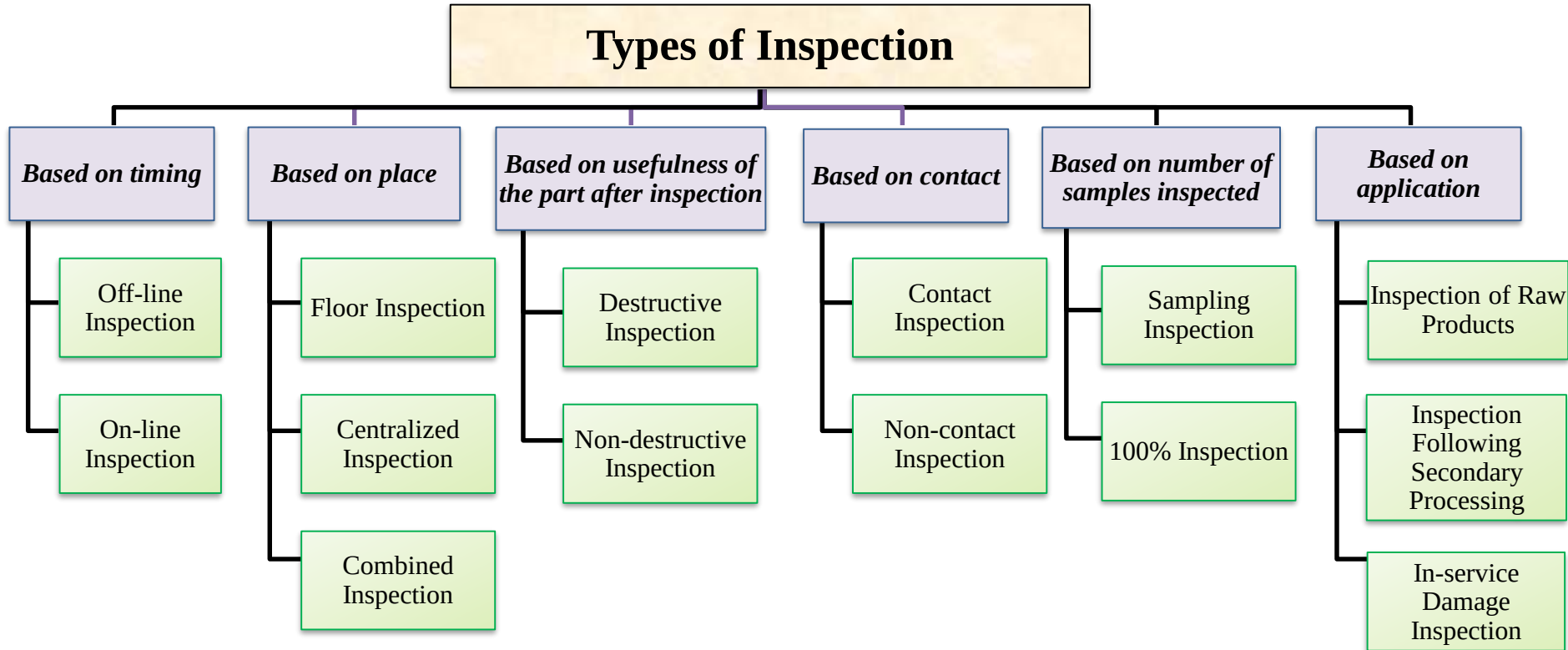
- ❑ Design for Inspection (DFI) is an engineering principle based on Design for X (DFX) methodology, where X is variable.
- ❑ It proposes that inspection methods and measurement instruments used to certify manufacturing conformity, should be considered early in design of products.
- ❑ DFI describes the process of designing or engineering a product in order to facilitate the measurement in order to reduce the overall costs of manufacturing and delivering products that satisfy customers.
- ❑ If the inspection method and instruments are considered and selected at the design stage, the likelihood that a tolerance feature cannot be inspected or requires a specialised instrument is substantially reduced.

Design Guidelines:

- Production processes should be designed in such a way that features of the products are easy to inspect with readily available measurement instruments, and so that measurement uncertainty is considered in the tolerance that are applied.
- Inspection can represent a significant percentage of an existing product's manufacturing cost. DFI may naturally be called for in redesign of a product to reduce that cost component when it is high.
- The use of modules in product design simplifies inspection and testing activities as it helps run tests before the final assembly is put together.



Classification of Inspection:



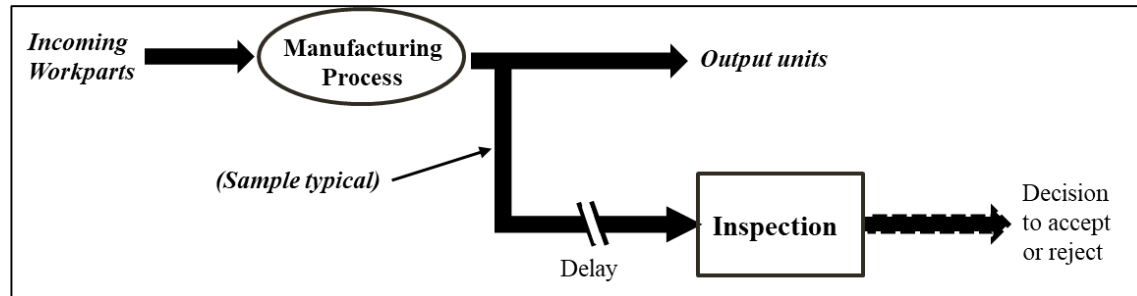
Classification based on Timing:

- The timing of the inspection procedure in relation to the manufacturing process is an important consideration in quality control.
- Based on the timing, inspection can be classified into two categories:
 1. Off-line inspection
 2. On-line inspection

I. Off-line Inspection

- Off-line inspection is performed away from the manufacturing process, and there is generally a time delay between processing and inspection.

❖ **Example:** Parts which require specialized testing equipment or environment such as medical devices, aerospace components, etc.



II. On-line Inspection

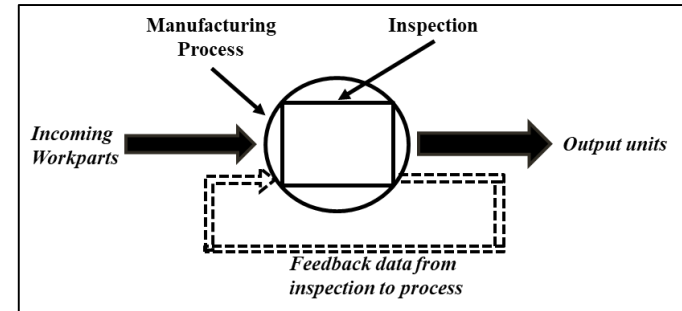
- Online inspection systems are integrated tightly into the production process.
- Online inspection offer great benefit in process efficiency and catching defects in near real-time.
- It is an alternative to off-line inspection, in which the procedure is performed when parts are made, either as:
 - ✓ *An integral step in the processing or assembly operation, or*
 - ✓ *Immediately afterward.*
- They can be further divided into two categories:

On-line/In-process
Inspection

On-line/post-process
Inspection

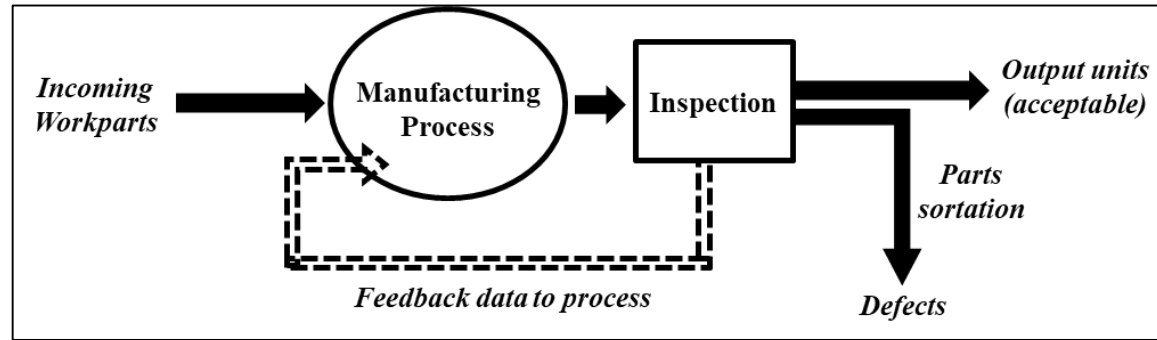
a) On-line/In-process Inspection:

- ❖ This is achieved by performing the inspection procedure during the manufacturing operation.
- ❖ As the parts are being made, the inspection procedure is measuring, or gauging the parts simultaneously.



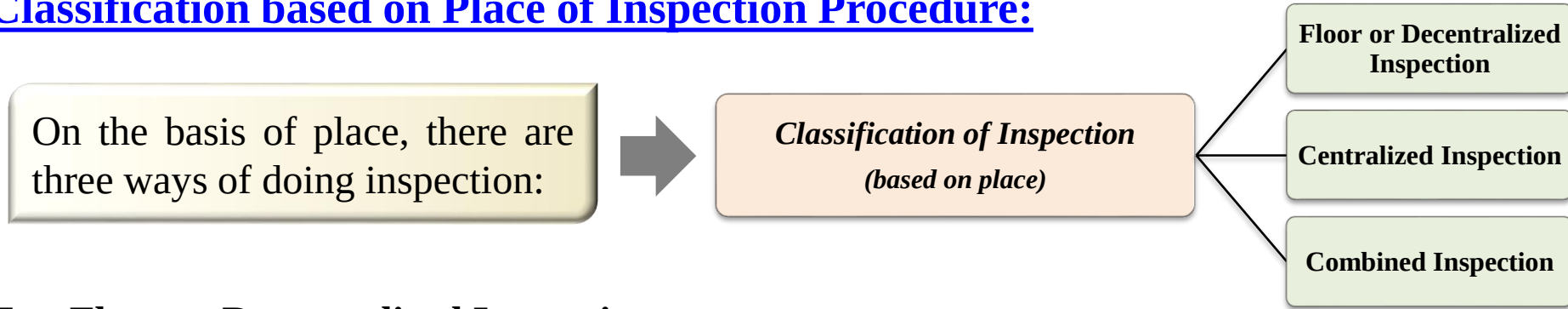
b) On-line/Post-process Inspection

- ❖ In this type, the measurement or gauging procedure is accomplished immediately following the production process.
- ❖ Even though it follows the process, it is still considered an on-line method because it is integrated with the manufacturing workstation, and the results of the inspection can immediately influence the production operation of the next part.



- ❑ Technologically, automated on-line/in-process inspection of the product is usually difficult and expensive to implement, as an alternative on-line/post process procedures are often used.

Classification based on Place of Inspection Procedure:



I. Floor or Decentralized Inspection

- It suggests the checking of materials in process at the machine or in the production time by patrolling inspectors.
- It requires the inspector to be fully equipped with all their devices or equipment.
- These inspectors moves from machine to machine and from one to the other work centres. Inspectors have to be highly skilled.
- This method of inspection minimise the material handling, does not disrupt the line layout of machinery and quickly locate the defect and readily offers field and correction.

Advantages, Disadvantages & Suitability of Floor or Decentralized Inspection:

Advantages:

- Encourage co-operation of inspector and foreman.
- Random checking may be more successful than batch checking.
- Does not delay in production.
- Saves time and expense of having more batches of work for inspection.

Disadvantages:

- Possibility of biased inspection because of worker.
- High cost of inspection because of numerous sets of inspections and skilled inspectors.

Suitability:

- Heavy products are produced.
- Different work centres are integrated in continuous line layout.

II. Centralized Inspection

- Materials in process may be inspected and checked at centralised inspection centre which are located at one or more places in the manufacturing industry.
- The inspection staff is more experienced and skilled in this case.
- Sophisticated and reliable instruments and techniques are used to measure the quality, hence centralised inspection is reliable and accurate.

Advantages:

- Better quality check-up.
- Closed supervision.
- Absence of workers pressure.
- Orderly production flow and low inspection cost.

Disadvantages:

- More material handling.
- Delays of inspection room causes wastage of time.
- Work of production control increases.
- Due to non-detection of machining errors in time, there may more spoilage of work.

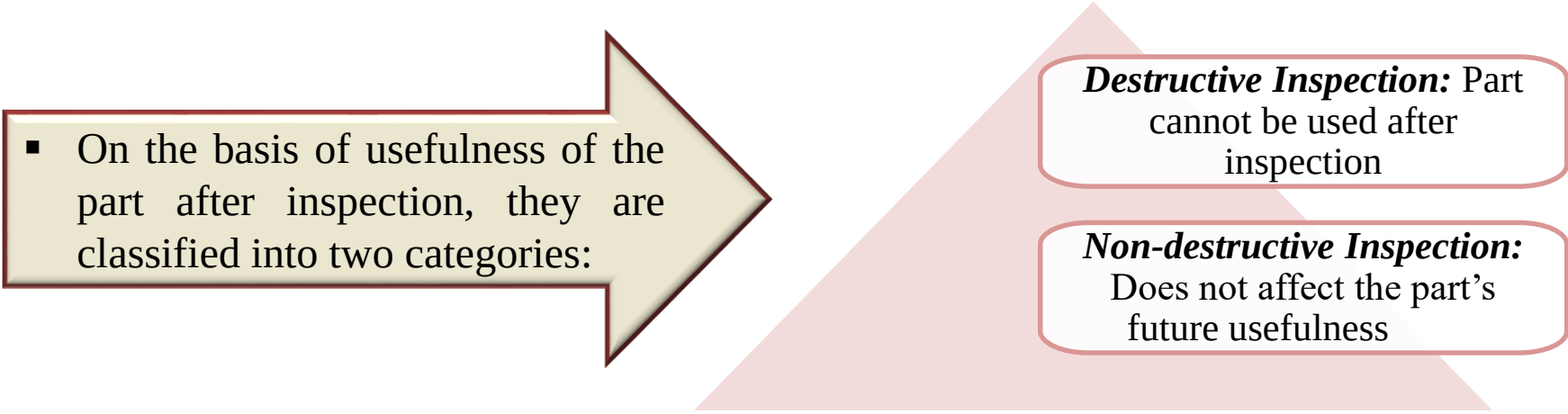
Suitability:

- Incoming materials inspection.
- Finished product inspection.
- Departmental inspection.
- High precision parts of delicate products.

III. Combined Inspection

- It is a combination of two methods: floor and centralized inspection methods.
- This is perhaps the best method as it encompasses all of the benefits to reduce issues.
- The main objective is to locate and prevent defect which may not repeat itself in subsequent operation to see whether any corrective measure is required and finally to maintain quality economically.

Classification based on the Usefulness of the Part after Inspection:

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- On the basis of usefulness of the part after inspection, they are classified into two categories:

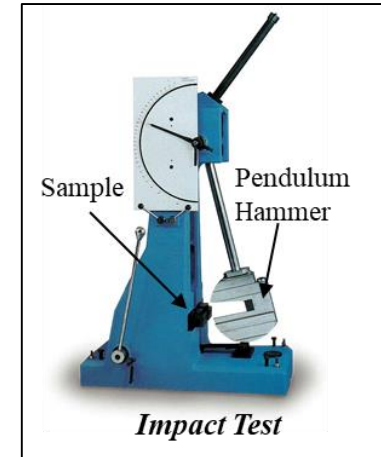
Destructive Inspection: Part cannot be used after inspection

Non-destructive Inspection: Does not affect the part's future usefulness

I. Destructive Inspection

- Destructive tests are carried out to the specimens' failure, in order to understand a specimen's performance or material behaviour under different loads.
- These tests are generally much easier to carry out, yield more information, and are easier to interpret than non-destructive testing.
- While destructive testing is intrinsically more revealing; it also is costly to a manufacturing operation due to material loss and, for obvious reasons, it is not suitable for in service material testing.

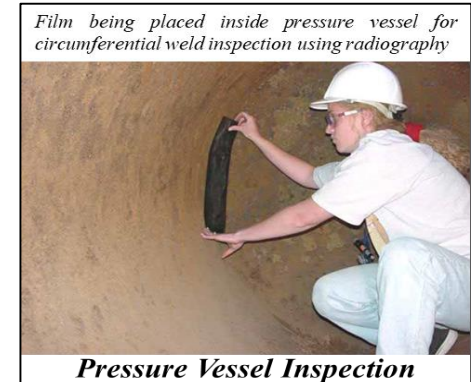
Examples:



II. Non-destructive Inspection

- Non-destructive inspection or Non-destructive evaluation (NDE) is a method of materials testing to assess the characteristics of a component without altering or destroying it.
- NDT is important in the materials testing industry where quick, dependable information on finished or raw material is needed.
- This may occur during the production stage, during the service life of a material or product, or as a diagnostic tool in the event of material failure.
- NDT is contrary to destructive testing such as stress or bend testing where critical material properties are determined through achieving specimen failure.

Examples:

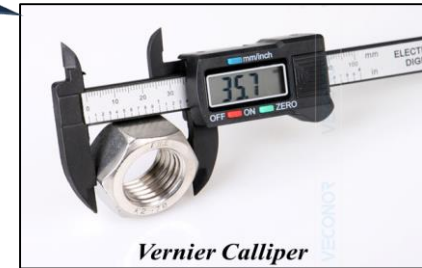
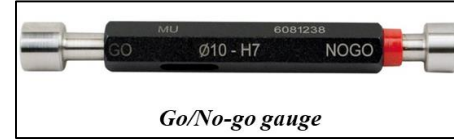


Classification based on Contact:

- On the basis of contact between object and instrument, inspection techniques can be divided into two broad categories:

- Contact Inspection
- Non-contact Inspection

Examples of
contact inspection:

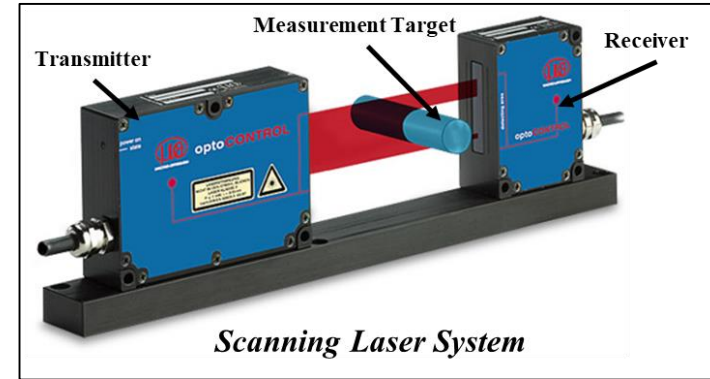
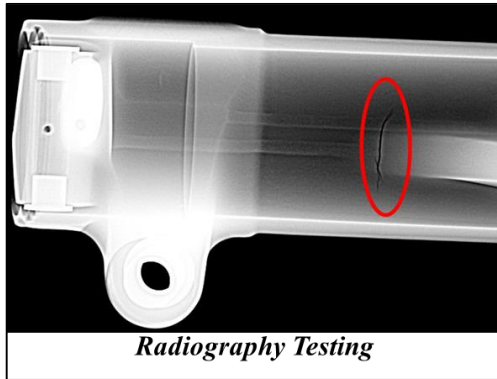


I. Contact Inspection

- In contact inspection, physical contact is made between the object and the measuring and gauging instrument.
- Typically contact is achieved using a mechanical probe or other device that touches the item, and allows the inspection procedure to occur.
- By its nature, contact inspection is concerned with some physical dimension of the part, and so contact methods are widely used in manufacturing and production industries to assess metal parts.

II. Non-contact Inspection

- In non-contact inspection no physical contact is made.
 - Non-contact inspection techniques use sensors instead of a mechanized probe favoured by contact inspection methodologies.
 - The sensor is located at a certain distance from the object to be inspected, to measure or gauge the desired features of the object.
- ❖ **Example:** Radiography Testing, Visual Inspection, Lasers Metrology i.e. Scanning Laser Systems.



Classification based on Number of Samples Inspected:

❑ On the basis of number of samples inspected, it can be classified into two parts:

- 1) 100% Inspection
- 2) Sampling Inspection

I. 100% Inspection

- This type will involve careful inspection in detail of quality at each strategic point or stage of manufacture where the test involved is non-destructive and every piece is separately inspected.
- It requires more number of inspectors and hence it is a costly method.
- There is no sampling error. This is subjected to inspection error arising out of fatigue, negligence, difficulty of supervision etc. Hence complete accuracy of influence is seldomly attained.
- It is suitable only when a small number of pieces are there or a very high degree of quality is required.

Examples: Jet engines, Aircraft, Medical and Scientific equipment.

Problems with 100% Inspection-

- Very expensive
- When product must be destroyed
- Inspection must be very tedious so defective items do not slip through inspection.

II. Sampling Inspection or Acceptance Sampling

- Sampling Inspection involves inspecting a relatively small number of items from a batch or lot and then using the results of this sample to either accept or reject the entire lot.
- The accept/reject criteria is the number of defective items found in the sample.
- This method is most useful when product testing is expensive, destructive, or time consuming.

Examples : Electrical bulbs, radio bulbs, washing machine, destructive tests conducted for the products whose endurance or ultimate strength properties are required etc.

□ Depending upon the number of samples being inspected, it can be further classified into four types:

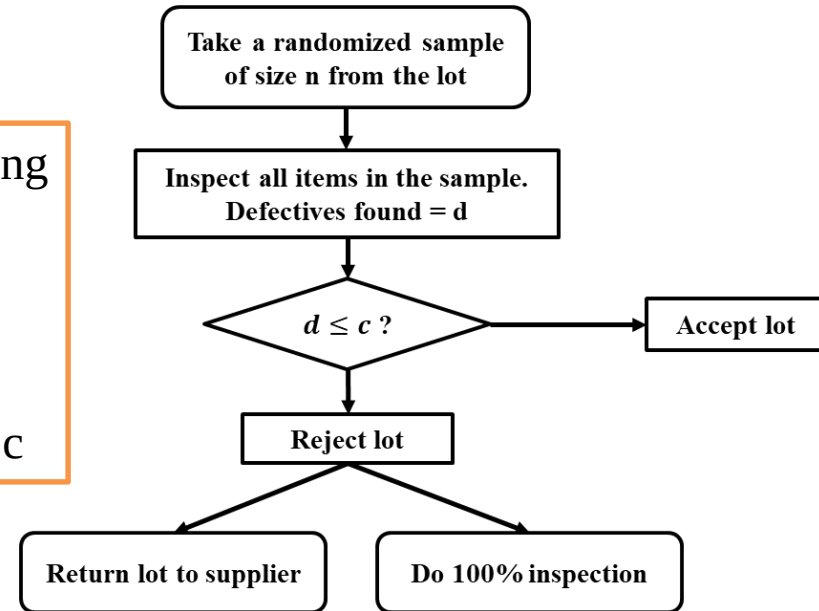
- 1) *Single Sampling*
- 2) *Double Sampling*
- 3) *Multiple Sampling*
- 4) *Sequential Sampling*

1. Single Sampling:

- When a decision on acceptance or rejection of the lot is made on the basis of only one sample, acceptance plan is known as single sampling plan.
- It is the most common and easiest plan to use.

Single sampling plan is defined by the following parameters:

- Lot size, N
- Samples size, n
- Decision criterion or acceptance number, c



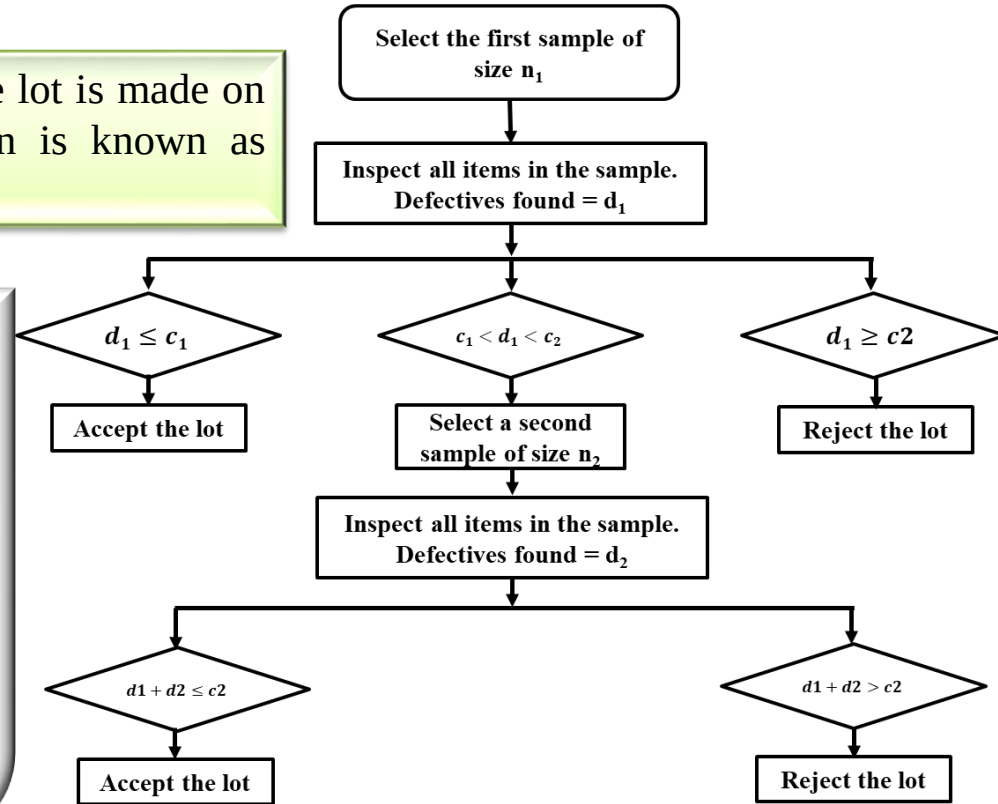
Single Sampling Procedure

2. Double Sampling:

When a decision on acceptance or rejection of the lot is made on the basis of two samples, then acceptance plan is known as double sampling plan.

Double sampling plan is defined by the following parameters:

- i. Lot size, N
- ii. Sample size of first sample, n_1
- iii. Acceptance number for first sample, c_1
- iv. Sample size of second sample, n_2
- v. Acceptance number for both sample, c_2



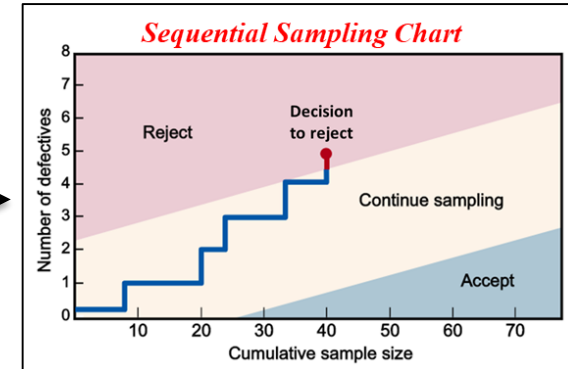
Double Sampling Procedure

3. Multiple Sampling:

- ❑ In multiple sampling, a lot is accepted or rejected based upon the results obtained from several samples (more than 2) drawn from the lot.
- ❑ Two limits are specified for each sample.
- ❑ Cumulative number of defects are compared to limits for each successive sample:
 - ❖ If number of defects < lower limit, accept the lot.
 - ❖ If number of defects > upper limit, reject the lot.
 - ❖ If number of defects between limits, continue sampling.
- ❑ Continue sampling until accept or reject lot based on all sample data.

4. Sequential Sampling:

- It is an extreme case of multiple sampling, in which sampling might continue until the lot is exhausted.
- Items are randomly selected from the lot and inspected one at a time.
- **Results are compared to sequential-sampling chart.** →
- Chart guides decision to reject, accept, or continue sampling (select another item), based on cumulative results.
- Average number of items inspected is generally lower with sequential sampling.



Advantages of Sampling Inspection:

- Sampling inspection is cheaper and quicker and it requires less number of Inspectors.
- It is subjected to sampling errors but the magnitude of sampling error can be estimated.
- In the case of destructive test, random or sampling inspection is desirable.
- This type of inspection governs wide currency due to the introduction of automatic machines or equipment which are less susceptible to change variable and hence require less inspection.
- It is suitable for inspection of products which have less precision importance and are less costly.
- Rejection of a complete batch on the basis of a sample decidedly pressurizes for improvements in quality.

Disadvantages of Sampling Inspection:

- Risk included in chance of bad lot acceptance and good lot rejection.
- Sampling inspection provides less information than 100% inspection.

Classification based on Application:

- On the basis of their application in manufacturing, they can be classified into three main categories:
 - Inspection of raw products
 - Inspection following secondary processing
 - In-service damage inspection

I. Inspection of Raw Products:

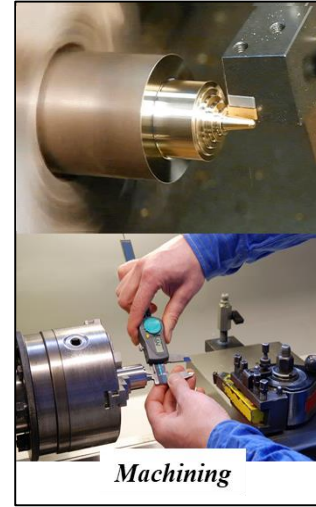
➤ This include the raw material or subcontracted parts from the suppliers for example:

- ✓ Castings
- ✓ Forgings
- ✓ Extrusions, etc.

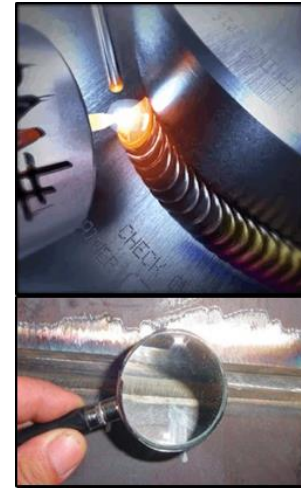


II. Inspection Following Secondary Processing:

- Secondary manufacturing processes are the process, which are used to further modify the output of the primary manufacturing processes in order to improve the material properties, surface quality, surface integrity, appearance and dimensional tolerance.
- This includes the following processes: machining, welding, grinding, heat treating, plating, etc.



Machining



Inspection of Welding

III. In-service Damage Inspection:

- It is performed to assess the quality of critical engineering structures using non-destructive inspection techniques to avoid their failure.
- It includes power plant inspection, wire rope inspection, aircraft inspection, bridge inspection, etc.
- In service damages, that can occur are cracking, Corrosion, Erosion/Wear, Heat Damage, etc.



Wire Rope Inspection

Drawbacks of Inspection:

- Inspection merely separates good and bad items. It is no way to prevent the production of bad items.
- Inspection adds to the cost of the product but not for its value.
- It requires more man power/operations to maintain quality control and adds more time to the initial process.
- It is partially subjective, often the inspector has to judge whether a product passes or not.
Example: Inspector discovering a slight burnish on a surface must decide whether it is bad enough to justify rejection even with micrometres a tight or loose fit change measurement by say 0.0006 inches. The inspectors design is important as he enforces quality standards.
- Fatigue and Monotony may affect any inspection judgement.

Summary:

- Inspection is an important tool to reduce the manufacturing cost by controlling the product quality at different stages.
- As inspection adds to the cost of the product but not for its value, DFI concepts are used at design stage so that products are easy to inspect with readily available instruments.
- Classification of inspection activities on the basis of different parameters has also been discussed.
- In this course, all the inspection techniques will be discussed by categorizing them into destructive and non-destructive inspection.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 03: Destructive Inspection-I



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What is Destructive Inspection?

Definition: Destructive tests (or destructive physical analysis, DPA) are defined as those tests which are performed to a material through the use of tools or machines, which produce an irreversible alteration of their chemical composition or dimensional geometry.

Why Destructive Inspection is Important?

- These tests are generally much easier to carry out, yield more information, and are easier to interpret than non-destructive testing.
- Destructive testing is most suitable, and economic, for objects which will be mass-produced, as the cost of destroying a small number of specimens is negligible.
- It is usually not economical to do destructive testing where only one or very few items are to be produced (for example, in the case of a building).
- It is often less expensive to scrap a part to make a destructive quality test than to test the parts using more expensive non-destructive tests.



Destructive Testing of Materials:

Aim of Destructive Tests (DT):

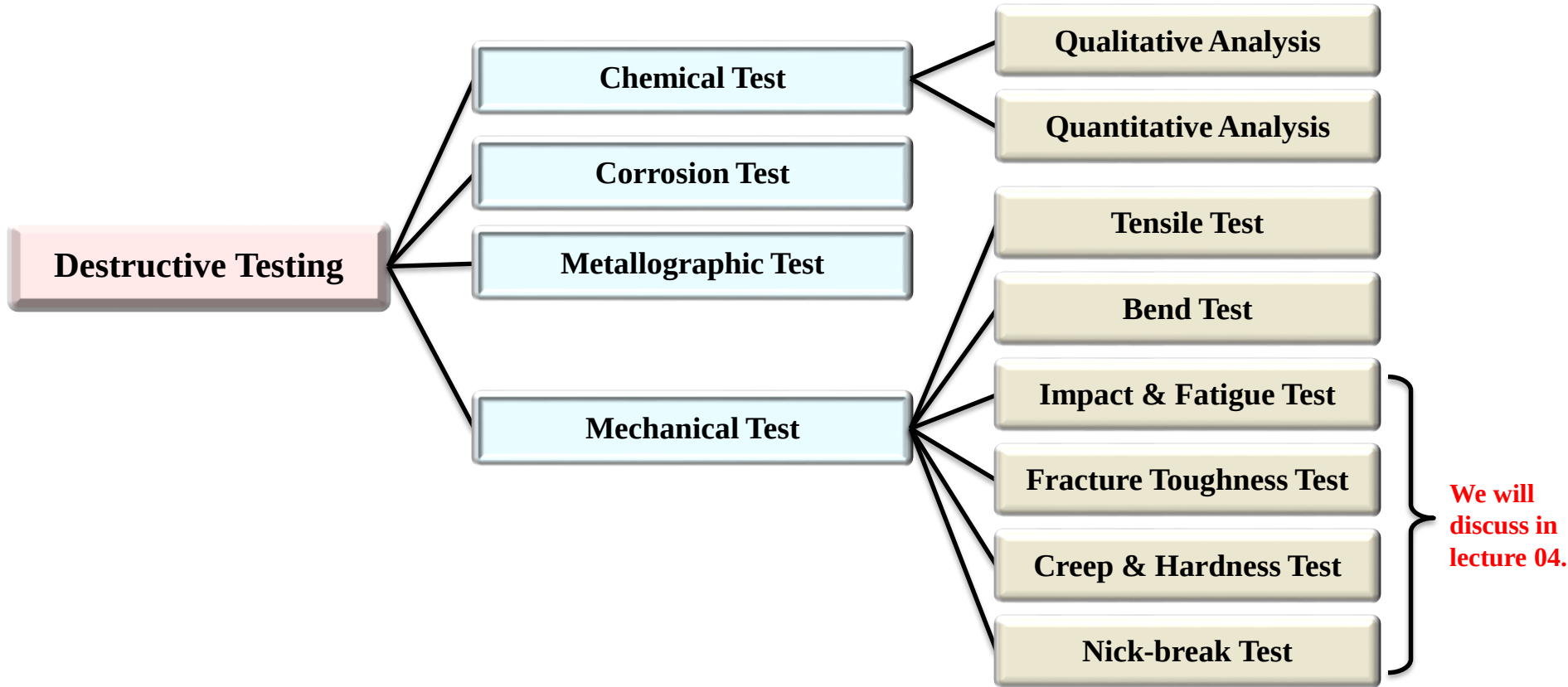
Determination of chemical, mechanical and metallurgical properties.

Evaluation and selection of material for a specific environment and a certain application.

Determination of service life of a component under given loading conditions.

- Destructive tests are best when used together with non-destructive methods: this combination gives the best information on materials.
- Non-destructive tests show if cracks, corrosion or other faults exist. Destructive tests in turn indicate how and when the objects are in danger of breaking down or failing.
- Destructive testing of materials include mechanical testing (tensile, bend and impact tests), hardness testing, macro and micro testing as well as material analysis and metallographic examinations.
- It is also useful in some scenario of reverse engineering for finding the relevant / similar material for replacing / renewing a material or component.

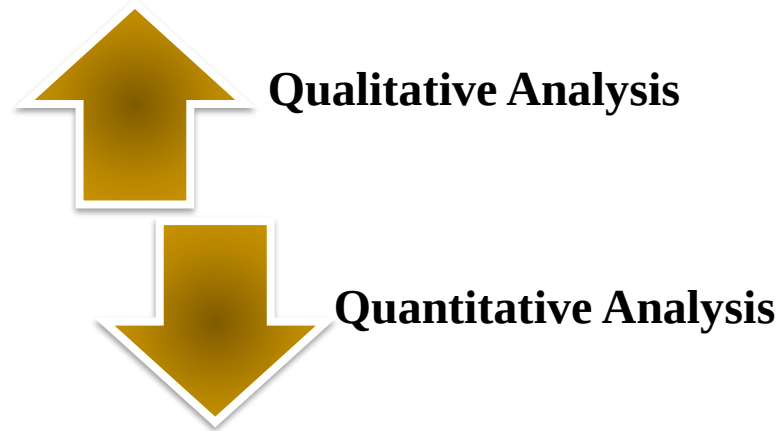
Classification of Destructive Testing:



I. Chemical Tests:

Objective of Chemical Test:

- ❖ To determine chemical composition of materials.
- Chemical analysis of materials is important to ensure that we are getting the material that is appropriate for the intended end use.
- These techniques can be grouped into two categories:



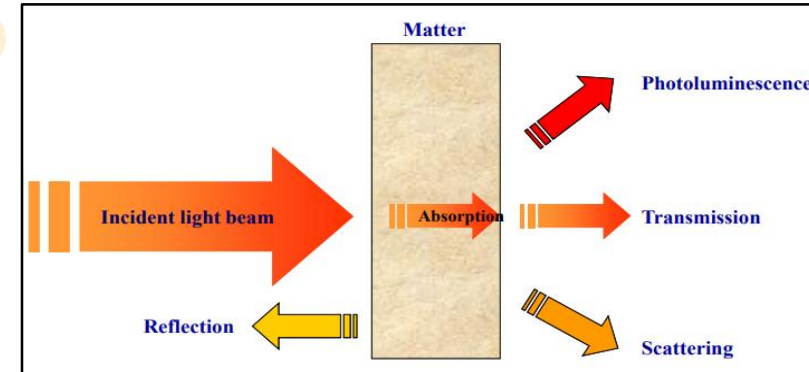
1) Qualitative Analysis:

- These methods are used to determine which elements exist in a sample.
- Some most commonly used qualitative analysis techniques are:
- All these spectroscopic analysis techniques work on the principle of spectroscopy which describes the interaction of radiation with matter.
- These methods differ with respect to the species to be analyzed (e.g., molecular or atomic spectroscopy), the type of radiation-matter interaction to be monitored (e.g., absorption, emission, or diffraction), and the region of the electromagnetic spectrum used in the analysis.

Mass Spectrometry, Atomic Spectroscopy, X-ray Fluorescence, Particle-induced X-ray Emission, and X-ray Photoelectron Spectroscopy.

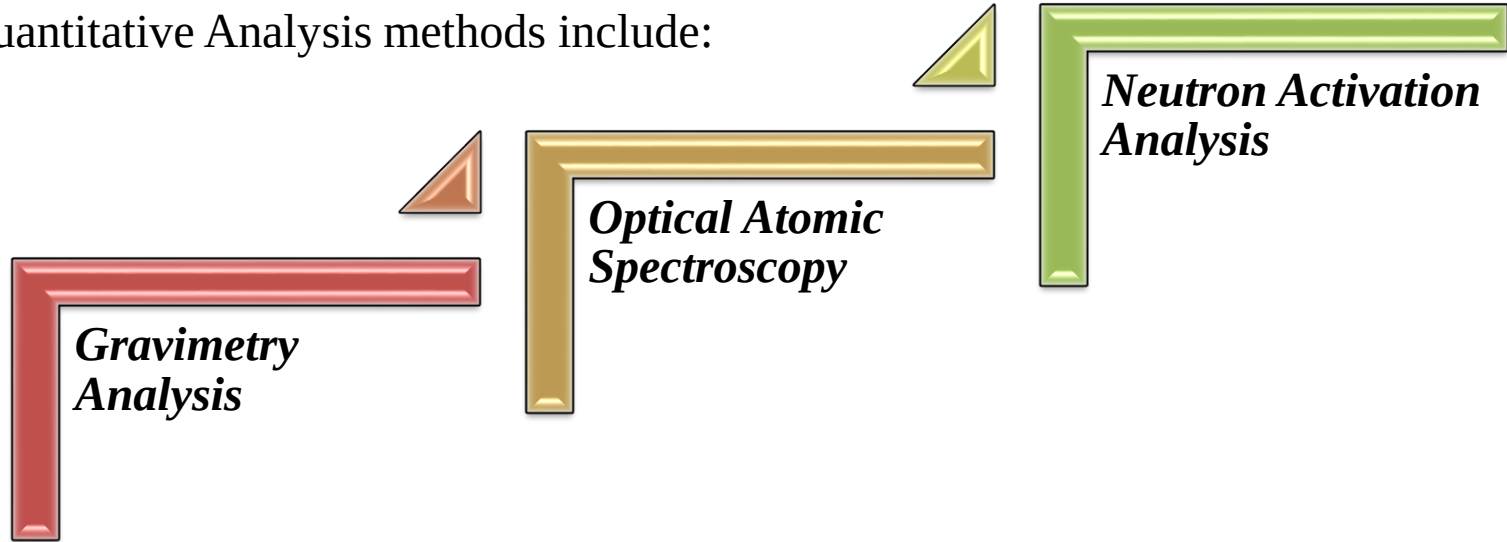
Principles of Spectroscopy:

If matter is exposed to electromagnetic radiation, the radiation can be absorbed, transmitted, reflected, scattered or undergo photoluminescence. Photoluminescence is a term used to designate a number of effects, including fluorescence, phosphorescence, and raman scattering.



2) Quantitative Analysis:

- Quantitative analysis is the determination of the mass of each element or compound present.
- Quantitative Analysis methods include:



❖ Gravimetry Analysis:

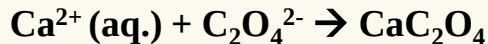
- In this method, the sample is dissolved and then the element of interest is ***precipitated*** and its mass measured or the element of interest is ***volatilized*** and the mass loss is measured.

Example:

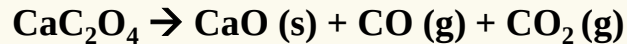
- ✓ ***Volatilization Method:*** To determine the water content of a compound by vaporizing the water using thermal energy (heat).
- ✓ ***Precipitation Method:*** Determination of the amount of calcium in water.

Step-1 An excess of oxalic acid, $\text{H}_2\text{C}_2\text{O}_4$, is added to a measured, known volume of water.

Step-2 By adding a reagent (ammonia), the calcium will precipitate as calcium oxalate.



Step-3 The precipitate is collected, dried and ignited to high (red) heat which converts it entirely to calcium oxide.



Step-4 The pure precipitate of calcium oxide is cooled, then measured by weighing, and the difference in weights before and after reveals the mass of calcium oxide.

The amount of calcium oxide can then be used to calculate the amount of calcium in the original mix.

❖ Optical Atomic Spectroscopy:

- In optical spectroscopy, energy absorbed to move an electron to a higher energy level (higher orbital) is absorbed in the form of photons.
- Because each element has a unique number of electrons, an atom will absorb energy in a pattern unique to its elemental identity (e.g. Ca, Na, etc.) and thus will absorb photons in a correspondingly unique pattern.
- The type of atoms present in a sample, or the amount of atoms present in a sample can be deduced from measuring these changes in light wavelength and light intensity.

❖ Neutron Activation Analysis:

- Neutron activation is the process in which neutron radiation induces radioactivity in materials, and occurs when atomic nuclei capture free neutrons, becoming heavier and entering excited states.
- In this method, sample is bombarded with neutrons, causing the elements to form radioactive isotopes.
- The radioactive emissions and radioactive decay paths for each element are well known. Using this information, it is possible to study spectra of the emissions of the radioactive sample, and determine the concentrations of the elements within it.

II. Corrosion Tests:

Objective: To determine the type and rate of corrosion.

- Conducted under laboratory conditions for accurate forecasting of products performance in service.
- Accelerated corrosion tests are used to get a better understanding of its mechanism or to determine the corrosion susceptibility of materials.
- An accelerated corrosion test is a necessary and powerful tool when used in:
 - ✓ *Material selection as a relative indicator of corrosion resistance.*
 - ✓ *Examining potential environments for new materials.*
 - ✓ *Determining corrosion control strategies of fielded items.*

III. Metallographic Tests:

- It is the study of physical structure and components of metals, by using microscopy.
- Ceramic and polymeric materials are also prepared and tested using metallographic techniques, hence these studies are called ceramography, plastography and, collectively called materialography.
- Some of their applications include:

Distribution of non-metallic inclusions in the weld.

Grain size measurements.

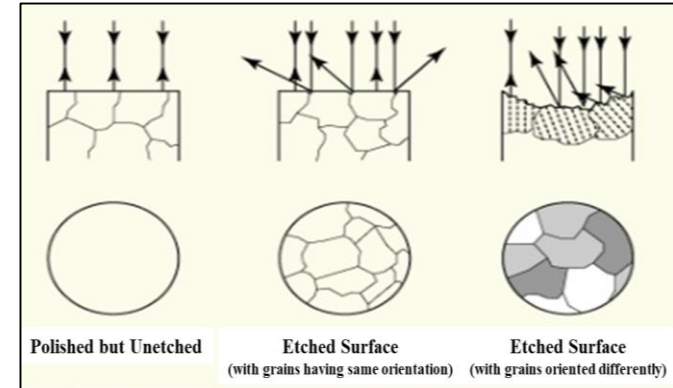
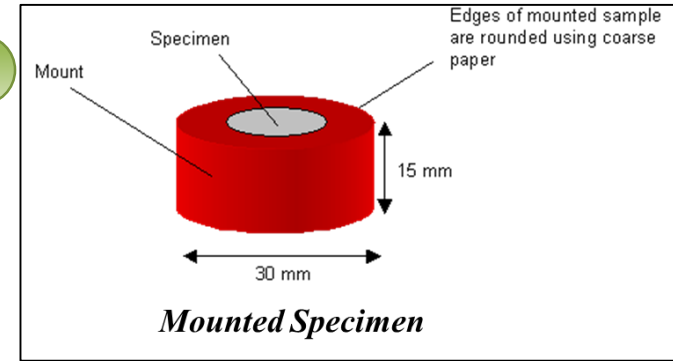
Nature and distribution of secondary phases.

Metallographic Test Procedure:

- Proper preparation of metallographic specimens to determine microstructure and content requires a rigid step-by-step process to be followed:

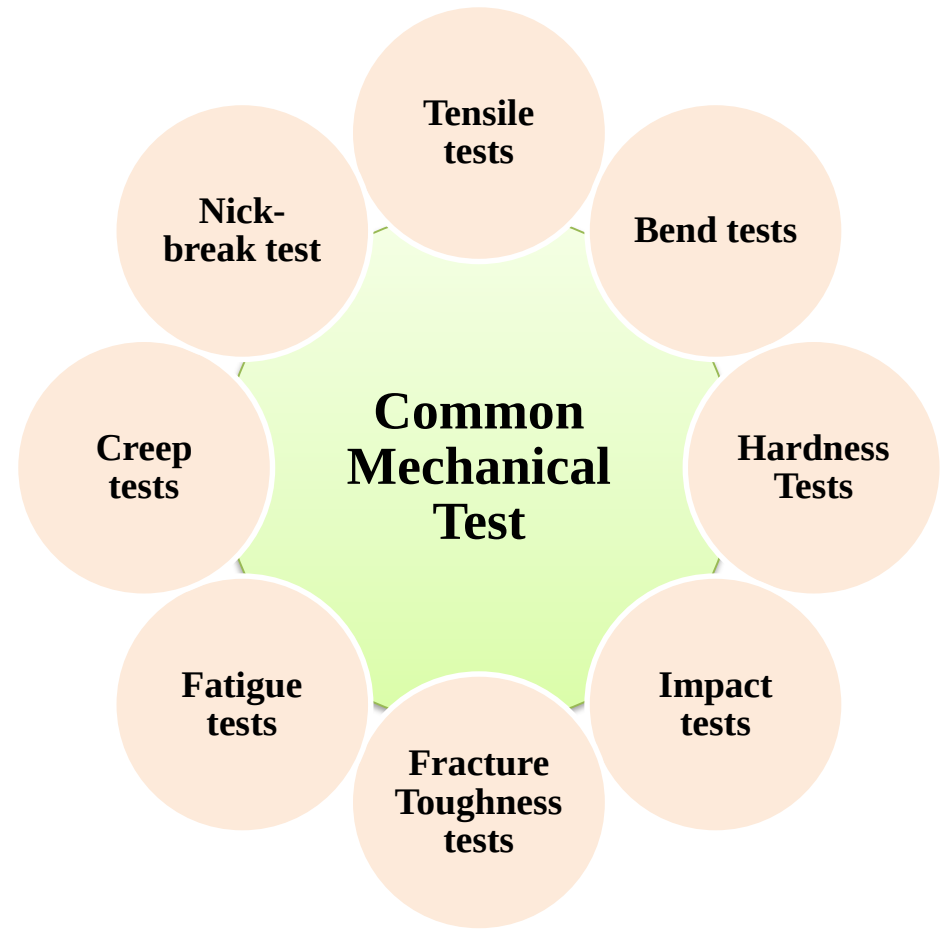
In sequence, the steps include:

- i. **Sectioning (Cutting):** Cutting a small representative piece of the metal to be studied.
- ii. **Mounting:** Specimens are mounted to facilitate easy handling during preparation and examination.
- iii. **Grinding:** Preparing the surface for metallographic examination as optically flat, reflective, smooth and scratch free.
- iv. **Polishing:** To remove deformations from grinding and obtain a surface that is highly reflective.
- v. **Etching:** It is used to reveal the microstructure of a specimen under the optical microscope by achieving contrast in the microstructure.
- vi. **Microscopic Examination:** To study the structure and constitution of metals and alloys using metallurgical microscopes and magnifications.



IV. Mechanical Tests:

- Mechanical testing is the testing of materials to find out its mechanical properties, for example its yield strength, hardness, fracture strength, etc.
- Mechanical testing is used to ensure that supplied materials will perform as expected under mechanical loading.

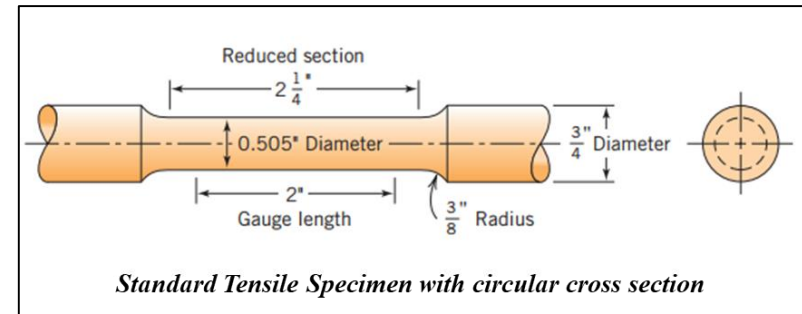


1. Tensile Tests:

- Tensile testing, also known as tension testing, is a fundamental materials science and engineering test in which a sample is subjected to a controlled tension until failure.
- It is probably the most fundamental type of mechanical test one can perform on material.
- Tensile tests are simple, relatively inexpensive, and fully standardized.
- Properties that are directly measured via a tensile test are: ultimate tensile strength, breaking strength, maximum elongation and reduction in area.
- From these measurements the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics.
- These properties are useful in comparisons of materials, alloy development, quality control, and design under certain circumstances.

Tensile Test Specimen:

Tensile test specimen generally have “dogbone” configuration with either circular or rectangular cross section.



Tensile Test Procedure:

- i. The specimen is mounted by its ends into the holding grips of the testing apparatus.
- ii. The tensile testing machine is designed to elongate the specimen at a constant rate.
- iii. It also continuously and simultaneously measure the instantaneous applied load (with a load cell) and the resulting elongations (using an extensometer).
- iv. A stress-strain test typically takes several minutes to perform and is destructive; that is, the test specimen is permanently deformed and usually fractured.

- ❖ *The output of tensile test is recorded as stress versus strain.*
- ❖ *Engineering stress, σ and strain, ϵ are defined by the following relations:*

$$\sigma = \frac{F}{A_0}$$

$$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

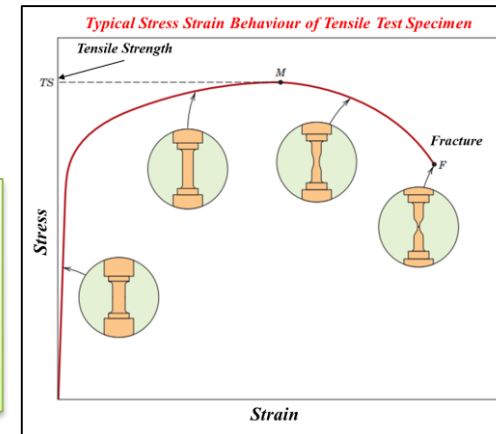
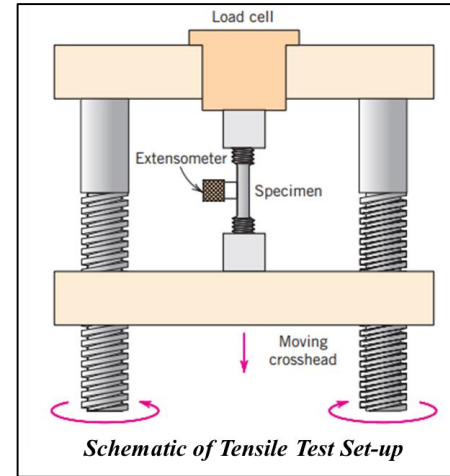
Where, F is instantaneous load applied perpendicular to specimen cross section, in units of Newton's (N).

A_0 is original cross sectional area before any load is applied (m^2).

l_0 is original length before any load is applied.

l_i is instantaneous length.

Δl is deformation, elongation or change in length at some instant.



Mechanical Properties Determination from Tensile Test:

✓ Yield Strength:

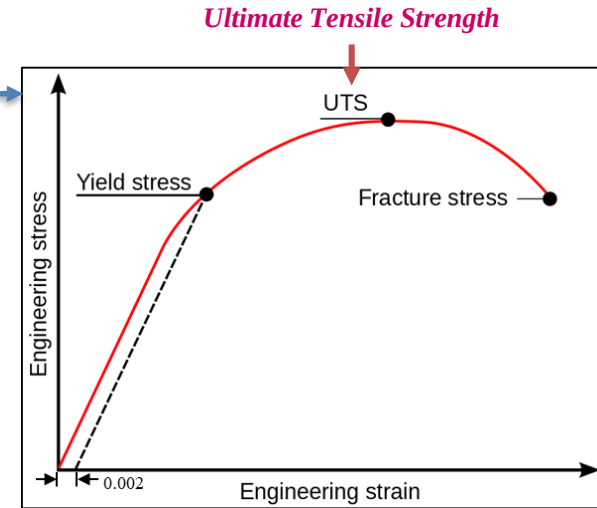
- The engineering stress at which, it is considered that plastic elongation of the material has commenced.

✓ Ultimate Tensile Strength (UTS):

- The maximum tensile stress that a material is capable of sustaining.

✓ Ductility:

- It is a measure of the degree of plastic deformation that has been sustained at fracture.
- Ductility may be expressed quantitatively as either percent elongation or percent reduction in area.



✓ Elongation:

$$\%EL = \frac{(l_f - l_0)}{l_0} \times 100$$

✓ Reduction of Area:

$$\%RA = \frac{(A_0 - A_f)}{A_0} \times 100$$

l_0 = Original gauge length.

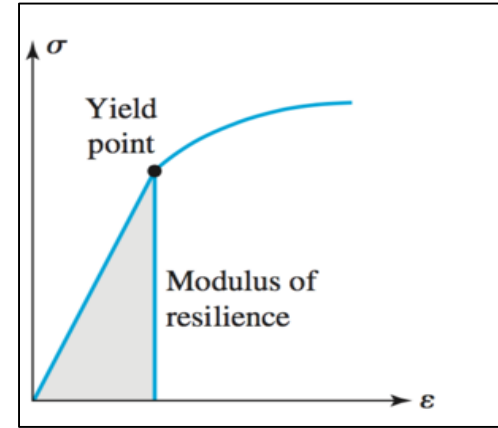
l_f = Fracture length.

A_0 = Original cross-sectional area.

A_f = Cross sectional area at the point of fracture.

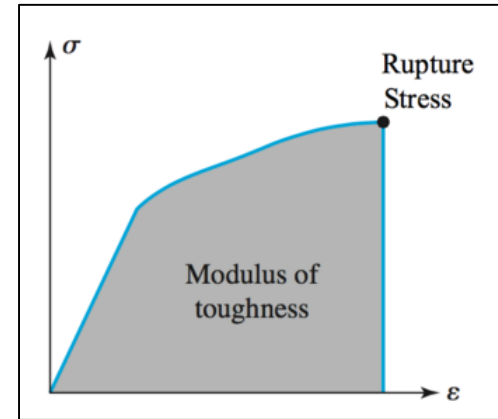
✓ Resilience:

- Resilience may be defined as the energy absorbed by a material in undergoing elastic deformation up to the elastic limit.
- Modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding.



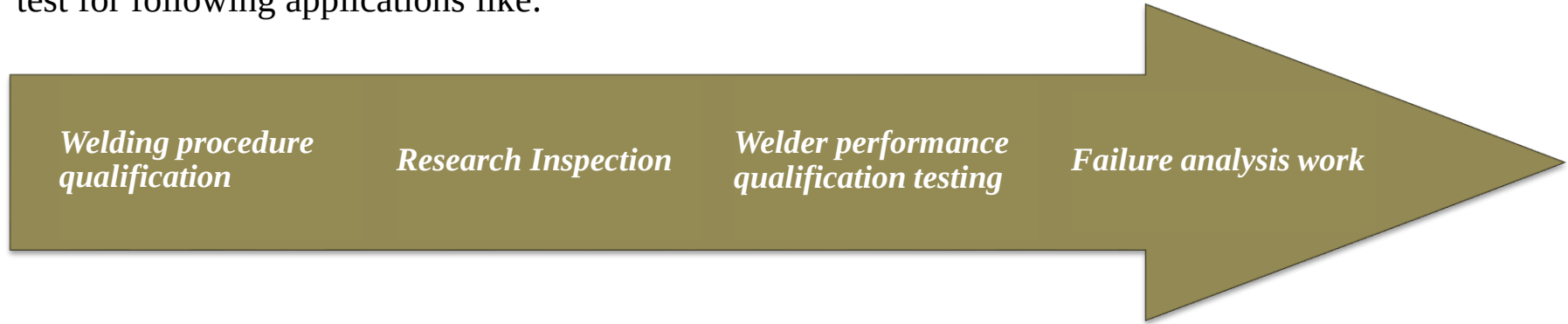
✓ Toughness:

- Toughness is the total amount of energy which a material can absorb up to the point of fracture.
- It is the area under the stress-strain curve up to the point of fracture.



Tensile Testing of Weldments:

- Weld joints are generally subjected to destructive tests such as hardness, toughness, bend and tensile test for following applications like:



- Tensile testing of weldments is carried out to determine the ultimate tensile strength (UTS) and yield point (YP) under static loading of base metal, weld metal and the welded joint.

- For weldments, different type of tensile tests performed are:

All weld metal test

Longitudinal butt weld test

Transverse butt weld test

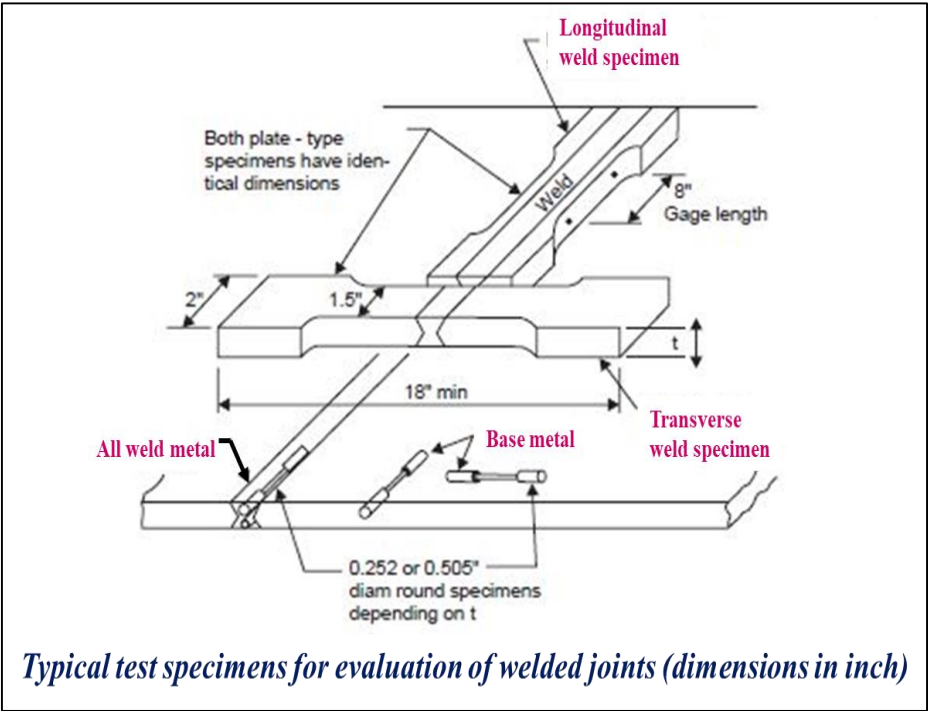
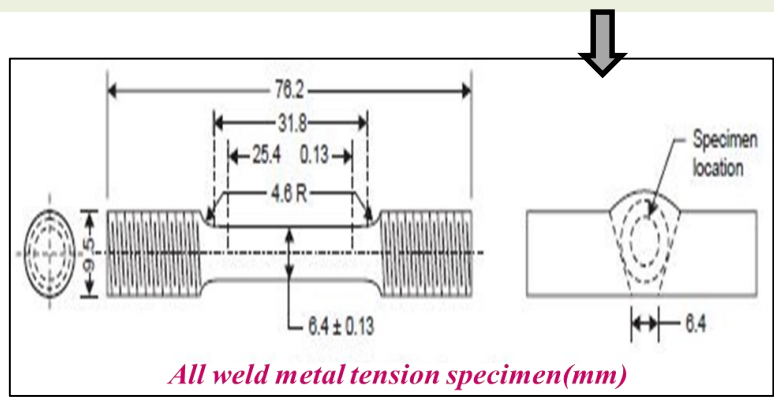
Tension shear test

Specimen Preparation:

To determine the tensile strength of weld metal alone or welded joint the samples are prepared which are of the types as shown in Figure.

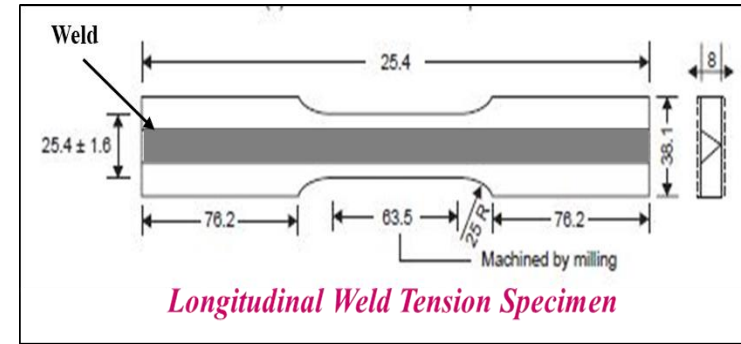
a) All Weld Metal Test:

In a commonly used weld tensile test, the axis of the test bar is parallel to the axis of the weld and the specimen is machined so that the entire bar consist of deposited weld metal with a diameter of 6.4 mm.



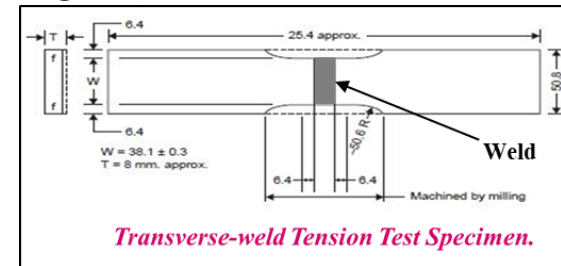
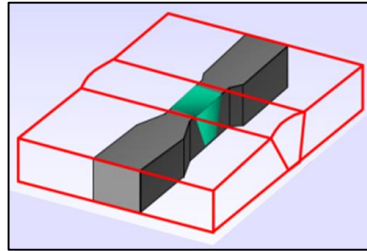
b) Longitudinal Butt Weld Test:

- Here the loading is parallel to the weld axis.
- It differs from all weld metal test in that it contains weld, HAZ and base metal along the gauge length.
- All these zone must strain equally and simultaneously.
- Weld metal elongates with base metal until failure occurs.
- This test thus provides more information about the composite joint than the transverse test specially when base metal and weld metal strengths differ significantly.



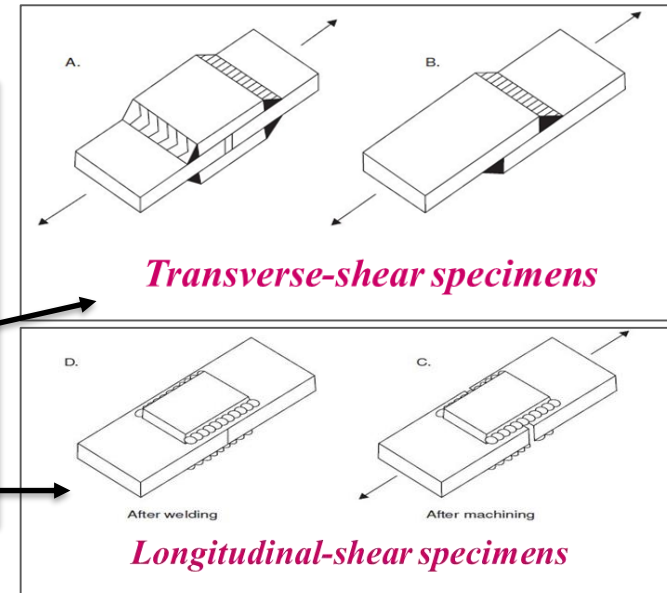
c) Transverse Butt Weld Test:

- In this test, if failure occurs in the base metal, it shows that the weld metal is stronger than base metal.
- If the failure occurs in the weld metal, means the weld strength is lower than the base metal.



d) Tension Shear Test:

- Tension shear tests may be used to evaluate the shear properties of fillet welds.
- Such tests are usually intended to represent completed joints in weldments and so prepared using similar procedures.
- Two types of specimens are usually employed, viz.,
 - i. **Transverse-shear Specimen**
 - ii. **Longitudinal-shear Specimen**



- In the **Transverse Shear Specimens**, double lap specimens are preferred because they are more symmetrical and therefore, the stress state under load better approaches pure shear.
- In **Longitudinal Fillet Weld Shear Test**, measure the strength of the fillet weld when the specimen is loaded parallel to the axis of the weld.
- The weld shearing strength is reported as load per linear *mm* or *MPa* based on the weld throat and type of specimen.

2. Bend or Flexure Tests:

- The flexure test method measures behaviour of materials subjected to simple beam loading.
- Unlike tensile test, a flexure test does not measure fundamental material properties. *Why?*

Because

- ✓ When a specimen is placed under flexural loading all three fundamental stresses are present: tensile, compressive and shear.
- ✓ So the flexural properties of a specimen are the result of the combined effect of all three stresses as well as (though to a lesser extent) the geometry of the specimen and the rate the load is applied.

- The most common purpose of a flexure test is to measure flexural strength and flexural modulus.

❖ **Flexural Strength:**

It is defined as the maximum stress at the outermost fiber on either the compression or tension side of the specimen.

❖ **Flexural Modulus:**

It is calculated from the slope of the stress vs. strain deflection curve.

- These two values can be used to evaluate the sample materials ability to withstand flexure or bending forces.

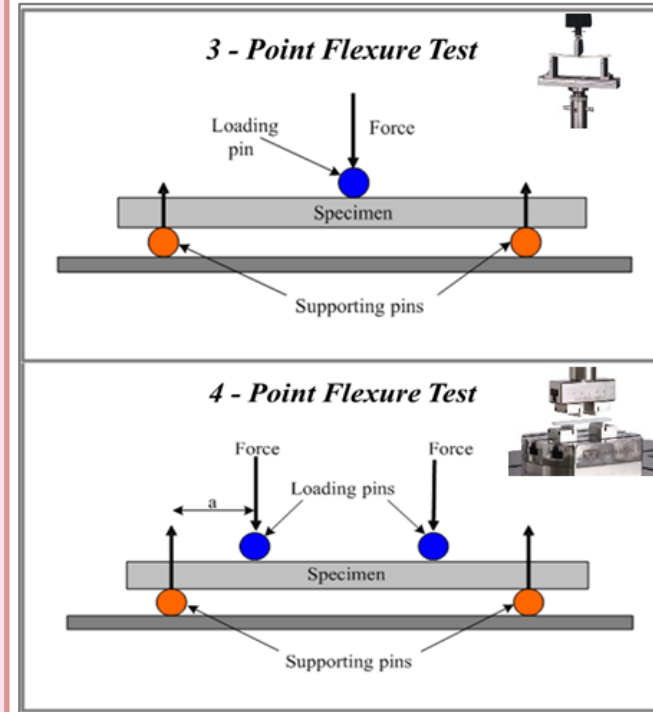
Procedure:

- i. The material is laid horizontally over two points of contact (lower support span).
- ii. Then a force is applied to the top of the material through either one or two points of contact (depending upon 3-point or 4-point flexure test) until the sample fails.

3-point Flexure Test - The loading force is applied in the middle by means loading pin.

4-point Flexure Test - The loading force is applied by means of two loading pins with a distance between them equal to a half of the distance between the supporting pins.

- iii. Maximum fiber stress and maximum strain are calculated for increments of load.
- iv. Results are plotted in a stress-strain diagram.



Calculation of Flexural Properties:

- **Flexural strength** is calculated at the surface of the specimen on the convex or tension side.
- **Flexural modulus** is calculated from the slope of the stress vs. deflection curve. If the curve has no linear region, a secant line is fitted to the curve to determine slope.

Example: 3 - Point Flexural Test

❖ Stress, $\sigma = \frac{Mc}{I}$

where, M = maximum bending moment

c = distance from centre of specimen to outer fibers

I = Moment of inertia of cross section

F = applied load

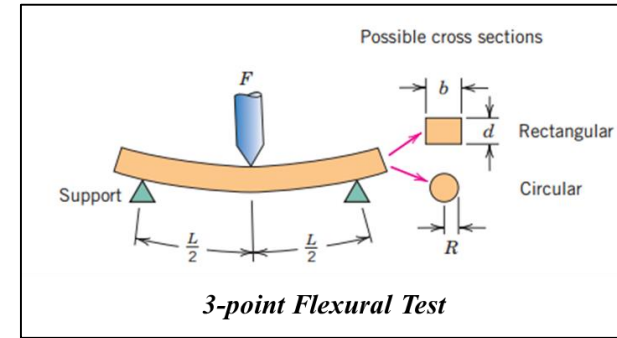
- ❖ For a rectangular cross section, the flexural strength σ_{fs} is equal to:

$$\sigma_{fs} = \frac{3F_f L}{2bd^2}$$

- ❖ When the cross section is circular, then

$$\sigma_{fs} = \frac{F_f L}{\pi R^3}$$

Where, F_f is the load at fracture, and L is the distance between support points.



	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

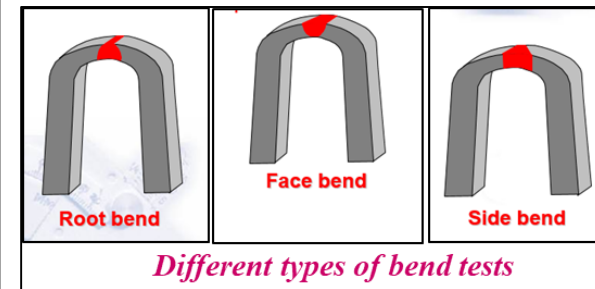
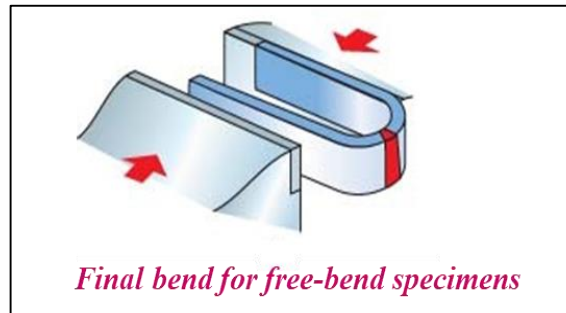
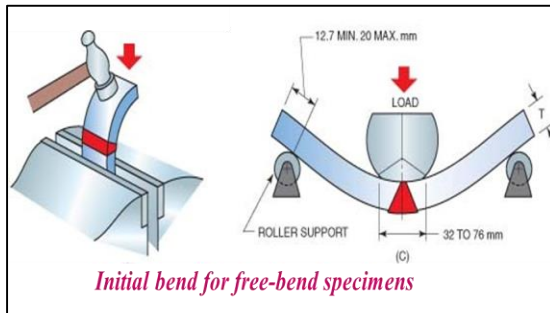
Flexural or Bend Testing of Weldments:

The quality of the weld, in terms of ductility of weld metal and HAZ as well as tests for opening of defects particularly lack of side wall fusion, root fusion, and penetration of welded joint are checked by means of a bend test.

- ✓ The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material.
- ✓ It is often used as a quality control test for butt-welded joints, having the advantage of simplicity of both test piece and equipment.
- ✓ Bend tests of weldments are sub-divided into two types:
 - a) **Free bend test,**
 - b) **Guided bend test**

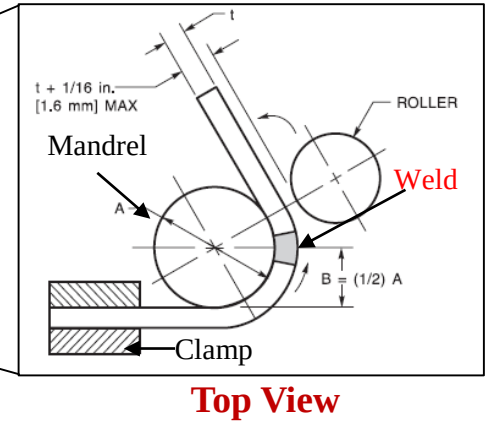
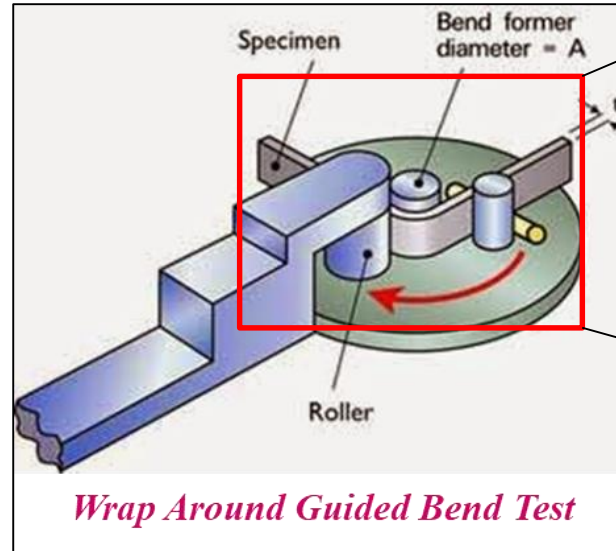
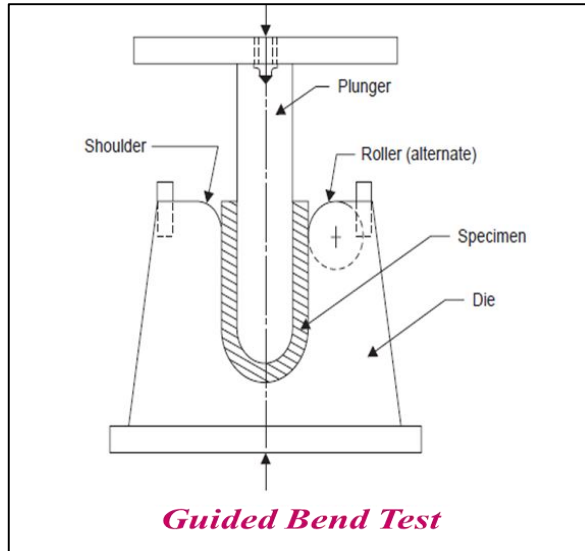
a) Free Bend Test:

- The free bend test has been devised to measure the ductility of the weld metal deposited in a weld joint.
- A test specimen is machined from the welded plate with the weld located in the centre.
- The ends of the specimen are then bent to form two 30 degree angles at approximately one-third of the length inward from the ends. It is done to ensure that all bending occurs in the weld.
- Then final bending is performed till the crack appears on the weld face of critical length or failure of the specimen.
- Due to inhomogeneity of the joint, there is a tendency for free bend test specimen to take up an irregular shape, so that the actual radius at various points differs from the specified value.



b) Guided Bend Test:

- In the guided bend test, guided bending is performed by placing the weld joint over the die.
- It offers better controlled conditions of the specimen and of the loading.
- It is costlier than the free-bend test.



Summary:

- Destructive inspection techniques are generally much easier to carry out, yield more information, and are easier to interpret than non-destructive testing.
- Destructive tests include chemical, corrosion, metallographic and mechanical tests.
- In this lecture, chemical, corrosion, metallographic, and some of the mechanical tests (tensile and flexural tests) have been discussed.
- Destructive tests like tensile and bend tests are also used for quality control of weldments.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 04: Destructive Inspection-II



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Classification of Destructive Testing:

Destructive Testing

Chemical Test

Corrosion Test

Metallographic Test

Mechanical Test

Qualitative Analysis

Quantitative Analysis

Tensile & Bend Test

Hardness Test

Impact Test

Fracture Toughness Test

Fatigue & Creep Test

Nick-break Test

Discussed in
lecture 03.

Will discuss in
this lecture.



3. Hardness Tests:

- Hardness is the ability of a material to resist indentation or penetration, to resist abrasive wear when a compressive force is applied.
- The ease with which the hardness test can be made has made it the most common method of inspection for metals and alloys.
- The principal purpose of the hardness test is to determine the suitability of a material for a given application, or the particular treatment to which the material has been subjected.

Classification of Hardness Tests (on the basis of amount of load applied):

- Depending upon the amount of load applied through indenter, hardness testing practices are divided into two categories: **Macrohardness** and **Microhardness**.

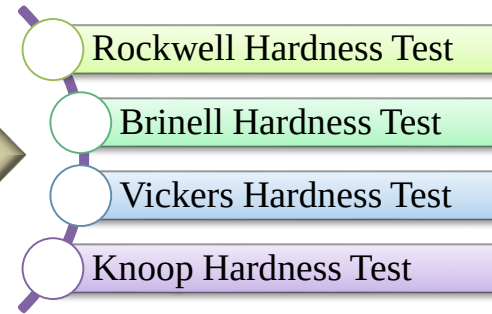
❖ **Macrohardness** - It refers to testing with applied loads on the indenter of more than 1 kg.

For example, the testing of tools, dies, and sheet material in the heavier gages.

❖ **Microhardness** - In microhardness testing, applied loads are 1 kg and below, and material being tested is very thin (down to 0.0125 mm, or 0.0005 in.). Applications include extremely small parts, thin superficially hardened parts, plated surfaces, and individual constituents of materials.

Classification of Hardness Tests (on the basis of type of indenter used):

On the basis of type and size of the indenter, four most widely used scales for hardness measurement are:



a) Rockwell Hardness Tests:

- The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills.
- The determination of the Rockwell hardness of a material involves the application of a minor load (F_0) followed by a major load (F_1).
- Indenters include:
 - ✓ *Spherical and hardened steel balls having diameters of $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ in.*
 - ✓ *Conical diamond (Brale) indenter, which is used for the hardest materials.*

- There are two general classifications of the Rockwell test:
 - Rockwell Hardness Test*
 - Rockwell Superficial Hardness test.*
- The significant difference between the two test classifications is in the test forces i.e. minor loads that are used.
- The initial minor load (preliminary test force) F_0 is 10 kg for the Rockwell hardness test and 3 kg for the Rockwell superficial hardness test.

From possible combinations of various indenters and different loads, *several different scales* are derived, which permit the testing of virtually all metal alloys (as well as some polymers).

- When specifying Rockwell and superficial hardness, both hardness number and scale symbol must be indicated.
- The scale is designated by the symbol HR followed by the appropriate scale identification.
- For example:** 80 HRB represents a Rockwell hardness of 80 on the B scale, and 60 HR30W indicates a superficial hardness of 60 on the 30W scale.

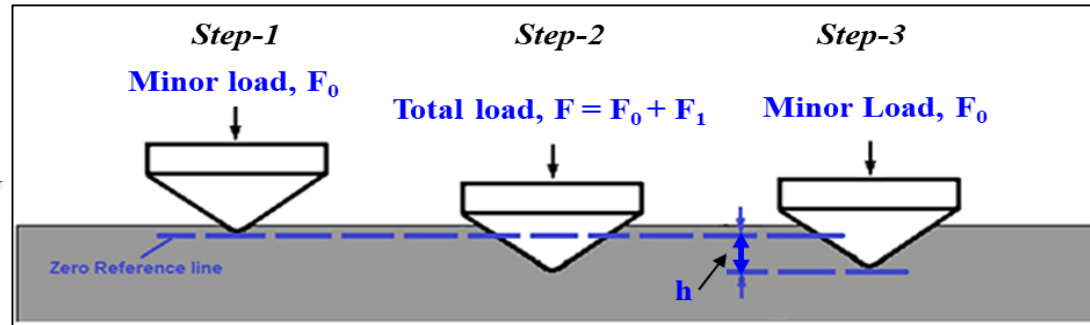
<i>Rockwell Hardness Test</i>		
Scale Symbol	Indenter	Major Load (kg)
A	Diamond	60
B	$\frac{1}{16}$ -in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$ -in. ball	100
F	$\frac{1}{16}$ -in. ball	60
G	$\frac{1}{16}$ -in. ball	150

<i>Rockwell Superficial Hardness Test</i>		
Scale Symbol	Indenter	Major Load (kg)
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$ -in. ball	15
30T	$\frac{1}{16}$ -in. ball	30
45T	$\frac{1}{16}$ -in. ball	45
15W	$\frac{1}{8}$ -in. ball	15

Test Procedure:

- The determination of the Rockwell hardness of a material involves the following procedure:
 - ❖ **Step 1:** The indenter is brought into contact with the test specimen, and the preliminary test force F_0 is applied. After holding the preliminary test force for a specified dwell time, the baseline depth of indentation is measured.
 - ❖ **Step 2:** The force on the indenter is increased at a controlled rate by the additional test force F_1 to achieve the total test force F . The total test force is held for a specified dwell time.
 - ❖ **Step 3:** The additional test force is removed, returning to the preliminary test force. After holding the preliminary test force for a specified dwell time, the final depth of indentation is measured.
- The Rockwell hardness value is derived from the difference h in the final and baseline indentation depths while under the preliminary test force.

h = Distance measurement taken representing difference between preload and major load position.



Calculation of Rockwell Hardness:

- The unit measurement for h is mm. From the value of h , the Rockwell hardness number is calculated as:

✓ *For scales using a diamond spheroconical indenter:*

$$\text{Rockwell Hardness} = 100 - \frac{h}{0.002}$$

$$\text{Rockwell Superficial Hardness} = 100 - \frac{h}{0.001}$$

✓ *For scales using a ball indenter:*

$$\text{Rockwell Hardness} = 130 - \frac{h}{0.002}$$

$$\text{Rockwell Superficial Hardness} = 100 - \frac{h}{0.001}$$

b) Brinell Hardness Tests:

- This test consist of impressing a special hardened steel or tungsten carbide ball into the specimen under test, using a definite load for a definite time and accuracy.
- The load for steel is generally 3000 kg and for softer metals, 500 kg.
- The diameter of the impression is measured by the eye, using a special high power Brinell microscope (graduated in tenth of millimetres).

Test Precautions:

- ✓ The surface to be tested should be flat and scratch free.
- ✓ Impressions should be taken at the representative locations.
- ✓ The load applied must be normal to the surface of the specimen.
- ✓ The test should not be used on the specimen of thickness less than about $\frac{1}{2}$ inch (13 mm).
- ✓ Impressions should not be taken closer than about two diameters from each other, else the cold work caused by the previous impression will produce wrong data.

Test Procedure:

- ❖ **Step 1:** The indenter is brought into contact with the test specimen in a direction perpendicular to the surface, and the test force F is applied. The test force is held for a specified dwell time and then removed.
- ❖ **Step 2:** The diameter of the indentation is measured in at least two directions perpendicular to each other. The Brinell hardness value is derived from the mean of the diameter measurements.

$$\text{Brinell Hardness (HBW)} = \frac{2F_{kgf}}{\pi D(D - \sqrt{D^2 - d^2})}$$

Symbols and Designations:

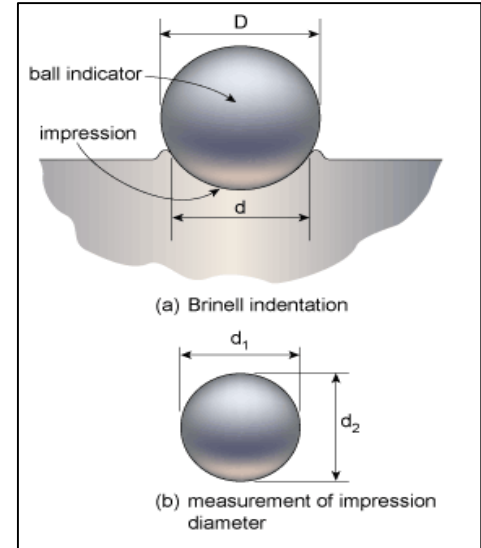
D = Diameter of the ball, mm

d = Average diameter value of the indentation, mm

F = Test force, N

F_{kgf} = Test force, kgf

$F_{kgf} = F/g$, where g is the acceleration due to gravity.



- ❖ Indenters for the Brinell hardness test shall be tungsten carbide balls of four allowed diameters (1, 2.5, 5 and 10 mm).
- ❖ **Brinell Hardness Scales** - The combinations of indenters and test forces define the Brinell hardness scales.
- ❖ Some of the standard Brinell hardness scales are given in the table. ➡

Designation of Brinell Hardness Values:

- Brinell hardness numbers shall be followed by the symbol HBW, and be supplemented by an index indicating the test conditions in the following order:
 - ✓ Diameter of the ball, mm.
 - ✓ A value representing the test force, kgf.
 - ✓ Applied force dwell time, s, if other than 10 s to 15 s.
- For HBW 10/3000 scale with 10 s to 15 s dwell time, Brinell hardness scale designation can be reported simply as HBW.

<i>Brinell Hardness Scales</i>			
Brinell Hardness Scale	Ball Diameter D (mm)	Nominal Value of Test Force F (N)	Nominal Value of Test Force $F_{kgf} = \frac{F}{g}$ (kgf)
HBW 10/3000	10	29420	3000
HBW 10/1500	10	14710	1500
HBW 10/500	10	4903	500
HBW 5/750	5	7355	750
HBW 5/250	5	2452	250
HBW 2.5/187.5	2.5	1839	187.5
HBW 1/10	1	98.07	10

Examples:

220 HBW = Brinell hardness of 220 determined with a ball of 10 mm diameter and with a test force of 29.42 kN (3000 kgf) applied for 10 s to 15 s.

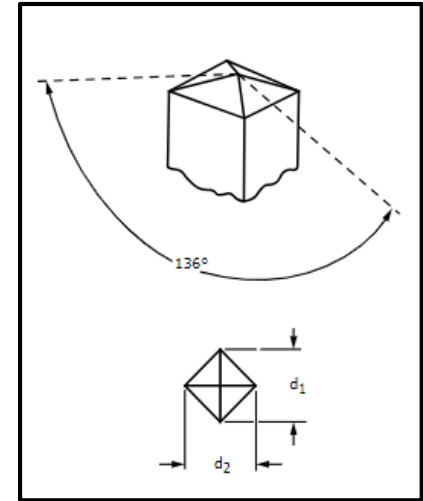
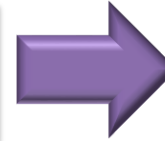
600 HBW 1/30/20 = Brinell hardness of 600 determined with a ball of 1 mm diameter and with a test force of 294.2 N (30 kgf) applied for 20 s.

c & d) Knoop and Vickers Microindentation Hardness Tests:

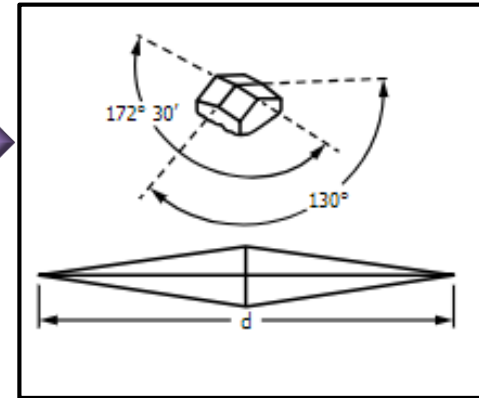
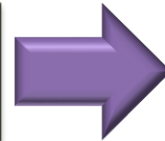
- Two other hardness-testing techniques are Knoop and Vickers (*sometimes also called diamond pyramid*).
- For each test a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen.
- Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000 g.
- The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number.
- Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be accurately measured.
- The Knoop and Vickers hardness numbers are designated by HK and HV, respectively, and hardness scales for both techniques are approximately equivalent.
- Knoop and Vickers are referred to as microindentation-testing methods on the basis of indenter size.
- Both are well suited for measuring the hardness of small, selected specimen regions; furthermore, Knoop is used for testing brittle materials such as ceramics.



Vickers indenter: Square-based pyramidal diamond with face angles of 136° .



Knoop Indenter: Rhombic-based, pyramidal diamond with longitudinal edge angles of 172.5° and 130° .



Test Procedure:

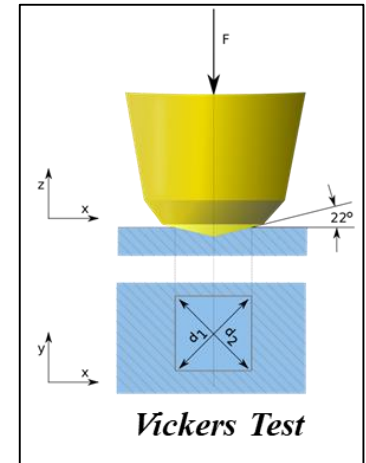
- ❖ **Step 1:** The applicable specified indenter is brought into contact with the test specimen in a direction normal to the surface, and the test force F is applied. The test force is held for a specified dwell time and then removed.
- ❖ **Step 2:**
 - **For the Vickers hardness test**, the lengths of the two diagonals are measured and the mean diagonal length is calculated, which is used to derive the Vickers hardness value.
 - **For the Knoop hardness test**, the length of the long diagonal is measured, which is used to derive the Knoop hardness value.

Calculation of Vickers hardness value:

$$HV = 1.8544 \times \frac{F_{(kgf)}}{d_v^2}$$

$F_{(kgf)}$ = Test force (kgf).

d_v = mean Vickers indentation diagonal length (mm).

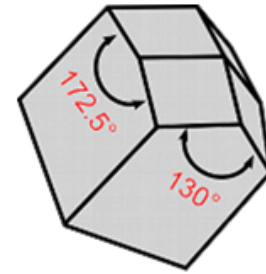


Calculation of Knoop hardness value:

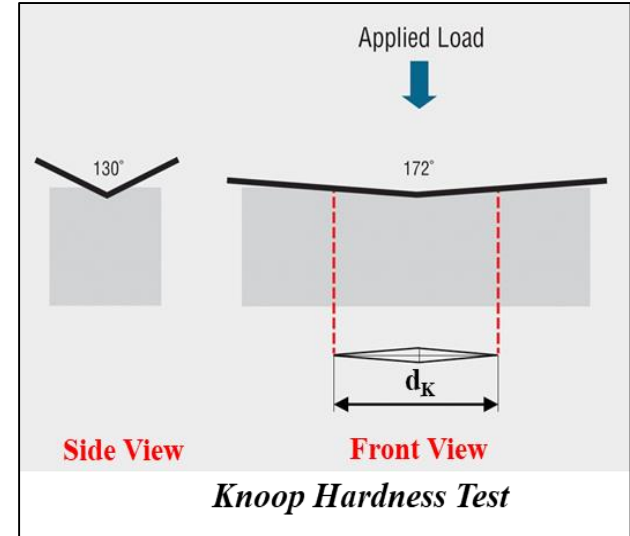
$$HK = 14.229 \times \frac{F_{(kgf)}}{d_K^2}$$

$F_{(kgf)}$ = Test force (kgf).

d_K = Knoop indentation long diagonal length (mm).



Indenter



Knoop Hardness Test

4. Impact Tests:

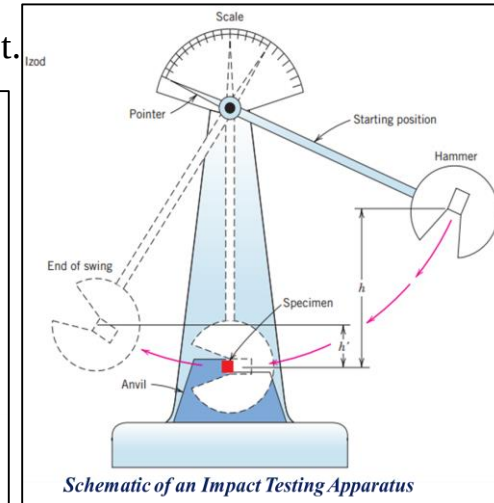
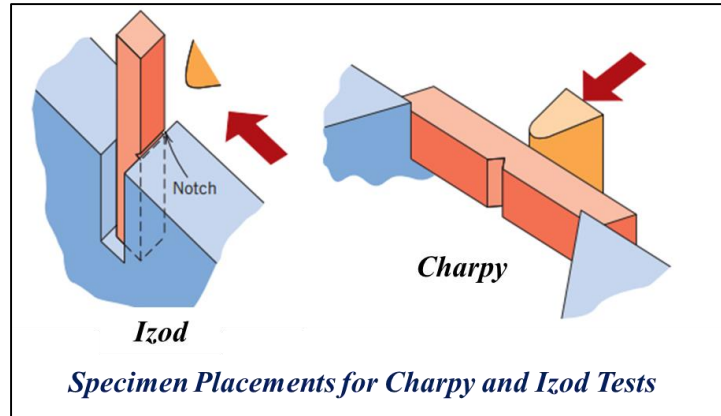
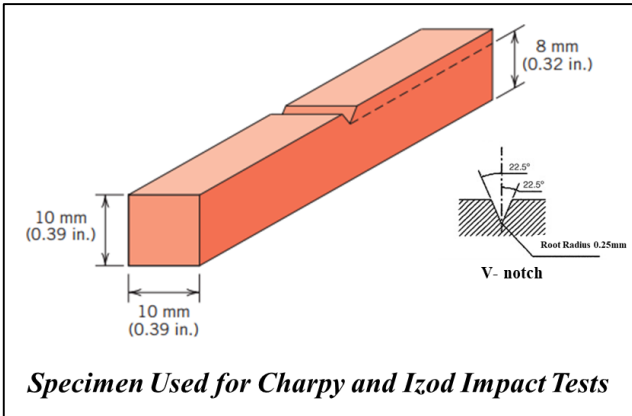
- Prior to the advent of fracture mechanics as a scientific discipline, impact testing techniques were established so as to ascertain the fracture characteristics of materials.
- Impact testing determines the relative toughness of a material, where toughness is defined as the resistance of a metal to fracture after plastic deformation has begun.
- In an impact test, this plastic deformation is begun and finished by swing of a weighted pendulum which strikes the test piece as it swings through its path along an arc.
- The energy that is required to fracture the test piece is recorded in Joules on the scale.
- Two major tests for determining impact toughness are:

Izod Test

Charpy Test

Charpy and Izod Test:

- The Charpy and Izod, are used to measure the impact energy, sometimes also termed notch toughness.
- For both Charpy and Izod, the specimen is in the shape of a bar of square cross section, into which a V-notch is machined.
- In Izod impact test, the specimen is supported as a cantilever beam.
- In Charpy impact test, the specimen is supported as a simple beam with load applied at the center.
- The notch in Izod test specimen is off the centre to facilitate holding in vice whereas the notch is in the centre of the specimen for charpy test.
- V- notch in Izod specimen faces the load whereas it is opposite to loading in Charpy test.



Charpy and Izod Test Procedure:

It comprises of following steps:

- i. Lift the hammer to an appropriate knife edge position and note the energy stored in the hammer.
- ii. Locate the test specimen on the machine supports.
- iii. Release the hammer from a fixed height h . The hammer will break the piece and shoot up the other side of the specimen.
- iv. Note the residual energy indicated on the scale by the hammer.
- v. Impact strength of the test specimen is the difference of the initial energy stored in hammer and the residual energy.

5. Fracture Toughness Tests:

- Fracture toughness is defined as fracture resistance of a material in the presence of cracks.
- It is used to refer the fractures as either ductile or brittle.
- Fracture toughness study of brittle materials is now fairly well established by Linear Elastic Fracture Mechanics (LEFM) and critical crack lengths for given stress condition.
- In LEFM the critical value of stress intensity factor (K) is referred to as the fracture toughness.
- The corresponding fracture toughness value for the materials of elastic-plastic region is referred to as J_c , which is a measurement of the energy required to grow a thin crack.

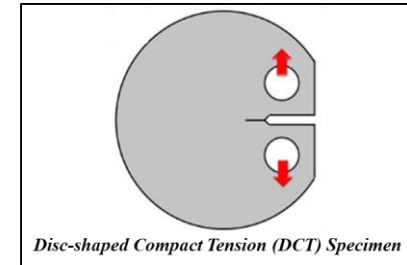
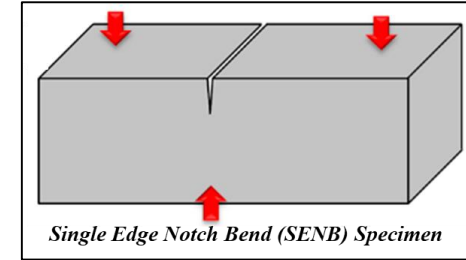
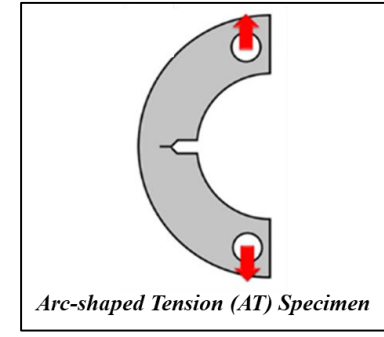
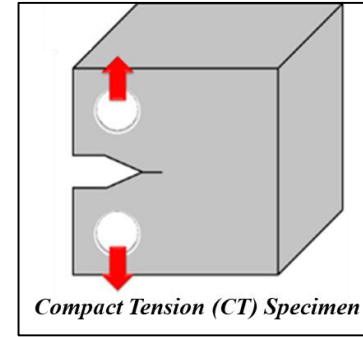
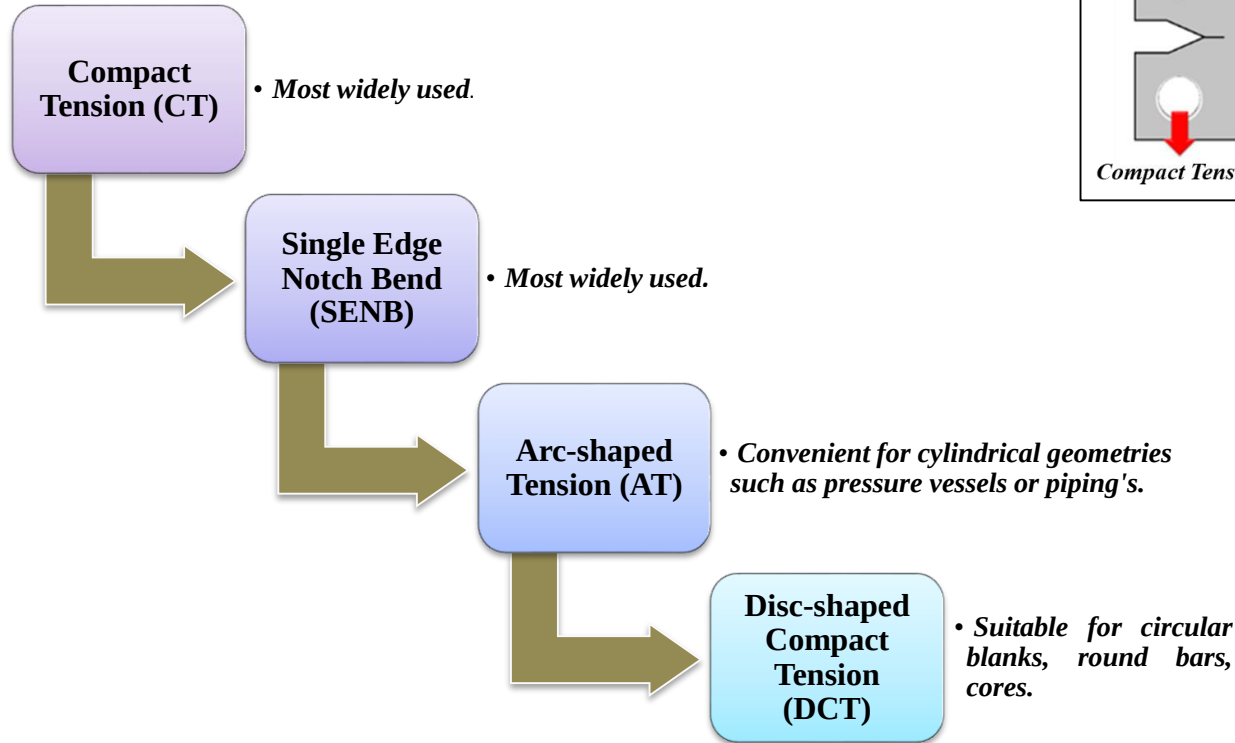
K_{Ic} - Test Technique:

- Experimental determination of the critical stress intensity factor (K_{Ic}) is most widely studied and developed.
- The critical stress intensity factor of a material depends on the thickness of the plate. However for a thick plate it is independent of the thickness because the material in front of crack tip deforms in plane strain.
- The experiment should be controlled so as to have its loading in plain strain only.



Various Test Specimens:

❖ Four kinds of test specimens commonly used are:



K_{Ic} - Test Procedure:

- i. To begin with, K_{Ic} of the specimen is guessed.
- ii. Then, the specimen is prepared following several dimensional constraints which are based on the guessed value of K_{Ic} .
- iii. The crack tip is made very sharp with a fatigue growth.
- iv. The specimen is pulled in a tensile machine to obtain a relation between the load and the crack mouth opening displacement. This relation provides the critical load P_Q .
- v. Accounting for the crack length and geometry of specimen, the stress intensity factor K_Q corresponding to P_Q is determined using LEFM.
- vi. If K_Q satisfies all constraints on the geometry of the specimen and of fatigue growth, it becomes K_{Ic} .

➤ Other more popularly employed test methods for to determine the fracture toughness values for the elastic-plastic region are:

- a) ***Charpy V-notch (C_v) Test,***
- b) ***Drop Weight Nil-ductility Temperature (NDT) Test,***
- c) ***The Dynamite Tear (DT) Test,***
- d) ***Crack Tip Opening Displacement (CTOD) Test.***

➤ C_v and NDT test are ASTM standard methods, while DT test is a military standard and CTOD is a British standard test.



6. Fatigue Tests:

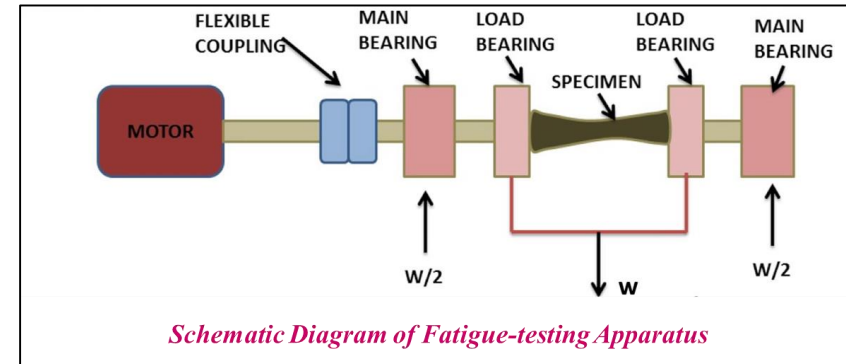
- Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components).
- Components subjected to repeated cyclic stress have a tendency to break at a stress considerably below their ultimate tensile strength.
- *The term “fatigue” is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling.*
- Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure.
- The stress under which such a failure takes place is called fatigue strength and the number of cycles after which failure occurs with the given conditions is called as fatigue life.
- Fatigue tests are designed to measure the effect of cyclic stress loading on the welded joint.
- Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning.



- The process of fatigue consists of three stages:
 1. **Crack Initiation** - Initial fatigue damage leading to crack nucleation and crack initiation.
 2. **Crack Propagation** - Progressive cyclic growth of a crack (crack propagation) until the remaining uncracked cross section of a part becomes too weak to sustain the loads imposed.
 3. **Fracture** - Final, sudden fracture of the remaining cross section.

Fatigue Test Procedure:

- i. To perform a fatigue test a sample is loaded into a fatigue tester or fatigue test machine.
- ii. The specimen is first subjected to the pre-determined test stress, then unloaded to either zero load or an opposite load. The applied stress may be axial, flexural, or torsional in nature.
- iii. This cycle of loading and unloading is then repeated until the end of the test is reached. The test may be run to a pre-determined number of cycles or until the sample has failed depending on the parameters of the test.



Modes of Fluctuating Stress Cycles:

❖ Several parameters used to characterize the fluctuating stress cycle.

- **Mean Stress:** It is the average of the maximum and minimum stresses in the cycle.

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

- **Range of Stress:** It is the difference between σ_{max} and σ_{min} .

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

- **Stress Amplitude:** It is the half of the range of stress.

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

- **Stress Ratio:** The stress ratio R is just the ratio of minimum and maximum stress amplitudes.

$$\sigma_R = \frac{\sigma_{min}}{\sigma_{max}}$$

❖ *In general, three different fluctuating stress–time modes are possible.*

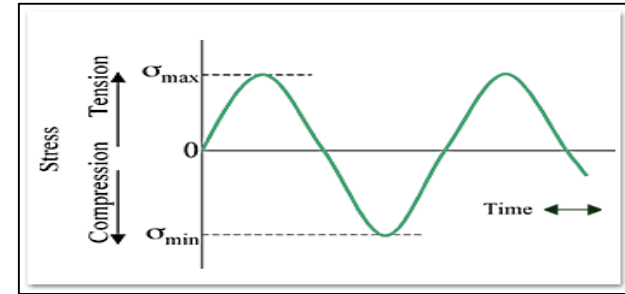
Reversed
Stress Cycle

Repeated
Stress Cycle

Random
Stress Cycle

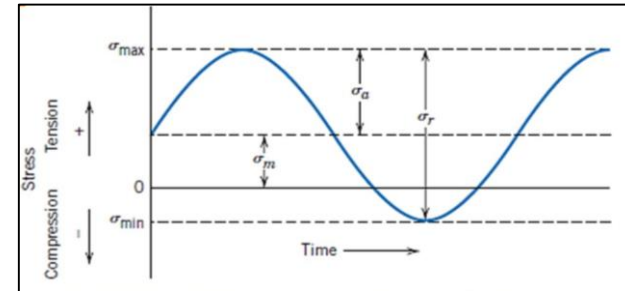
Reversed Stress Cycle:

- In this fatigue loading, the stress alternates from a maximum tensile stress (+) to a maximum compressive stress of equal magnitude.



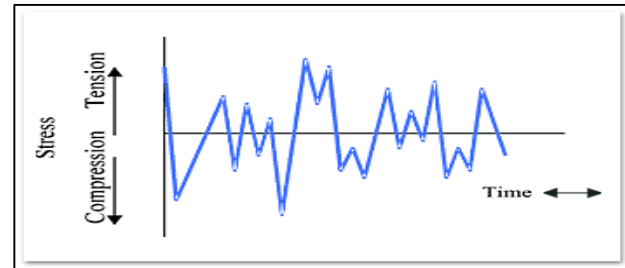
Repeated Stress Cycle:

- In this stress cycle, maximum and minimum stresses are asymmetrical relative to the zero-stress level.



Random Stress Cycle:

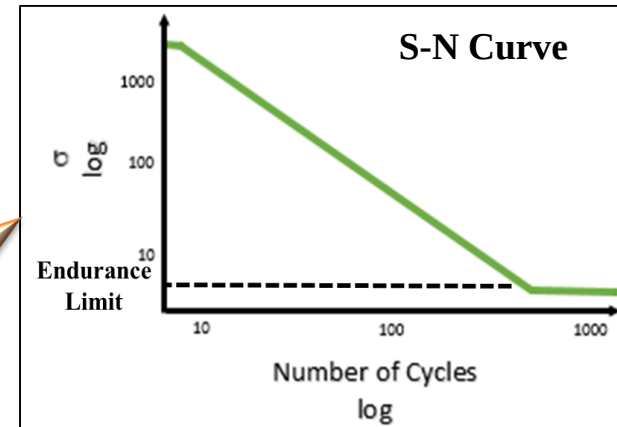
- In this stress cycle, no regular loading pattern is observed.



S-N Curve:

- A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude and the number of cycles to failure is counted.
- This procedure is repeated on other specimens at progressively decreasing maximum stress amplitudes.
- Data are plotted as stress S versus the logarithm of the number N of cycles to failure for each of the specimens.
- The values of S are normally taken as stress amplitudes (σ_a); on occasion, σ_{max} or σ_{min} values may be used.

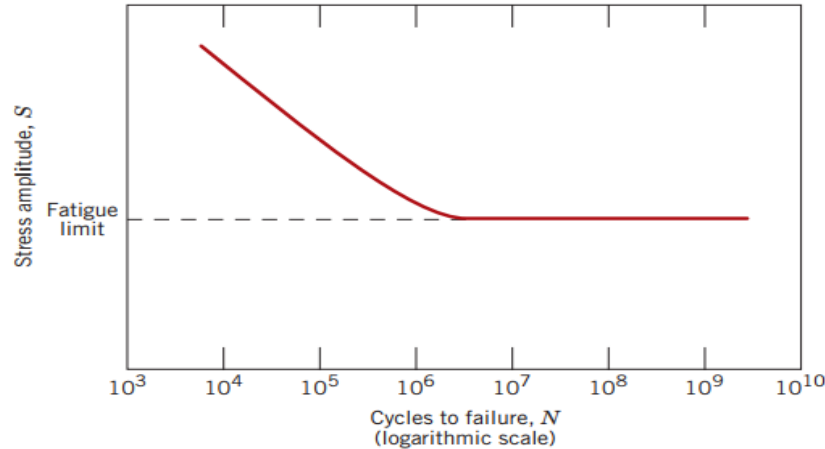
- ❑ The typical curve or S-N line shows that the fatigue strength, i.e. the stress at which the metal fail, drops as the number of stress cycles increases. The greater the number of cycles, lower the fatigue strength.
- ❑ It also shows that, below a certain level of stress material does not fail by cracking, no matter how many stress cycles is loaded. This is called as endurance limit of the material.



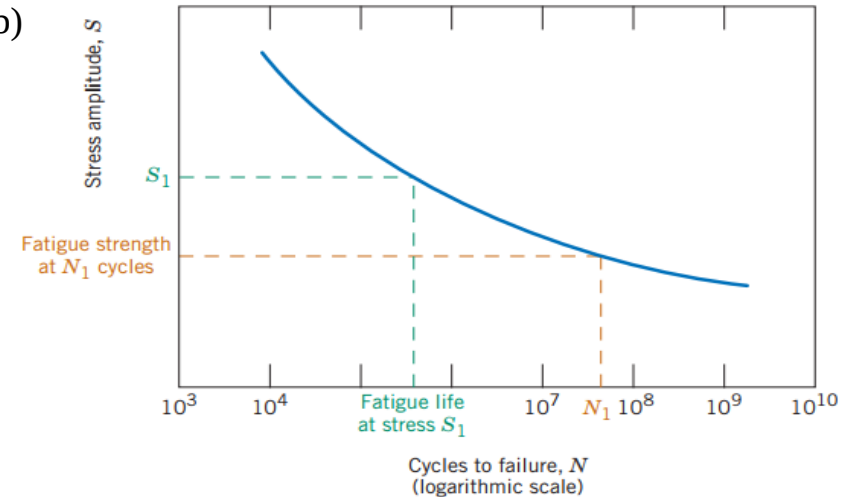
Two distinct types of S–N behaviour are observed with engineering materials:

- (a) A material that displays a fatigue limit, and
- (b) A material that does not display a fatigue limit.

(a)



(b)



Stress amplitude (S) versus logarithm of the number of cycles to fatigue failure (N) for different materials

7. Creep Rupture Tests:

- The gradual elongation or plastic deformation at higher temperature is called Creep, while the eventual fracture is called Rupture.
- Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses (e.g., turbine rotors in jet engines and steam generators that experience centrifugal stresses, and high-pressure steam lines).

Creep Test Procedure:

- ❖ A typical creep test consists of following two steps:
 - i. Subject a specimen to a constant load or stress while maintaining the temperature constant.
 - ii. Measure the deformation or strain and plot it as a function of elapsed time.
- ❖ Most tests are the constant load type, as constant stress provide a better understanding of the mechanisms of creep.



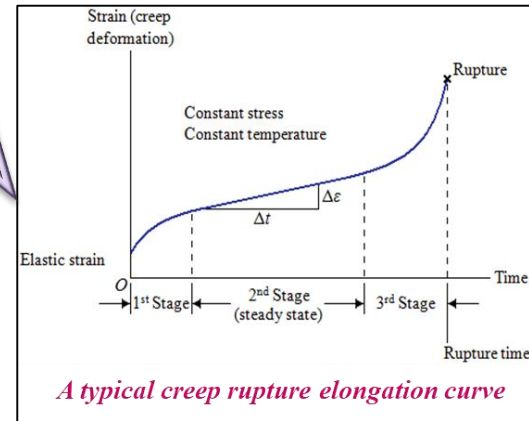
Additional Information of Creep Rupture Tests:

- The test specimen used to determine creep rupture strength is similar to that used for the already described tension tests
- The test is conducted in an appropriate furnace and load is generally applied in the form of constant dead weights.
- Elongation can be monitored by the help of some attachments like extensometers or LVDT.
- The creep test is monitored up to a predetermined time and elongation is measured in this time period.
- In rupture test, the test is carried out up to the failure of the specimen.
- Creep and rupture data are most often reported as log-log plots of stress versus time to attain a specific percentage creep elongation or time to rupture at a constant temperature.

Creep Rupture Elongation Curve:

A typical creep curve shows three distinct stages with different creep rates.

- ❖ **Stage 1:** On initial application of load, the creep rate is high and decreasing with time. This is first stage creep or primary creep.
- ❖ **Stage 2:** The second stage of have minimum creep rate and the period is maximum in creep.
- ❖ **Stage 3:** In the third stage, the creep rate is again increased and results as necking.

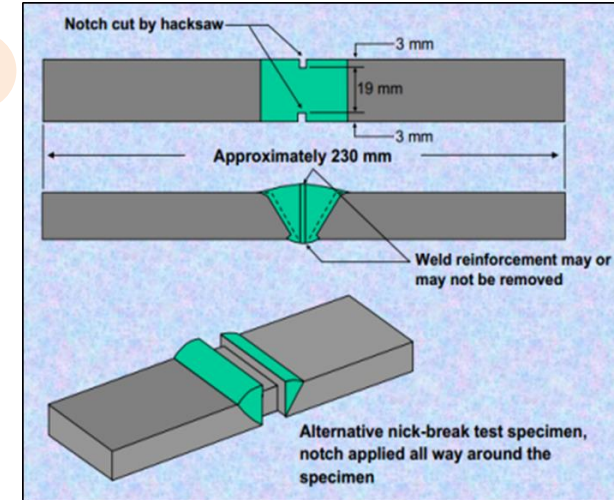


8. Nick-Break Tests:

- A nick break test is a type of destructive testing that is used to evaluate the quality of a weld.
- This test shows up any centreline defects, such as lack of fusion, gas pockets, slag inclusion, incomplete penetration and the degree of porosity in the weld bead.
- Fillet welds may be similarly tested by notching and bending. One requirement of the fillet nick-break test is that there should be no tack welds on the other side of fillet weld.

Nick-Break Test Procedure:

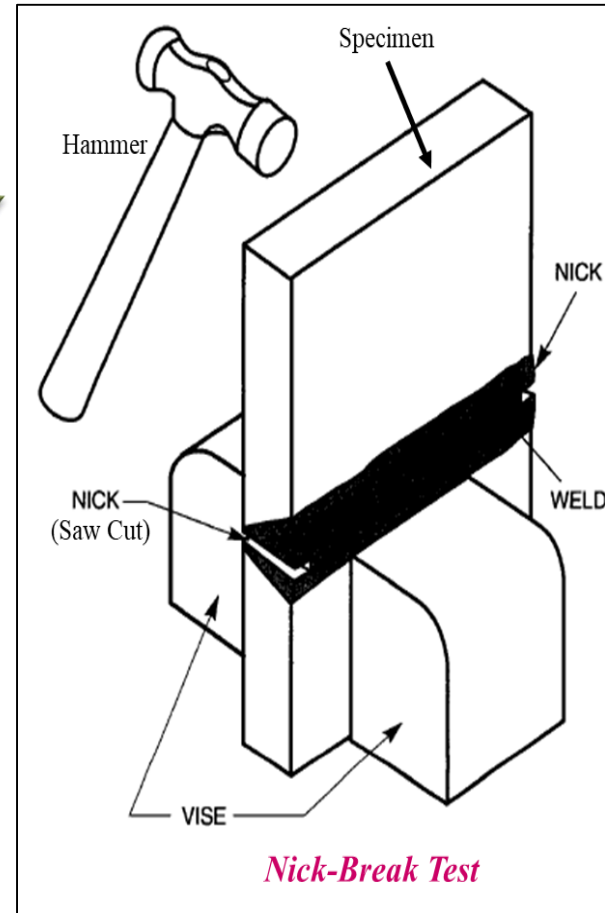
- To perform a nick break test, a specimen is prepared out of the weld metal.
- An artificial notch or a groove (act as stress concentrator) is intentionally introduced by a hacksaw or a cutting disc on the weld face, along the primary axis of the weld.
- The specimen is then broken and the fracture surface is observed at the conclusion of the nick break test.



Nick Break Test Specimen

Example of Nick-Break Testing of Fusion Weld:

- Cut a strip about 20 mm wide at right angle to the weld axis.
- Make a saw cut down the centre line of the weld 3 to 6 mm deep.
- By holding one-half of specimen in a vice and giving the other half a sharp blow with hammer or by bending in a machine, the weld is broken.



Summary:

- ❖ Mechanical testing techniques e.g. hardness tests, impact tests, fracture toughness tests, fatigue tests, creep tests, and nick-break test have been discussed.
- ❖ The ease with which the hardness test can be made has made it the most common method of inspection for metals and alloys.
- ❖ Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses, which requires to understand their creep behaviour.
- ❖ Nick-break test of weldment is performed to detect centreline defects, such as lack of fusion, gas pockets, slag inclusion, incomplete penetration and the degree of porosity in the weld bead.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 05: Testing of Composite Materials



Dr. Kaushik Pal

Associate Professor

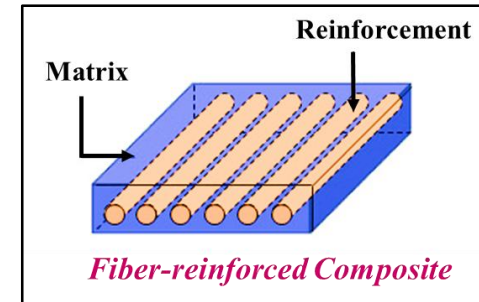
Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



What are Composite Materials?

- Composite materials are multiphase materials (with measurable fraction of every phase), obtained by artificial combination of different materials, so as to attain properties that the individual components by themselves cannot attain.
 - Composite materials are not the by-product of any chemical reaction between two or more of its constituents.
-
- There are two major components in a composite:
 - Reinforcement (Discontinuous/dispersed phase):
 - Material that provide strength to the matrix.
 - Matrix (Continuous phase):
 - Material that holds the reinforcement in place.



Role of Matrix and Reinforcing Phases:

Matrix: In a composite material, the matrix material serves the following functions:

- Holds the fibres together.
- Protects the fibres from environment.
- Distributes the loads evenly between fibres so that all fibres are subjected to the same amount of strain.
- Helps to avoid propagation of crack growth through the fibres by providing alternate failure path along the interface between the fibres and the matrix.
- Enhances transverse properties of a laminate.
- **Classification of Matrix Material:** Metal, Polymer, Ceramic.

Reinforcement:

- The role of the reinforcement is to strengthen and stiffen the composite through prevention of matrix deformation by mechanical restraint.
- **Classification of Reinforcement:** Particles, Fibers (including whiskers).



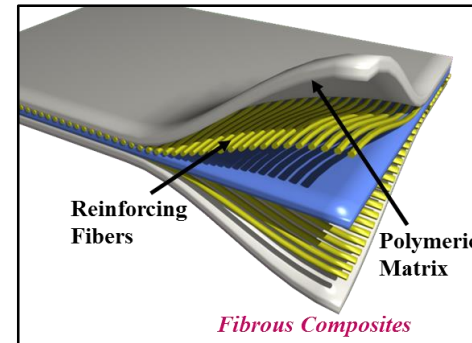
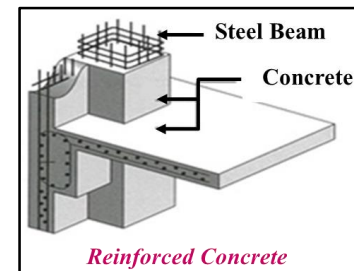
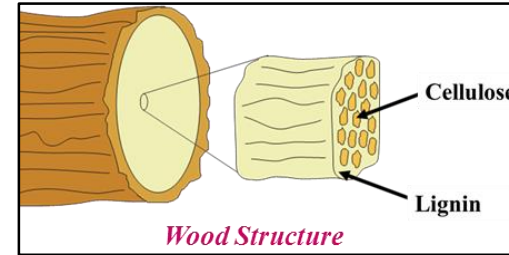
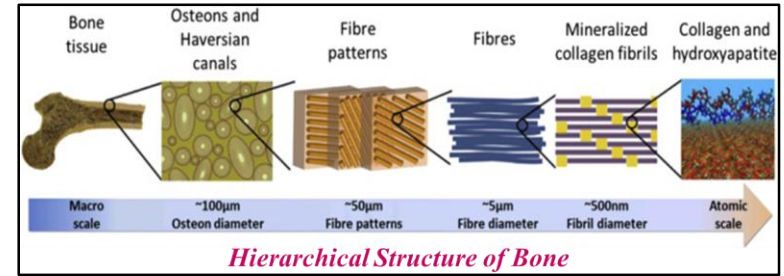
Examples:

❖ Naturally Occurring Composites:

- ✓ **Bone:** Collagen fibers embedded in hydroxyapatite matrix.
- ✓ **Wood:** Cellulose fibers held together by lignin matrix.

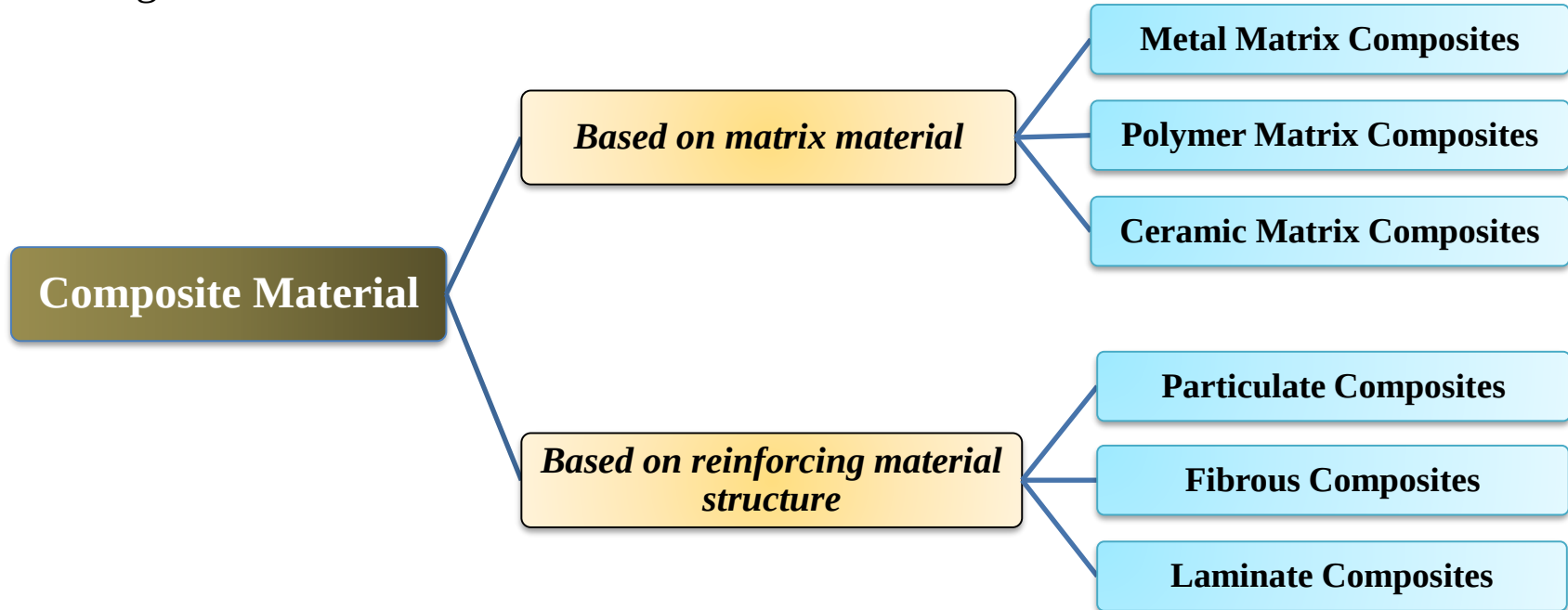
❖ Man-made Composites:

- ✓ **Reinforced Concrete:** Steel reinforcing bars embedded in the concrete.
- ✓ **Fibrous Composites:** Variety of fibers (glass, Kevlar, carbon, nylon, etc.) bound together by a polymeric matrix.
- ✓ **Cermets:** Composite material composed of ceramic and metal materials.



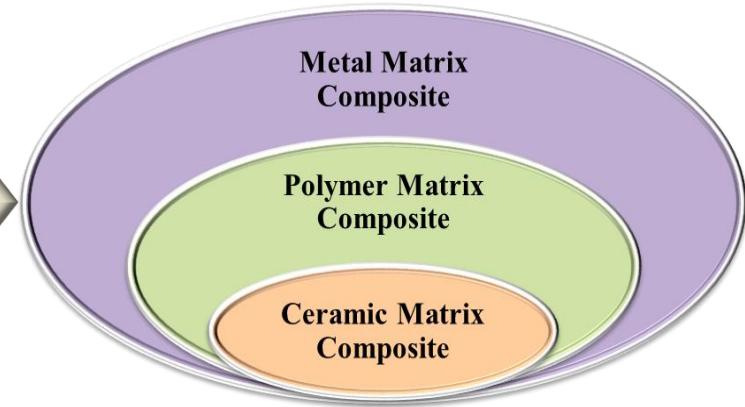
Classification of Composite Materials:

The composite materials are commonly classified based on the type of matrix material or reinforcing material structure.



Classification based on Matrix Material:

Based on the type of matrix material used to fabricate the composites, they can be divided into three categories:

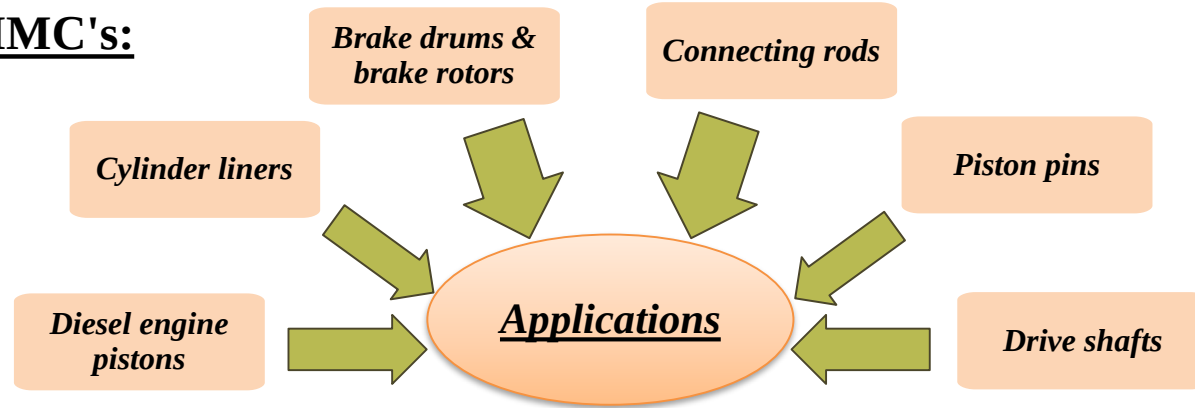


1) Metal Matrix Composites:

- They consist of fibers or particles surrounded by a metallic matrix.
 - Most metals and alloys can be used as matrices and they require reinforcement materials to be stable over a range of temperature and should be non-reactive too.
 - Processing of a metal-matrix composite tends to be much more expensive than that of a polymer-matrix composite due to the high processing temperature required.
- Most common constituent materials used in this category are:
 - ✓ **Matrix Material:** Al, Be, Mg, Ti, Fe, Ni, Co, and Ag
 - ✓ **Reinforcement Material:** SiC, Al₂O₃, B₄C, TiC, TiB₂, W, steel fibers, graphite, and a number of other ceramics.

Factors Affecting Properties of MMC's:

- ✓ Type of metallic matrix.
- ✓ Reinforcement material.
- ✓ Reinforcement morphology.
- ✓ Reinforcement volume fraction.
- ✓ Orientation.
- ✓ Matrix alloy composition.
- ✓ Heat treatment.

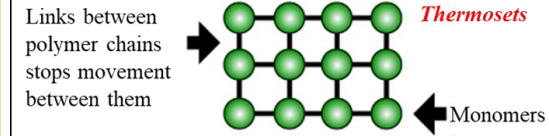


2) Polymer Matrix Composites:

- Polymer matrix composite (PMC) is composed of a variety of short or continuous fibers bound together by an organic polymer matrix.
- They are very popular due to their low cost and simple fabrication methods.
- Based upon the type of polymer matrix, they can be further classified into two parts:

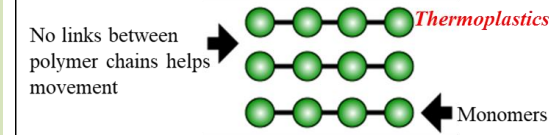
Thermoset Composites:

- Thermoset polymers are used as matrix material, which once cured into a solid form, cannot be returned to their original uncured form.
- **Examples of thermosets:** Polyester, polyurethanes, epoxy.



Thermoplastic Composites:

- Thermoplastic polymers, which can be moulded, melted and remoulded without altering their physical properties, are used as matrix.
- **Examples of thermoplastics:** Polyethylene, polypropylene, polyvinyl chloride.



Applications:

- Aerospace and military aircraft.
- Automotive industry.
- Construction.
- Medical devices.



Airless Tyre
(glass fiber/PET composite)



Inlet manifold
(polyamide composite reinforced by
Al-Cu-Fe-B quasicrystals)

Drawbacks:

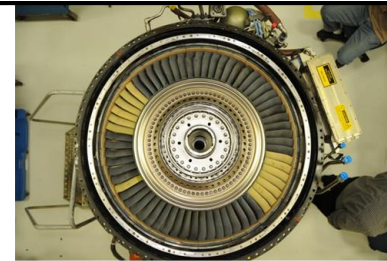
- Environmental degradation.
- Moisture absorption from environment causes swelling in the polymer as well as a decrease of T_g .
- The moisture absorption increases at moderately high temperatures. These hydrothermal effects can lead to internal stresses in the presence of fibres in polymer composites.
- A thermal mismatch between polymer and fibre may cause cracking or debonding at the interface.

3) Ceramic Matrix Composites:

- These materials are those in which one or more distinct ceramic phases are intentionally added to another, in order to enhance some property that is not possessed by the monolithic ceramic materials.
- Basic reinforcements which are included in the ceramic matrices are: *carbon, glasses, glass-ceramics, oxides and non-oxides*.
- Ceramic matrix composites overcome the major *demerits (such as brittle failure, low fracture toughness and limited thermal shock resistance)* of monolithic ceramics.
- Processing temperature for CMCs is extremely high compared to polymer or metal matrix composites which leads to a very difficult and expensive processing.

Applications:

- ✓ Heat shield systems for space vehicles.
- ✓ Components for high temperature gas turbines.
- ✓ Brake disks and break system components.
- ✓ Slide bearings components.



Turbine rotor with blades made from CMCs



Engine nozzle made from CMCs

Classification based on Reinforcing Material Structure:

- There are different types of reinforcements that go into the composite material e.g. fibers, particulate, whiskers and layers.

On the basis of the structure of the reinforcing material, composites can be broadly classified into three parts:

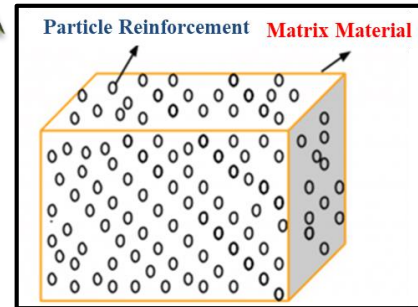
Particulate Composites

Fibrous Composites

Laminate Composites

1) Particulate Composites:

- Particulate Composites consist of a matrix reinforced by a dispersed phase in form of particles.
- Particulate composite are generally used to enhance performance at high temperature.
- Particulate composite are not very fracture resistance unlike fibrous composites.
- Particles tend to increase the stiffness of material but do not have so much influence on composite's strength.



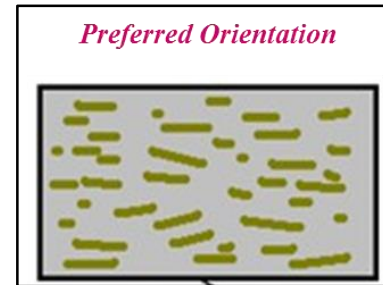
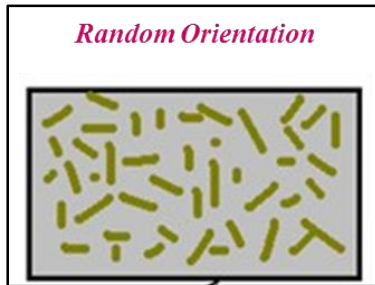
❖ Particulate composites can be further classified into two parts on the basis of orientation of particles.

a) **Composites with random orientation of particles:**

✓ Orientation of particle is randomly distributed in all directions (Example: concrete).

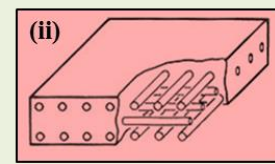
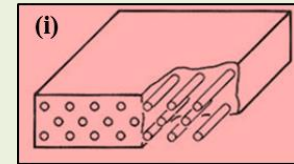
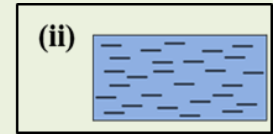
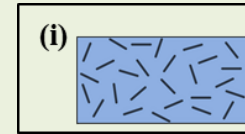
b) **Composites with preferred orientation of particles:**

✓ Particle orientation is aligned to specific directions (Example: extruded plastics with reinforcement particles).



2) Fibrous Composites:

- They have fibres of reinforcing materials suspended in binding matrix.
- Unlike particles, a fibre has high length to diameter ratio and further its diameter may be close to its crystal size.
- These reinforcing phases may have random orientation where they are randomly distributed in all direction or may have preferred orientation where these are aligned to a specific direction.
- On the basis of fiber length, they can be further classified as:
 - a) Short-fiber Reinforced Composites:** They consist of a matrix reinforced by a dispersed phase in form of discontinuous fibers (length $< 100 \times$ diameter).
 - i. Composites with Random Orientation of Fibers.*
 - ii. Composites with Preferred Orientation of Fibers.*
 - b) Long-fiber Reinforced Composites:** They consist of a matrix reinforced by a dispersed phase in form of continuous fibers.
 - i. Unidirectional Orientation of Fibers.*
 - ii. Bidirectional Orientation of Fibers.*

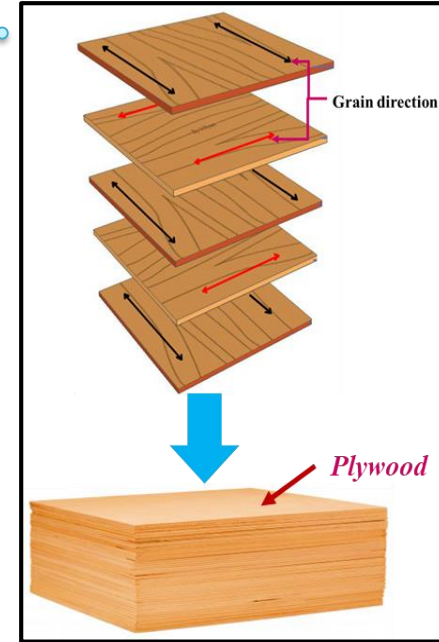


3) Laminar Composites:

- A laminar composite is composed of several two dimensional sheets/layers with different fiber orientations cemented together.

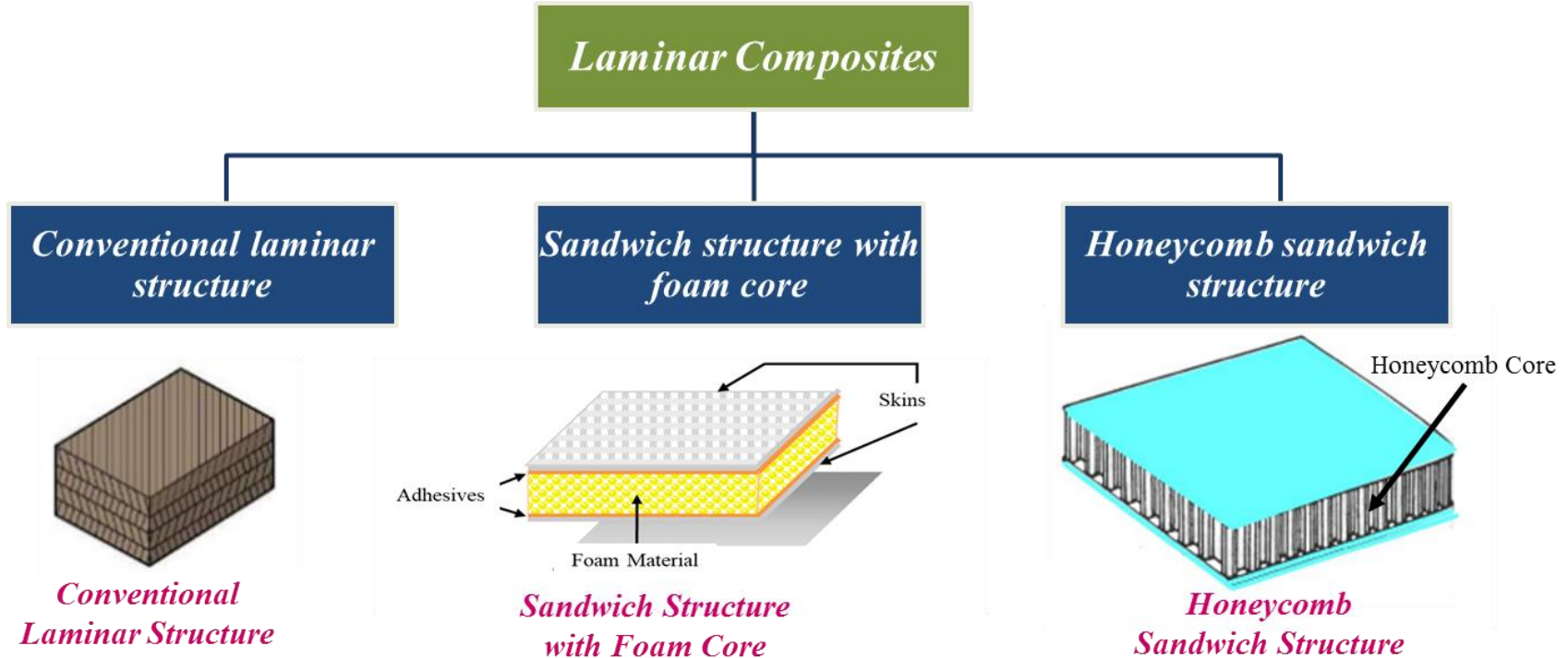
Example: Adjacent wood sheets in plywood are aligned with the grain direction at right angles to each other.

- A laminar composite has relatively high strength in a number of directions in the two-dimensional plane.
- However, the strength in any given direction is, of course, lower than it would be if all the fibers were oriented in that direction.
- A laminar composite often uses different materials in its layers to gain the advantage of combining the particular properties of each.



Types of Laminar Composites:

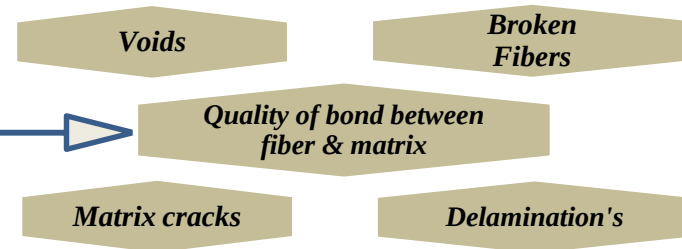
- There are three types of laminar composites generally found:



Testing of Composite Materials:

- Testing of material has got very much importance as it gives the required physical, mechanical and other properties for the use of that material in given application.
- The quality assessment of the composites used in the specimens to be tested must be done prior to the testing whenever possible.
- If the composite used in the specimens is of low quality with defects then the property measured are spurious.
- It can mislead the design and analysis procedure and result in a premature and catastrophic failure of the structure.
- Hence, the quality assessment of composites before it is used in specimen or actual structure fabrication is essential.

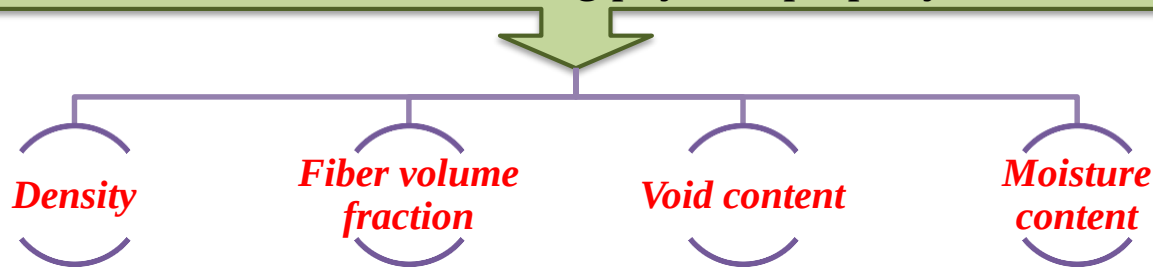
The following quality assessment in composites is essential:



Physical Characterization of Composite Materials:

- Physical characterization is determination of all the physical properties of a given material such as density, fiber volume fraction, void content, coefficient of thermal expansion, heat conduction coefficients, moisture content, etc.
- Physical properties of the composite play an important role in the measured mechanical properties.
- There is a direct dependence of mechanical properties on the physical properties.
 - For example, the mechanical properties are directly dependent on fibre volume fractions.

Here, we will consider the following physical property measurements:

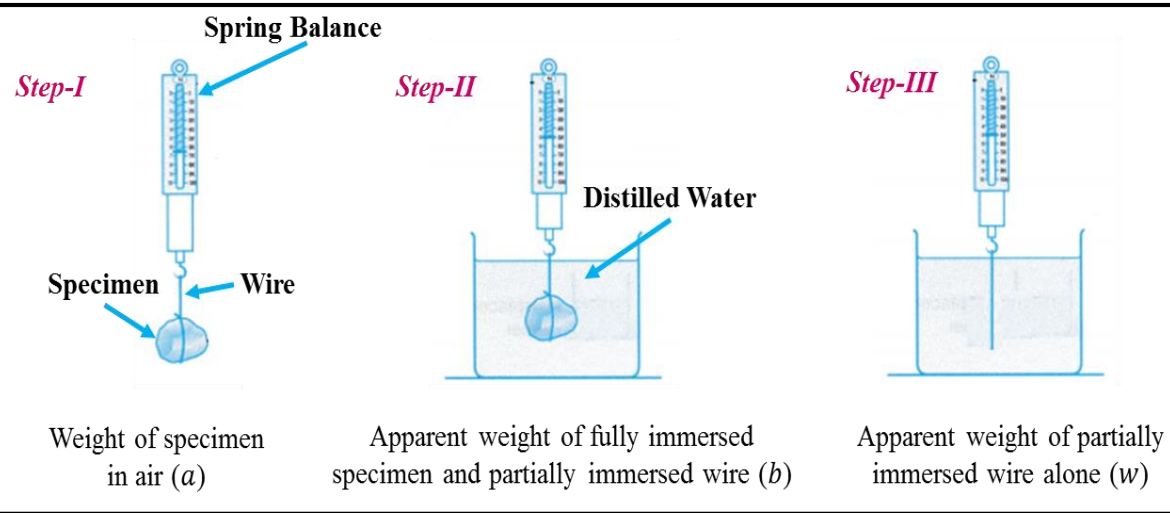


❖ Density:

- A material's density is defined as mass of the material per unit of its volume.
- It is basically a measurement of the degree of compactness of a substance.
- One of the most common use of density is in how different materials interact when mixed together. For example:
 - a) Wood floats in water because it has a lower density.
 - b) Anchor sinks in water because the metal has higher density.
 - c) Helium balloons float in air because the density of helium is lower than the air.
- The procedure for measuring the density of a composite material is same as that used for any other solid and is based on ASTM specification D792-86.

Test Procedure:

- The procedure consists of the following steps:
 - Weigh specimen in air to the nearest 0.1 mg.
 - Attach specimen to analytical balance with a thin wire and weigh while the specimen and portion of the wire are immersed in distilled water.
 - Weigh wire alone, partially immersed up to the same point as in the previous step.



- The density of material at 23°C can be calculated as follows:

$$\rho = \frac{a}{a + w - b} \times (0.9975)$$

ρ = density, (in g/cm³)

a = weight of specimen in air,

b = apparent weight of fully immersed specimen and partially immersed wire,

w = apparent weight of partially immersed wire alone,

Density of distilled water at 23 °C (in g/cm³) = 0.9975 g/cm³

❖ Fiber Volume Fraction:

- It is the percentage of fiber volume in the entire volume of a fiber reinforced composite material.
- A variety of methods exists for determination of fiber volume fraction, an important property of a composite.
- Generally, fiber volume fraction ranges from 30% to 65%. The lower end depend upon the significance of property contribution of the fibers whereas the upper depends upon the effective, defect-free packing.

Methods to Determine Fiber Volume Fractions:

- There are four main methods to determine fiber volume fraction present in a composite:
 1. Acid Digestion Method.
 2. Optical Microscopy method.
 3. Resin Burning-off Method.
 4. Gravimetric Relation Method.

1. Acid Digestion Method:

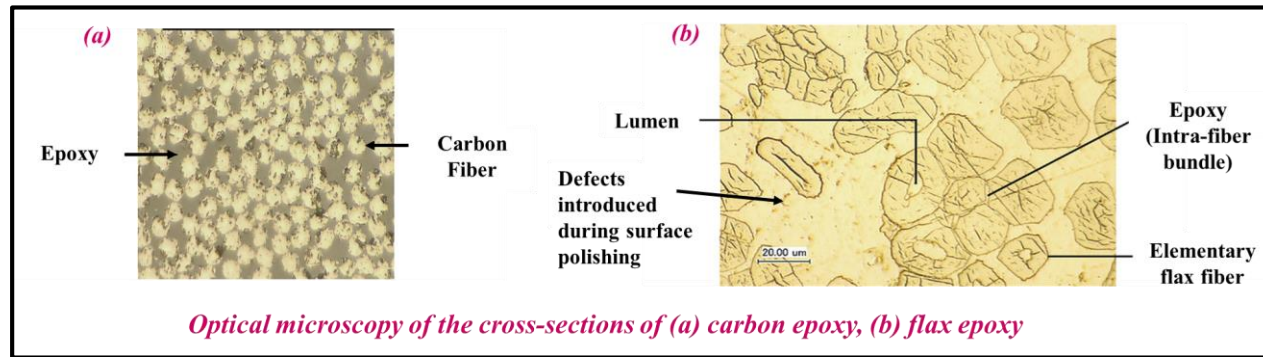
- This method involves the digestion of matrix material using an acid which does not attack the fibers.

Procedure:

- The matrix material is digested or dissolved by putting a measured volume of composite in an acid bath.
 - Following digestion, the remaining fibers are washed, dried, and weighed.
 - Knowing the initial weight of the composite specimen as well as the density of the composite, volume of the entire specimen can be calculated.
 - Thus, knowing the density and weight (step-2) of the fibers, the volume of fibers and the fiber volume fraction can be determined.
- One should be careful to choose the liquid for digestion such that the fibers are not digested.
 - Generally, hot nitric acid is used for carbon/epoxy composite.
 - The ASTM standard used for digestion method are D3171-76 (1990) for polymeric composites and D3553-76 (1989) for metal matrix composites.

2. Optical Microscopy based Techniques:

- It involves potting sectioned samples of the laminate, polished using standard metallographic techniques, and obtaining digital cross-sectional photomicrographs using an optical microscope and magnifications between 100 and 2500.
- Digital images may be recorded at a number of locations along the length and through-the-thickness of the laminate.
- Computer programs aid in the analysis of fiber ratio in the photomicrograph of the polished composite specimen.
- This method is preferred as a non-destructive approach to determining fiber volume fraction.



3. Resin Burning-off Method:

- This method applies to composites with a reinforcement such as glass or ceramic that is not affected by high-temperature environments or a reinforcement such as carbon when the temperature can be adequately controlled to minimize degradation of the fiber during burn off.

Test Procedure:

- ✓ Heat up the composite to a temperature at which resin will melt and fibers remain stable.
- ✓ After burning off resin, weigh the fibers.
- ✓ Now, fiber volume fraction can be calculated from the initial weight of composite and fiber's weight.

4. Gravimetric Relation Method:

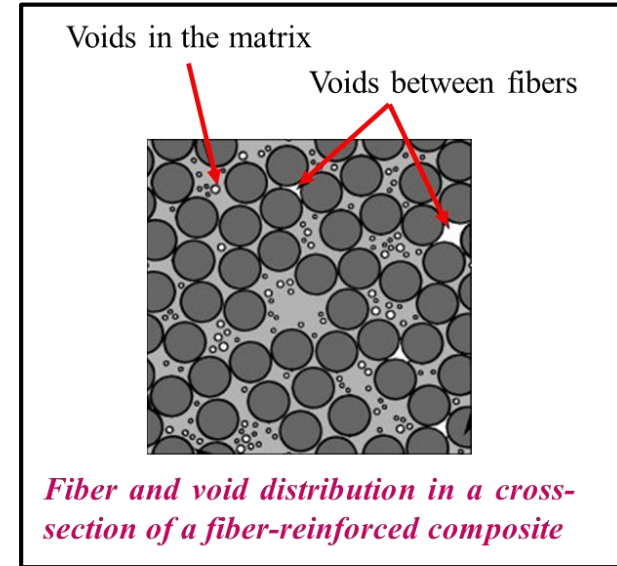
- This method determines the density of composites and then calculates the fiber volume fraction knowing the density of the fiber and the matrix.
- When it can be confirmed that the composite material has zero or negligible (less than 1%) porosity, the fiber volume fraction can be obtained from the densities of the composite and the constituents by the following gravimetric relation:

$$V_f = \frac{\rho_c - \rho_m}{\rho_f - \rho_m}$$

Where,
 V_f = Fiber volume fraction,
 ρ_f = Density of fiber,
 ρ_c = Density of composite,
 ρ_m = Density of matrix material

❖ Void Content:

- A void is a pore that remains unoccupied in a composite material.
- A void is typically the result of an imperfection from the processing of the material and is generally deemed undesirable.
- Because a void is a non-uniformity in a composite material, it can affect the mechanical properties and lifespan of the composite.
- Voids can act as a crack nucleation site as well as allow moisture to penetrate the composite and contribute to anisotropy of the composite.
- For aerospace applications, a void content of approximately 1% is appropriate for performance while other grades of composites can have between 3%-5% void content.



Void Content Calculation:

- Consider a composite consisting of fiber and matrix. Take the following symbol notations:

$v_{c,f,m}$ = volume of composite, fiber, and matrix, respectively.

$\rho_{c,f,m}$ = density of composite, fiber, and matrix, respectively.

- For composites with a certain volume of voids v_v the volume fraction of the voids V_v is defined as:

$$V_v = \frac{v_v}{v_c}$$

- The total volume of composite (v_c) with voids is given by:

$$v_c = v_f + v_m + v_v \quad \dots \text{Eq. (1)}$$

- By definition of the experimental density ρ_{ce} of a composite, the actual volume of the composite is:

$$v_c = \frac{w_c}{\rho_{ce}} \quad \dots \text{Eq. (2)}$$

- By the definition of the theoretical density ρ_{ct} of the composite, the theoretical volume of the composite is

$$v_f + v_m = \frac{w_c}{\rho_{ct}} \quad \dots \text{Eq. (3)}$$

- Substituting eq. 2 and 3 in 1 , we have

$$\frac{w_c}{\rho_{ce}} = \frac{w_c}{\rho_{ct}} + v_v$$

- The volume of void is given by:

$$v_v = \frac{w_c}{\rho_{ce}} \left(\frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \right) = v_c \left(\frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \right)$$

- Now volume fraction of the voids is

$$V_v = \frac{v_v}{v_c} = \left(\frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \right)$$

**In general, if void content < 1% => good composite
if void content > 5% => poor composite**

❖ Moisture Content:

- Moisture content or water content is the quantity of water contained in a material.
- Composite materials when exposed to the environment or water absorb moisture.
- Absorption of the moisture results in the expansion and affects the degradation of the mechanical as well as thermal properties.
- Moisture content in a composite is given in terms of moisture by weight.

Procedure: *To measure the moisture content, there are following steps as:*

- i. A sample is weighed at the ambient conditions.
- ii. Then, sample is dried and weighed again.
- iii. The average amount of absorbed moisture in material can be calculated, as follows:

$$M, \% = \frac{W_i - W_o}{W_o} \times 100$$

$M, \% =$ *Percentage moisture content,*
 $W_i =$ *Initial specimen mass,*
 $W_o =$ *Oven-dry specimen mass.*

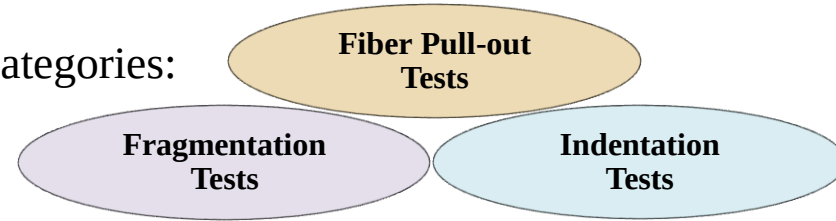
- iv. The difference in these two weights per unit weight of the dry sample gives the weight change due to moisture content.

Precautions:

- ❖ While drying, care should be taken to avoid excessively high drying temperatures and high thermal excursions that may induce thermal cracking, oxidation, or mass loss, or combinations of the three in the material.
- ❖ Wear clean, non-linting gloves when handling specimens.

Mechanical Behaviour Testing of Composite Materials:

- In an effort to understand the mechanical behaviour of composites at the microscopic level, a number of test techniques have been and continue to be developed.
- The principal aim of these tests is to evaluate the shear strength of fiber resin interface and any frictional effects that may be present.
- These micro-mechanical test methods fall into three categories:



a) Fiber Pull-out Tests:

- The fiber/matrix interface plays an important role in controlling the macroscopic mechanical properties of fiber composites and it is often characterized by Fiber Pull-out Test.
- In this test, a single fiber is embedded in a thin sheet or film of matrix material and the force required to pull the fiber out of the film is determined.
- Interfacial shear strengths are calculated using pull-out forces for fibers with a range of embedded lengths.

Pull-out Test Procedure:

- i. A length of the fibre is embedded in the matrix.
- ii. Loading is applied at the free end and leads gradually to pull out of the fibre.
- iii. The Force displacement curve is recorded.

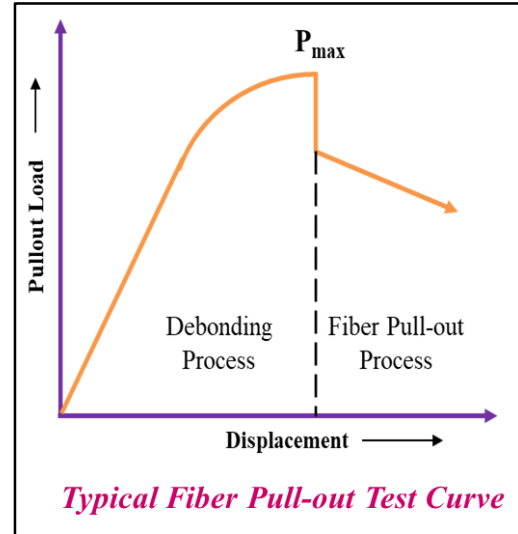
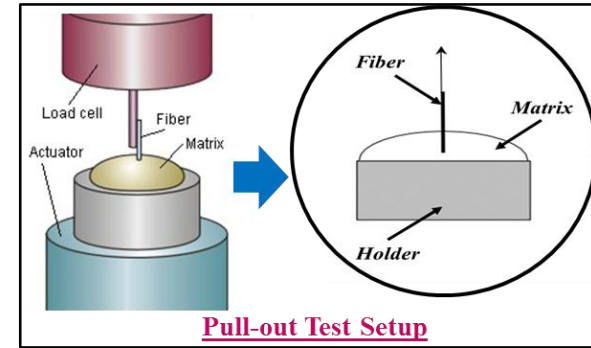
Pull-out Test: Load-displacement Curve

- Initially, the load increases linearly with displacement
- Matrix plasticity may lead to non linearities.
- After a maximum load value, there is a sudden drop which lasts until the pull out of the fibre.
- The interfacial strength is defined as a function of the maximum load P_{max} :

$$\tau = \frac{P_{max}}{2\pi Rl} \quad \text{Where, } P_{max} = \text{maximum pull-out load,} \\ l = \text{embedded length, and } R = \text{fiber radius.}$$

- The maximum stress on the fiber σ_{max} should not exceed its strength σ_{fu} :

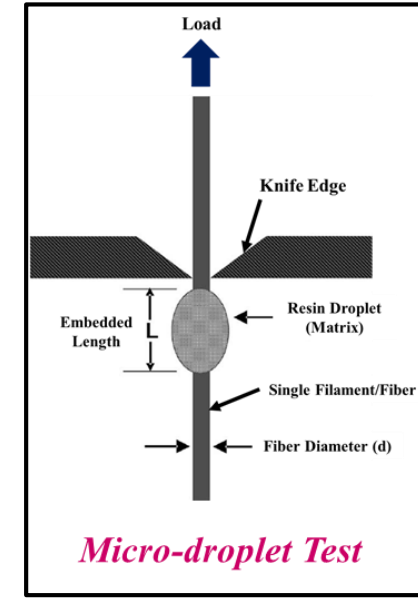
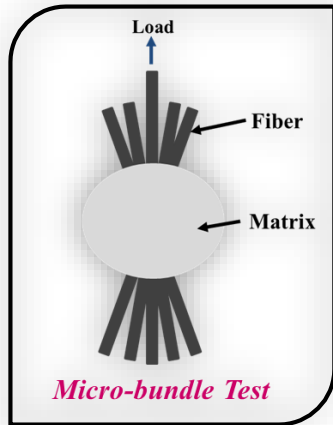
$$\sigma_{max} = \frac{P_{max}}{\pi R^2} \leq \sigma_{fu}$$



Pull-out Test: Other Variations

Micro-droplet Test:

- This test includes higher accuracy, simpler stress field of cylindrical symmetry and elimination of size effect.
- The embedded fiber length can also be easily determined.

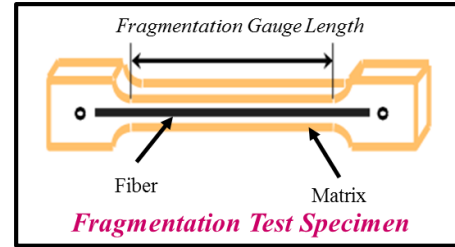


Micro-bundle Test:

- ✓ This test is used to account for the high fiber volume fraction of real composites.

b) Fragmentation Tests:

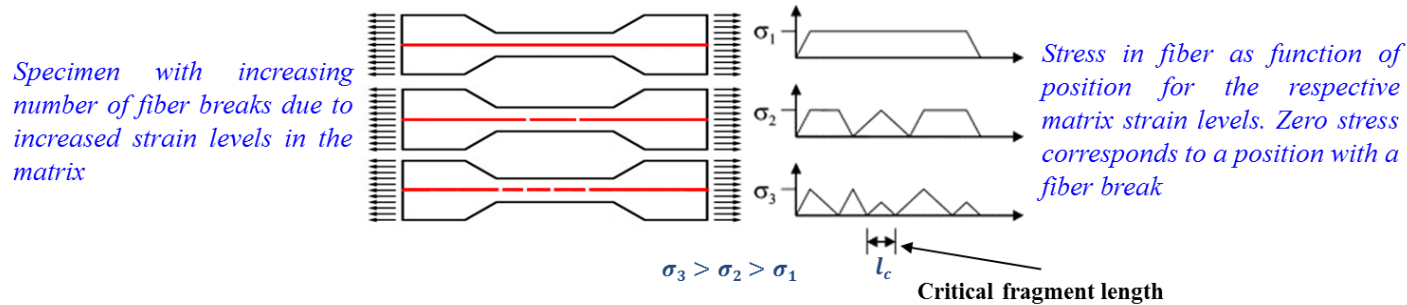
- This test is developed from the early work of Kelly and Tyson, who investigated brittle tungsten fibers that broke into multiple segments in a copper matrix composite.
- Each test specimen for the fragmentation test consists of one fiber encapsulated in a chosen matrix and normally has a *dogbone* shape.



Fragmentation Test Procedure:

- ✓ Specimens are elongated in a tensile tester, which results in fiber breakage.
- ✓ Experiment is done under a light microscope so that fragmentation process can be observed in-situ.
- ✓ The fiber inside the resin breaks into increasingly smaller fragments at locations where the fiber's axial stress reaches its tensile strength.
- ✓ When the fiber breaks, tensile stress at the fracture location reduces to zero. Due to constant shear in the matrix, tensile stress in the fiber increases roughly linearly from its ends to a plateau in longer fragments.

- ✓ The higher the axial strain, the more fractures will be caused in the fiber, but at some level (known as saturation stage) the number of fragments will become constant as the fragment length is too short to transfer enough stresses into the fiber to cause further breakage.



Calculation of Interfacial Shear Strength:

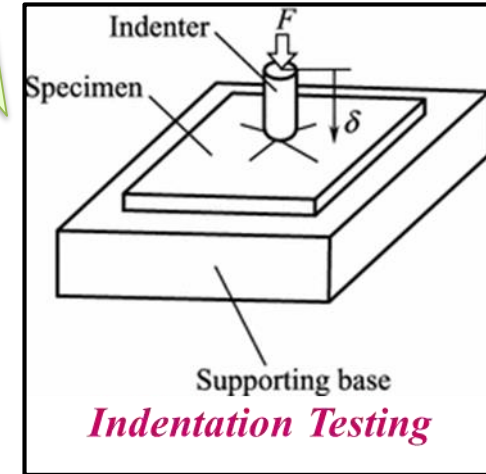
- To derive interfacial strength, the stress field must be defined. For constant shear, the average shear strength at the interface is given by:

$$\tau = \frac{\sigma_{fu} d}{2l_c}$$

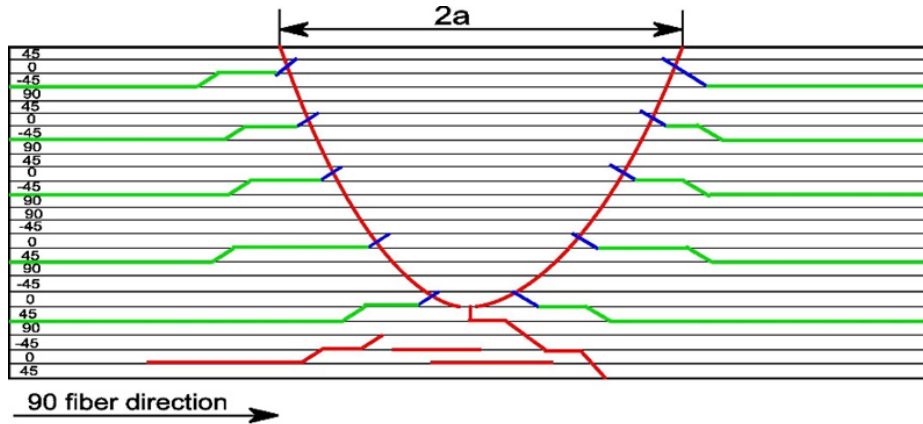
Where, σ_{fu} is the fiber strength at the critical length, d is the fiber diameter and l_c is the critical fragment length of the fiber (the average fragment length at saturation stage i.e. no more breaks occur when applying further strain to the specimen).

c) Indentation Tests:

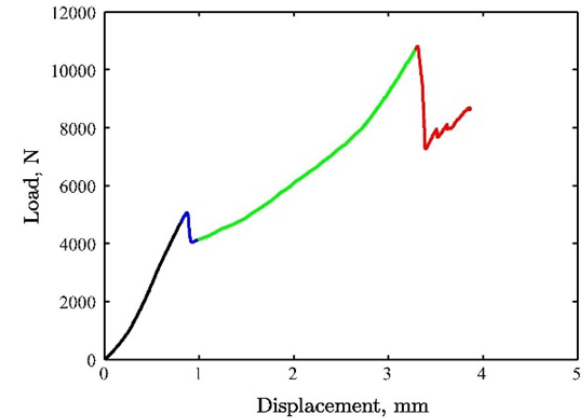
- This test gives knowledge about damage from concentrated out-of-plane forces, which is one of the major design concerns of many structures made of advanced composite laminates.
- It is performed on a grinded and polished surface.
- A flat, square composite plate is subjected to an out-of-plane, concentrated force by slowly pressing a hemispherical indenter into the surface.
- The damage resistance is quantified in terms of a critical contact force to cause a specific size and type of damage in the specimen.
- The damage response is a function of the test configuration; comparisons cannot be made between materials unless identical test configurations, test conditions, etc. are used.



Indentation Damage in Composite Laminates:



Schematic representation of indentation damage



Related load-displacement curve

- These figures summarize the sequence of damage events observed in indentation tests along with its correlation with the load–displacement curve.
- The load displacement curve is plotted using four different colours, each colour corresponding to the damage mechanism represented in another figure of the same colour.

Failure Modes in Micro-mechanical Test Methods:

- Specimen configuration and loading conditions determine failure modes that may be present.

<i>Test</i>	<i>Specimen</i>	<i>Load</i>	<i>Failure Modes Present</i>
Pull-out	Single fiber	Tension	Interfacial failure (cohesive or adhesive), matrix yielding, fiber end surface loaded
Micro-droplet	Single fiber	Tension	Interfacial failure (cohesive or adhesive), matrix yielding, non-uniform loading
Micro-bundle	Single fiber in bundle	Tension	Interfacial failure (cohesive or adhesive), matrix failure, fiber failure
Fragmentation	Single fiber	Tension	Progressive damage accumulation by fiber failure, local matrix yielding, local matrix cracking, fiber-matrix debonding
Indentation	Single fiber in composite	Compression	Interfacial failure, fiber crushing

- Not all tests are appropriate for testing the properties of the three classes of composites and the primary limitation of using a particular test is the fabrication of the specimen.
 - ✓ **PMC**- Specimens for all the tests can be made.
 - ✓ **MMC**- These are currently restricted to fragmentation and indentation tests.
 - ✓ **CMC**- These are confined to the indentation test because of the low interfacial shear stresses in these systems.

Summary:

- Composite materials, their types and applications have been discussed.
- The testing of composite material has got very much importance as it gives the required physical, mechanical and other properties for the use of that material in given application.
- Several physical and mechanical property measurement methods have also been discussed.
- These test methods are used for quality assessment during the composite materials development before it is used in actual structure.

THANK YOU





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INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 06: Nondestructive Inspection- Visual Inspection



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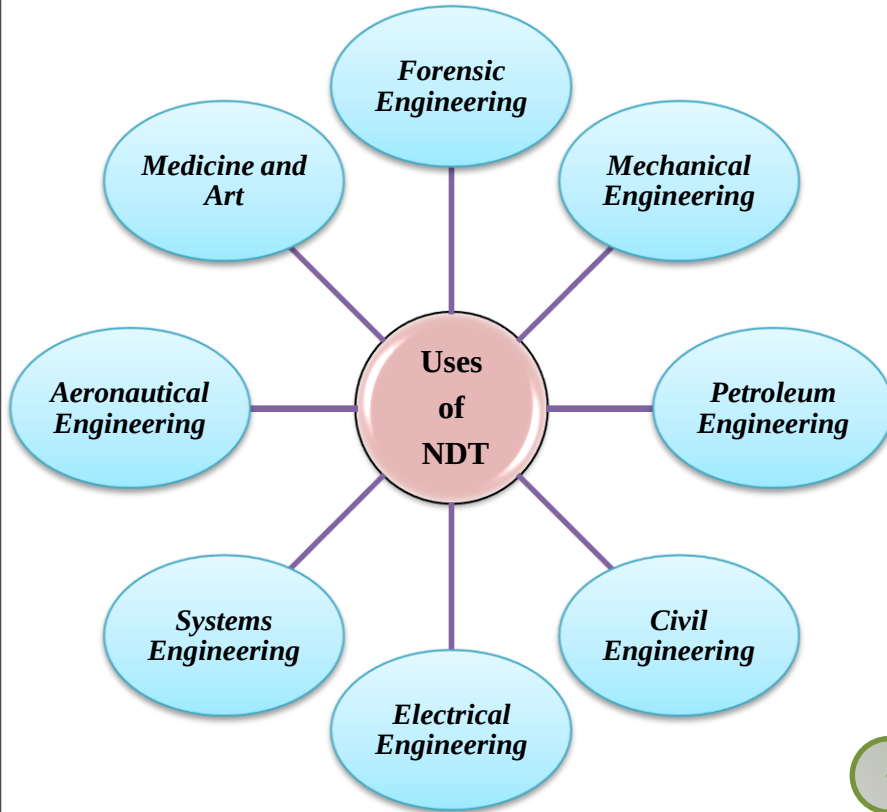
Joint faculty: Centre of Nanotechnology



Nondestructive Inspection:

- **Non-destructive testing (NDT)** is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system.
- Terms non-destructive examination (NDE), non-destructive inspection (NDI), and non-destructive evaluation (NDE) are also commonly used to describe this technology.
 - It is a highly valuable technique that can save both money and time in product evaluation, troubleshooting, and research.
 - Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness.
 - Non-destructive tests are used in manufacturing, fabrication and in-service inspections to ensure product integrity and reliability, to control manufacturing processes, lower production costs and to maintain a uniform quality level.
 - During construction, NDT is used to ensure the quality of materials and joining processes during the fabrication and erection phases, and in-service NDT inspections are used to ensure that the products in use continue to have the integrity necessary to ensure their usefulness and the safety of the public.

What are some uses of NDT Methods?



Non-destructive evaluation can be conveniently divided into nine distinct areas:

1. Flaw detection and evaluation.
2. Leak detection.
3. Metrology (measurement of dimension).
4. Location determination.
5. Structure or microstructure characterization.
6. Estimation of mechanical and physical properties.
7. Stress (strain) and dynamic response determination.
8. Signature analysis.
9. Chemical composition determination.

Selection of an NDT Method:

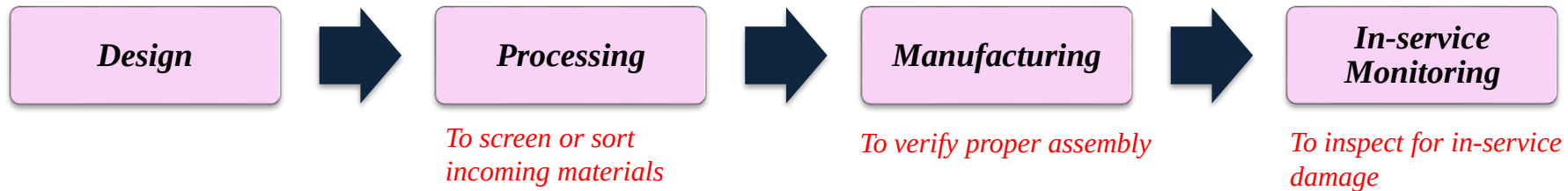
- Each NDT method has its own set of advantages and disadvantages and, therefore, some are better suited than others for a particular application.
- The NDT technician or engineer must select the method that will detect the defect or make the measurement with the highest sensitivity and reliability.
- The cost effectiveness of the technique must also be taken into consideration.

When planning NDT testing one should take into account a number of factors such as:

- Requirements regarding reliable and safe operation.
- Quality assurance level achieved.
- Characteristics of manufacturing processes, properties of materials used.
- Feasibility of NDT methods available.
- Economic criteria.

When are NDE Methods Used?

- There are NDE application at almost any stage in the production or life cycle of a component.
 - ✓ To assist in product development.
 - ✓ To screen or sort incoming materials.
 - ✓ To monitor, improve or control manufacturing processes.
 - ✓ To verify proper processing such as heat treating.
 - ✓ To verify proper assembly.
 - ✓ To inspect for in-service damage.

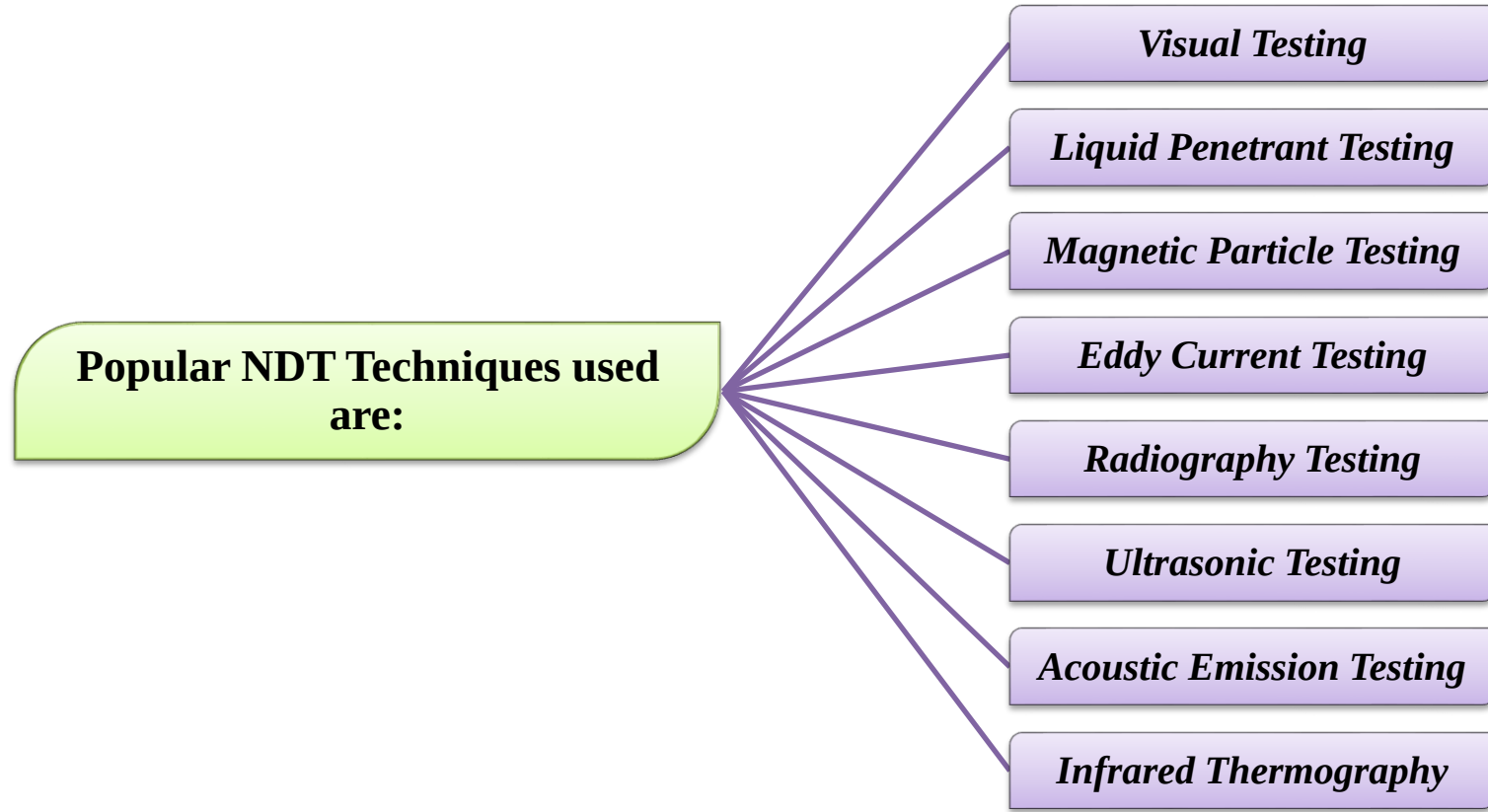


Benefits of Using NDT in Manufacturing:

- Use of NDT during all stages of manufacturing results in the following benefits:
 - a) It increases the safety and reliability of the product during operation.
 - b) It decreases the cost of the product by reducing scrap and conserving materials, labour and energy.
 - c) It enhances the reputation of the manufacturer as producer of quality goods.
 - d) It enables design of new products.

All of the above factors bring profitability to the manufacturer

Non-destructive Inspection Techniques:



Visual Inspection:

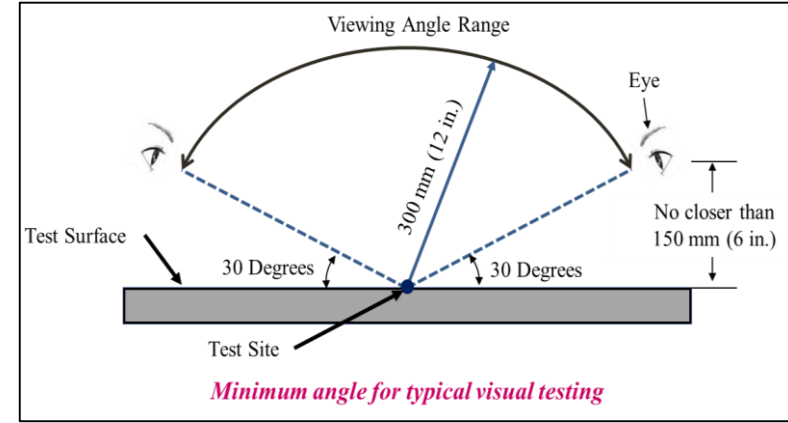


Visual Inspection is a non-destructive testing technique that provides a means of detecting and examining a variety of surface flaws, such as corrosion, contamination, surface finish, and surface discontinuities on joints (e.g., welds, seals, solder connections, and adhesive bonds).

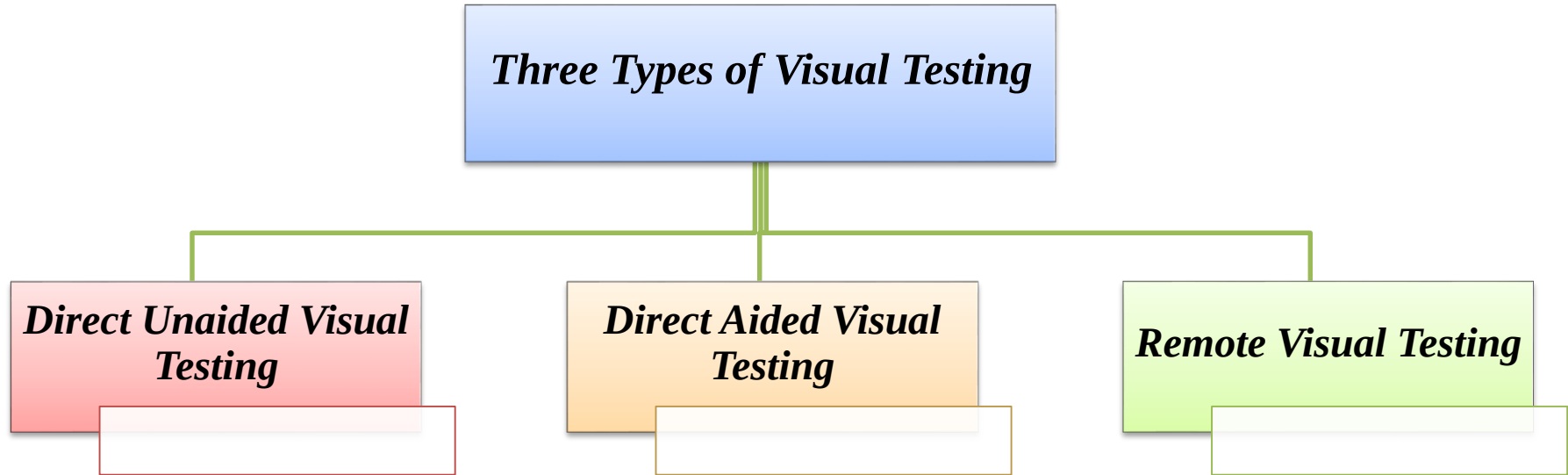
- It is the most cost effective method of detecting common defects in welding and castings.
- As it can be implemented easily throughout the progression of a job it is easy to eliminate simple errors and problems preventing the follow on effect.
- It is also the most widely used method for detecting and examining surface cracks, which are particularly important because of their relationship to structural failure mechanism.
- Even when other non-destructive techniques are used to detect surface cracks, visual inspection often provides a useful supplement.

Visual Angle and Distance:

- It is general recommendation for operator to be placed at a distance for his eye to be within 600 mm of the test surface at an angle not less than 30 degrees.
- The criterion set above is based on the eye's resolving power.
- Natural or artificial lighting of sufficient intensity and placement is needed to illuminate the test areas and to allow proper reading of weld gauges and other equipment.
- The visual test resolution is considered adequate when the examiner, by combination of lenses, access, lighting and angle of vision, can resolve a 0.8 mm wide black line or an artificial flaw located on the surface to be examined.

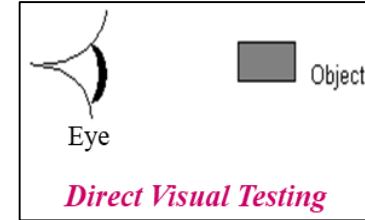


Classification of Visual Testing:



1. Direct Visual Testing:

- Direct visual examination is the type of examination made in situations where there is an access to the area of interest without any possibility of injury to the inspectors.
- There is no interruption between the eye and the object.
- Defects can be detected are: cracks, corrosion layer, physical damage, surface porosity, misalignment of mated parts, etc.



Examples:



Visual inspection for surface cracks



Inspection of car after assembly

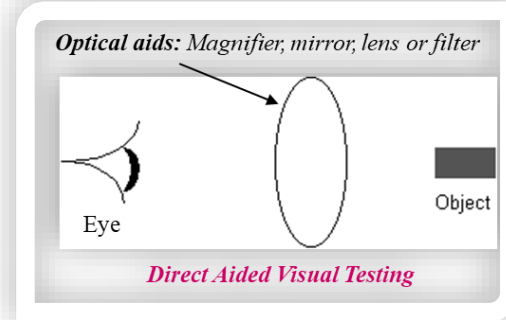


Direct visual inspection of welded parts

2. Direct Aided Visual Testing:

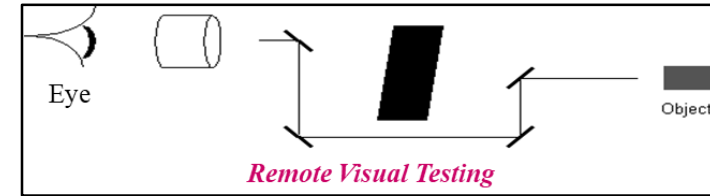
- The nature of the image is not modified.
- Modification of the image is only allowed by:
 - ✓ Magnification with for example a mirror, a lens, an endoscope;
 - ✓ Spectral or density filtering by a filter lens.

Examples:



3. Remote Visual Testing:

- The nature of the image is modified.
 - ✓ **For example:** The optical image is converted into an electronic image by a camera.
- **Equipment used:** Camera, robotic devices, fiber optics, portable video probes, etc.



Examples:



Robotic pipeline inspection crawler



Inspection of Aircraft using Fiberscope



Visual Inspection Microscope

Basic Procedure for Visual Inspection:

- It generally comprises of three steps as:
 - 1) Clean the inspection surface properly.
 - *(Contaminants such as oil, grease, scale, sand (on casting surface), etc. may interfere with interpretation of results).*
 - 2) Adequately illuminate the specimen with light.
 - *(Human eye is most sensitive to yellow-green light, with a wave length of 5560 Å).*
 - 3) Examine the specimen with eyes or take the assistance of light sensitive devices such as photocells.

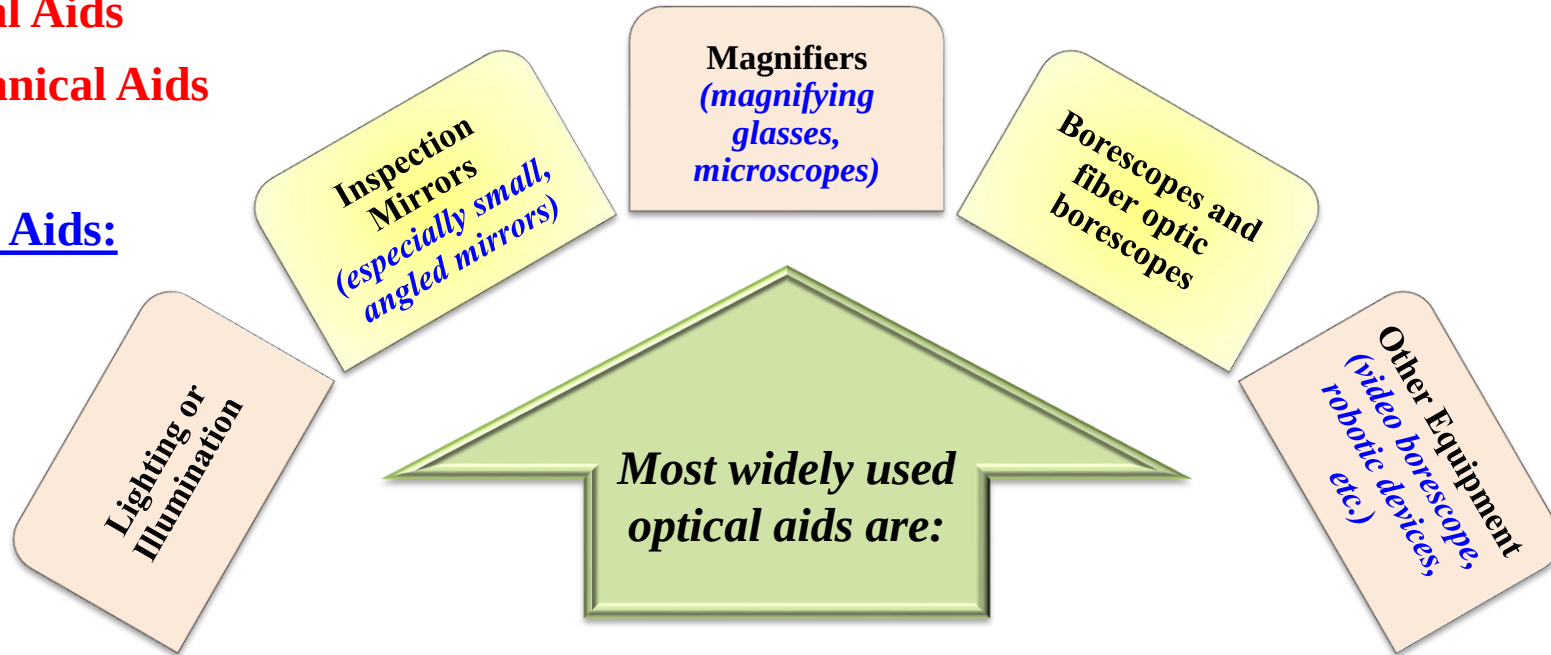
Visual Testing Equipment:

- Different kinds of equipment are used to improve the inspection quality.
- These equipment can be classified into two parts:

I. Optical Aids

II. Mechanical Aids

I. Optical Aids:



a) Lighting:

- The inspection surface illumination is of extreme importance.
- Adequate illumination levels should be established in order to ensure effective visual inspection.
- While designing lighting for an inspection system, we must consider what the inspection system should do:
 - ✓ *Look for a defect in a part,*
 - ✓ *Measure a part's dimensions, or*
 - ✓ *Determine the presence or absence of a feature.*
- While devising lighting for product's inspection, following things should be taken into account:
 - ✓ *Optical properties of product's surface.*
 - ✓ *Inspection surface geometry.*
 - ✓ *Colour of product's surface.*



Optical Properties of Product's Surface:

- The surfaces of products have optical properties that fall into one of three general reflectance categories:

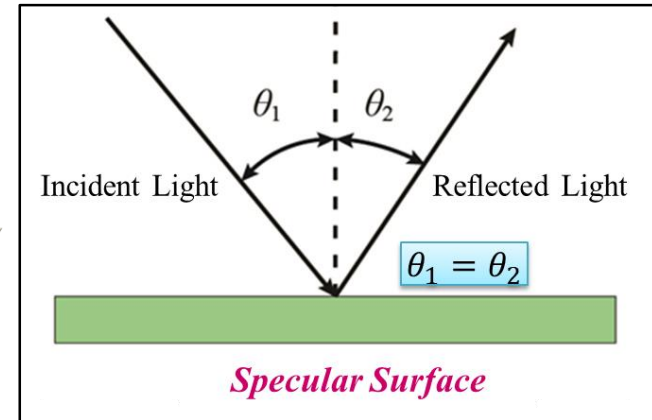
○ **Specular Reflection**

○ **Diffuse Reflection**

○ **Directional Reflection**

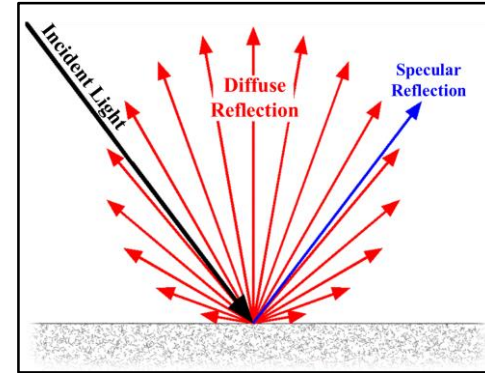
Specular Reflection:

- ❖ The specular reflection is a phenomenon where the incidence angle of light is equal to the angle of reflection.
- ❖ Specular surfaces are mirror like smooth and highly polished surfaces.



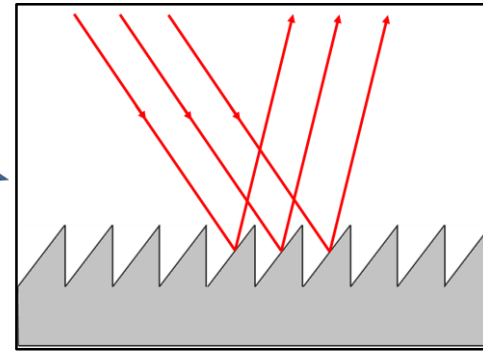
Diffuse Reflection:

- ❖ It is the reflection of light from a surface such that a ray incident on the surface is scattered at many angles rather than a just one angle as in the case of specular reflection.
- ❖ A surface built from a non-absorbing powder such as plaster, or from fibers such as paper, or from a polycrystalline material such as white marble, reflects light diffusely with great efficiency.
- ❖ Diffuse surfaces are rough and have a dull lustre.
- ❖ Many common materials exhibit a mixture of specular and diffuse reflection.



Directional Reflection:

- ❖ Directionally reflective surfaces typically contain fine grooves that reflect light generally in a preferred direction depending on the incidence angle.



Surface Geometry of Inspection Surface:

- ❖ In addition to a part's reflective properties, the surface's geometry must also be considered.
 - ✓ **Flat Surface:** Flat surface is self-explanatory, and achieving uniform illumination across it is typically easier than other geometries.
 - ✓ **Curved Surface:** The changing slope of a curved part can often pose a lighting problem that manifests itself as uneven illumination across the part. If the curved surface is specular or directionally reflective, glinting can occur, too.
 - ✓ **Prismatic Surface:** Prismatic parts contain sharp edges or steep slopes, and such parts can be difficult to illuminate because lighting can produce shadows or glints.

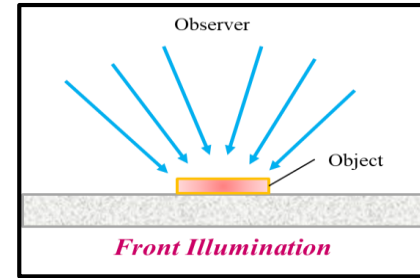
Colour of Inspection Surface:

- ❖ Contrasting colours may help your inspection system distinguish parts from backgrounds.
- ❖ If contrast differences are small, we can use colour filters or selective-wavelength illumination to enhance the contrast for our inspection system.

❖ Illumination Techniques:

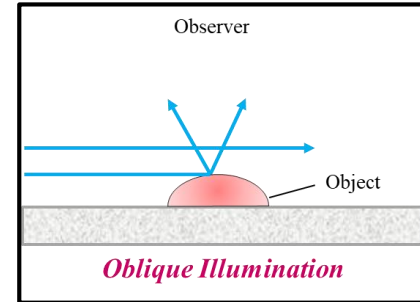
i. Front Illumination:

- Front illumination involves placing a light source and a camera/observer on the same side of a product to provide overall illumination.



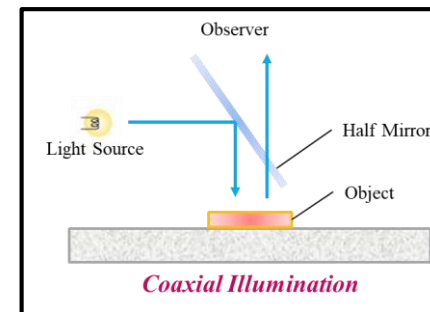
ii. Oblique Illumination:

- Placing a light source nearly perpendicular to a camera/observer provides oblique illumination.
- This technique is used to find surface irregularities such as burrs.



iii. Coaxial Illumination:

- It is another form of front lighting, which directs light down a camera's/observer's line of sight.
- Because this technique provides uniform illumination across your field of view, it can reduce shadows and some glinting.



iv. **Diffuse Back Illumination:**

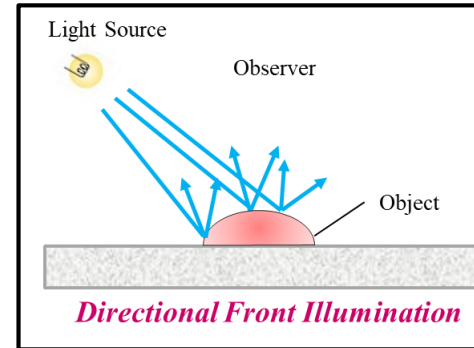
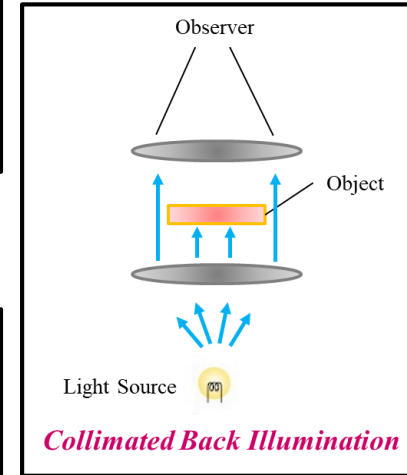
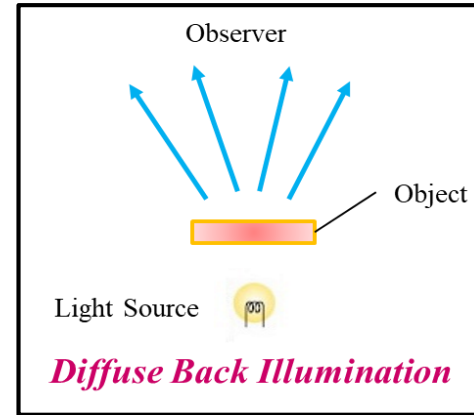
- The object is illuminated from the behind.
- It gives edge contrast to objects as well as aid in identifying defects or imperfections within translucent or opaque surfaces.

v. **Collimated Back Illumination:**

- It is a variation of back lighting, which uses collimated light to produce images with sharp edges, even for curved surfaces such as those on a cylinder or ball.

vi. **Directional Front Illumination:**

- Directional lighting lets an inspection system measure shadows and calculate the heights of components.



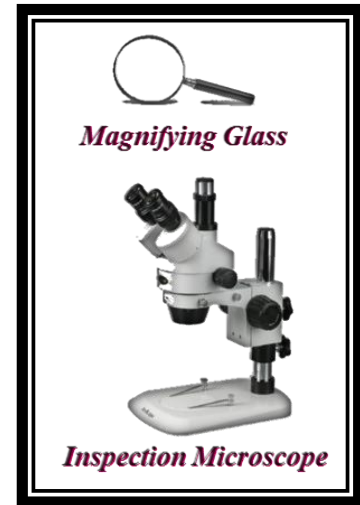
b) Inspection Mirrors:

- Inspection mirrors are used to improve the angle of vision.
- Inspection mirrors allow the inspectors to look inside piping, threaded and bored holes, inside castings, and other hardest to see places.



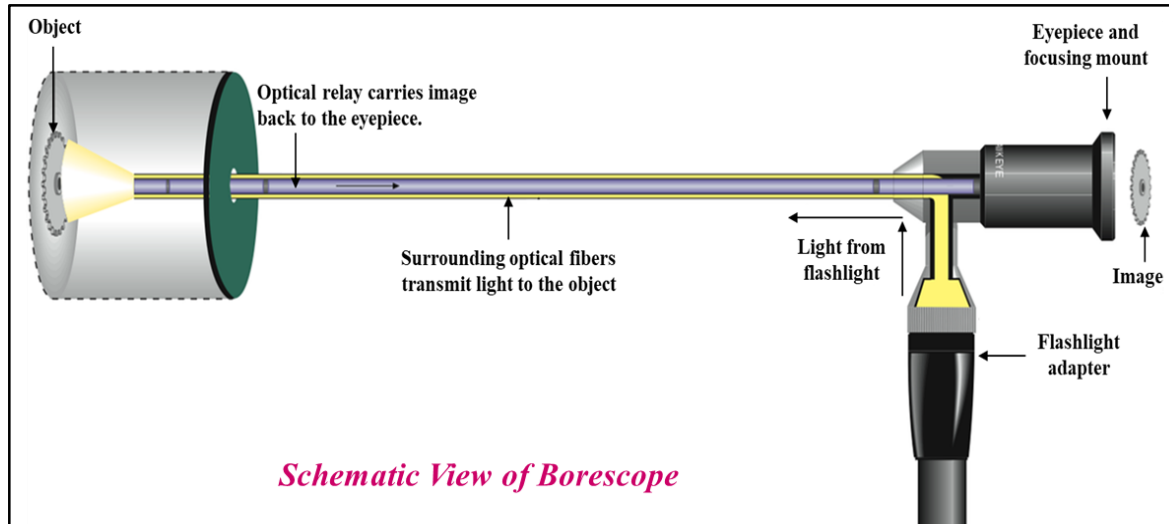
c) Magnifiers:

- Magnifying systems are used for evaluating surface finish, surface shapes (profile and contour gauging), and surface microstructures.
- An inspector with eye fatigue is likely to miss defects that would otherwise be detected.
- Therefore, it is important to ensure that the possibility of eye fatigue is minimized by using appropriate levels of magnification for the job.
- The equipment should have proper ergonomic function such as adjustability and positionability.



d) Borescopes:

- Borescopes are visual aids used for illuminating and observing internal, closed or otherwise inaccessible areas.
- They are designed for remote viewing in difficult to reach areas such as jet engines, cylinders, tanks, and various enclosed chambers.
- They are available in many different diameters and lengths, and are classified as **rigid** or **flexible**.



e) Other Equipment:

Portable Video Probes-

- Portable video probes allow inspectors to remotely perform examinations in closed chambers which are inaccessible by convention inspection means.
- Portable video inspection unit with zoom allows inspection of large tanks and vessels, railroad tank cars, sewer lines.

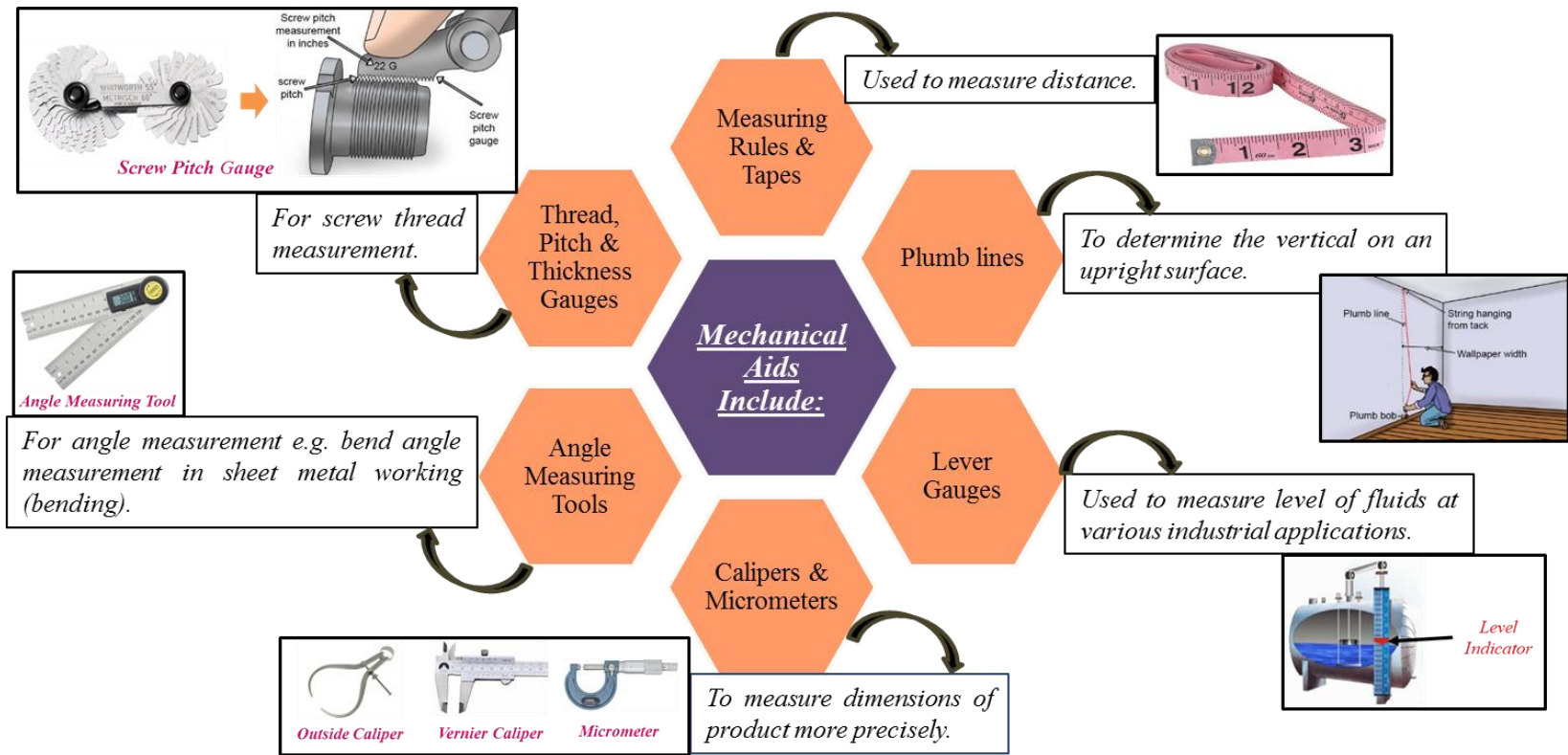


Robotic Devices-

- Robotics have been developed whereby cameras can be affixed to crawlers and submersibles.
- Robotic crawlers permit observation in hazardous or tight areas, such as air ducts, reactors, pipelines.
- Retrieval tools can be affixed to robotics to remove foreign objects.

II. Mechanical Aids:

- Several mechanical gauges are also used to assist the visual inspection examinations.



Mechanical Aid for Weldments:

❖ Welding Gauges:

- Welding fabrication uses fillet gauges to determine the width of the weld fillet, undercut gauges, angle gauges, skew fillet weld gauges, pit gauges, contour gauges, and a host of other specialty items to ensure product quality.

Examples

Universal Welding Gauge:

- ❖ It allows measuring of:
 - ✓ Height of flat weld
 - ✓ Height of fillet weld bead
 - ✓ Thickness of fillet weld
 - ✓ Bevel angle of weldment
 - ✓ Undercut depth of weld seam
 - ✓ Vertical misalignment



Universal Welding Gauge

Fillet Weld Gauge:

- ❖ It allows measuring of concavity or convexity of fillet weld.



Fillet Weld Gauge

Advantages of Visual Inspection:

- ✓ It is a routine procedure.
- ✓ The cost of visual inspection is low.
- ✓ It can be very effective where examination is made before, during and after manufacturing process.
- ✓ Testing is simple and testing speed is high.
- ✓ Testing is possible while test object is being used.
- ✓ Permanent records are available when latest equipment are used.

Limitations of Visual Inspection:

- ✓ The scope is limited to surface defects, as internal and sub-surface defects can not be found.
- ✓ Limited to the visual acuity of the observer/inspector.
- ✓ Eye fatigue may cause the defects to remain undetected.



Summary:

- Non-destructive inspection is a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage.
- It is divided into various methods, each based on a particular scientific principle.
- Visual inspection is the most common and widely used non-destructive testing technique and it is normally the first step in the examination process.
- Various optical and non-optical equipment are used to further assist and improve the visual inspection examinations.

THANK YOU





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INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 07: Dye Penetrant Inspection



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



Dye Penetrant Inspection:

- Dye penetrant inspection (DPI), also called liquid penetrate inspection (LPI) or penetrant testing (PT).
- It is widely applied and low-cost inspection method used to locate surface breaking defects in all non-porous materials (*metals, plastics, or ceramics*).
- This technique is used to detect casting, forging and welding surface defects such as hairline cracks, surface porosity, leaks in new products, and fatigue cracks on in-service components.

History of Penetrant Testing:

Before 1900's:

- A very early surface inspection technique involved the rubbing of carbon black on glazed pottery, whereby the carbon black would settle in surface cracks rendering them visible.
- Later, it became the practice in railway workshops to examine iron and steel components by the "*Oil and Whiting*" method.



1900's - Oil and Whiting Method:

- In this method, a heavy oil commonly available in railway workshops was diluted with kerosene in large tanks so that locomotive parts such as wheels could be submerged.
- After removal and careful cleaning, the surface was then coated with a fine suspension of chalk in alcohol so that a white surface layer was formed once the alcohol had evaporated.
- The object was then vibrated by being struck with a hammer, causing the residual oil in any surface cracks to seep out and stain the white coating.
- It is then carefully examined with magnifying glass.



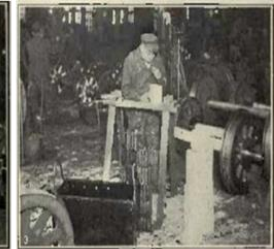
Pre-cleaning



Dipping in a hot bath of oil



Coating with a fine suspension of chalk in alcohol



Examination of the surface

1940 - Visible Dye Penetrant Method:

- More effective penetrating oils containing highly visible dyes were then developed to enhance flaw detection capability. This method, known as the visible or colour contrast dye penetrant method, is still used quite extensively today.

1942 - Fluorescence Dye Penetrant Method:

- In 1942, fluorescent dyes were added to the liquid penetrant.
- These dyes would then fluoresce when exposed to ultraviolet light (sometimes referred to as "black light") rendering indications from cracks and other surface flaws more readily visible to inspectors.
- Many of these early developments were carried out by **Magnaflux** in Chicago, IL, USA in association with **Switzer Bros.**, Cleveland, OH, USA.

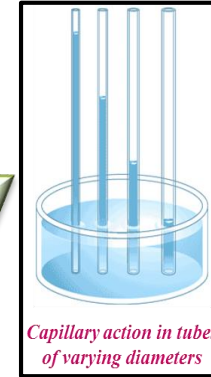


Principle of Dye Penetrant Inspection:

- DPI is based upon capillary action, where low surface tension fluid penetrates into clean and dry surface-breaking discontinuities.

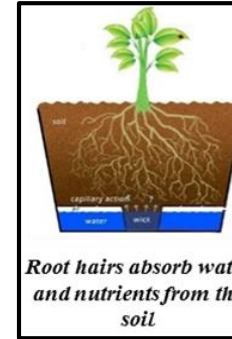
Capillary Action:

- ✓ Also known as capillarity, capillary motion, capillary effect, or wicking.
- ✓ It is the ability of a liquid to flow in narrow spaces without the assistance of, or even in opposition to, external forces like gravity.
- ✓ It occurs because of intermolecular forces between the liquid and surrounding solid surfaces.
- ✓ If the diameter of tube is sufficiently small, then combination of surface tension and adhesive forces between the liquid and container wall act to propel the liquid.



Examples from nature:

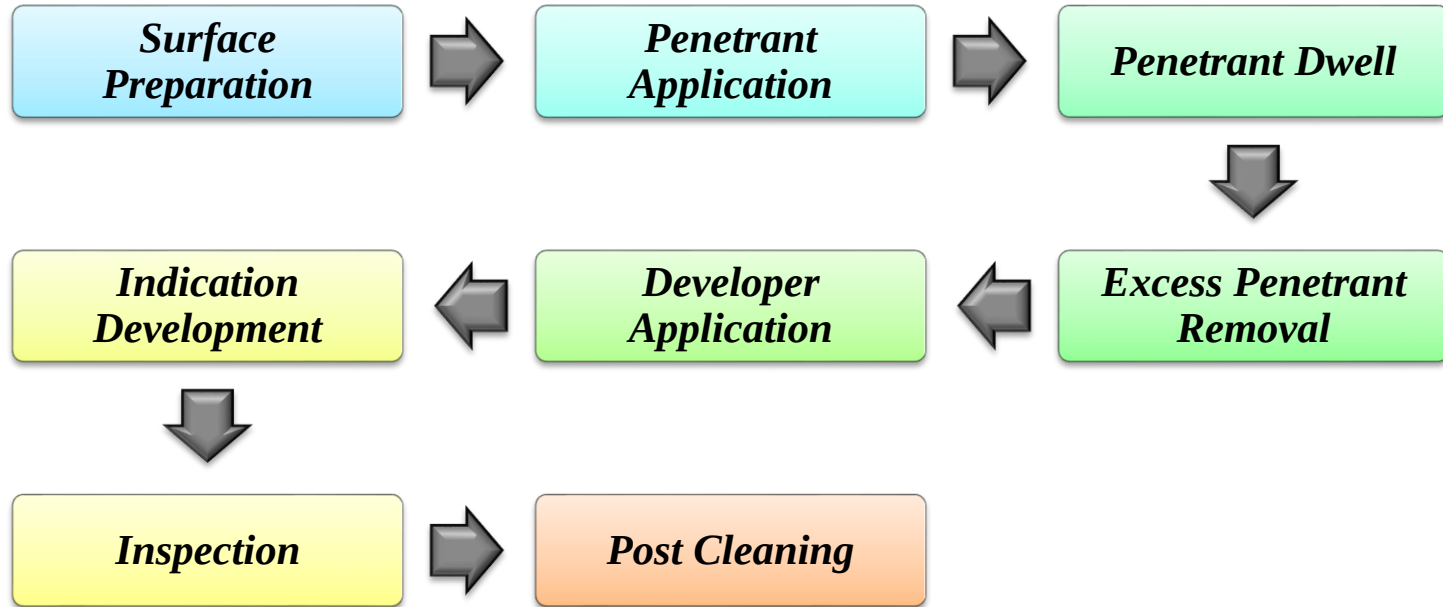
- ❖ Water movement in plants against the force of gravity.
- ❖ Blood flow through the human body.



Human body has miles of capillaries that carry blood to our entire body

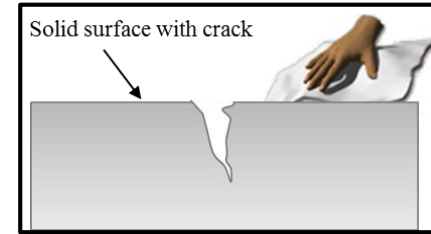
Test Procedure:

- Basic processing steps of dye penetrant inspection are as follows:



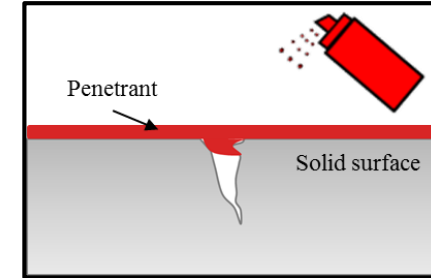
Step-1: Surface Preparation

- ✓ Most critical steps of a liquid penetrant inspection.
- ✓ The surface must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws.
- ✓ The sample may also require etching if mechanical operations such as machining, sanding, or grit blasting have been performed because these operations can smear metal over the flaw opening and prevent the penetrant from entering.



Step-2: Penetrant Application

- ✓ Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the part in a penetrant bath.



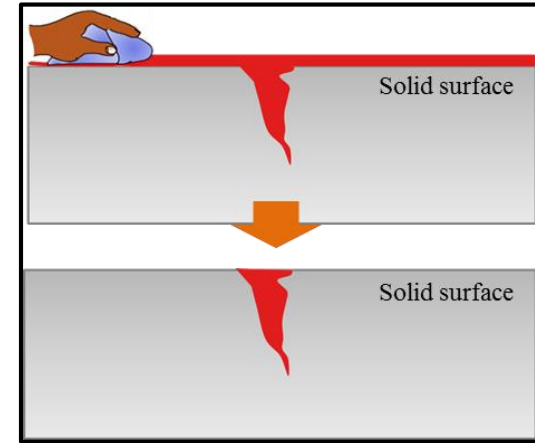
Step-3: Penetrant Dwell

- ✓ The penetrant is left on the surface for a sufficient time to allow as much penetrant as possible to be drawn from or to seep into a defect.
- ✓ Penetrant dwell time is the total time that the penetrant is in contact with the part surface.



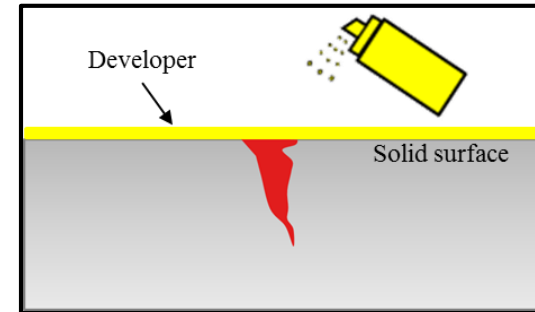
Step-4: Excess Penetrant Removal

- ✓ This is the most delicate part of the inspection procedure because the excess penetrant must be removed from the surface of the sample while removing as little penetrant as possible from defects.
- ✓ Depending on the penetrant system used, this step may involve cleaning with a solvent, direct rinsing with water, or first treating the part with an emulsifier and then rinsing with water.



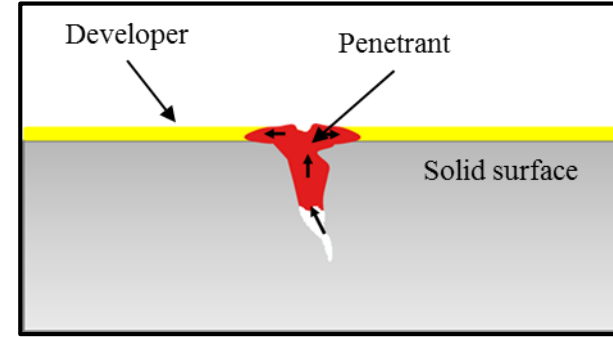
Step-5: Developer Application

- ✓ A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible.
- ✓ Developers come in a variety of forms that may be applied by dusting (dry powdered), dipping, or spraying (wet developers).



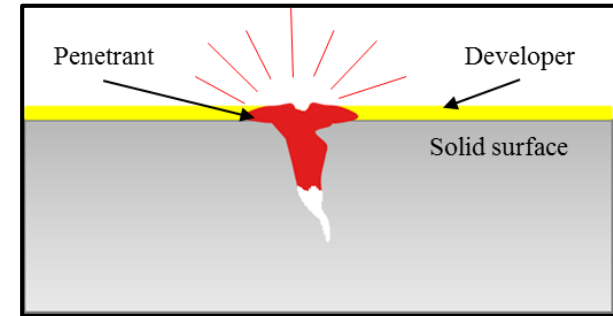
Step-6: Indication Development

- ✓ The developer is allowed to stand on the part surface for a period of time sufficient to permit the extraction of the trapped penetrant out of any surface flaws.
- ✓ This development time is usually a minimum of 10 minutes. Significantly longer times may be necessary for tight cracks.



Step-7: Inspection/Evaluation

- ✓ Inspection is then performed under appropriate lighting to detect indications from any flaws which may be present.



Step-8: Post Cleaning

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

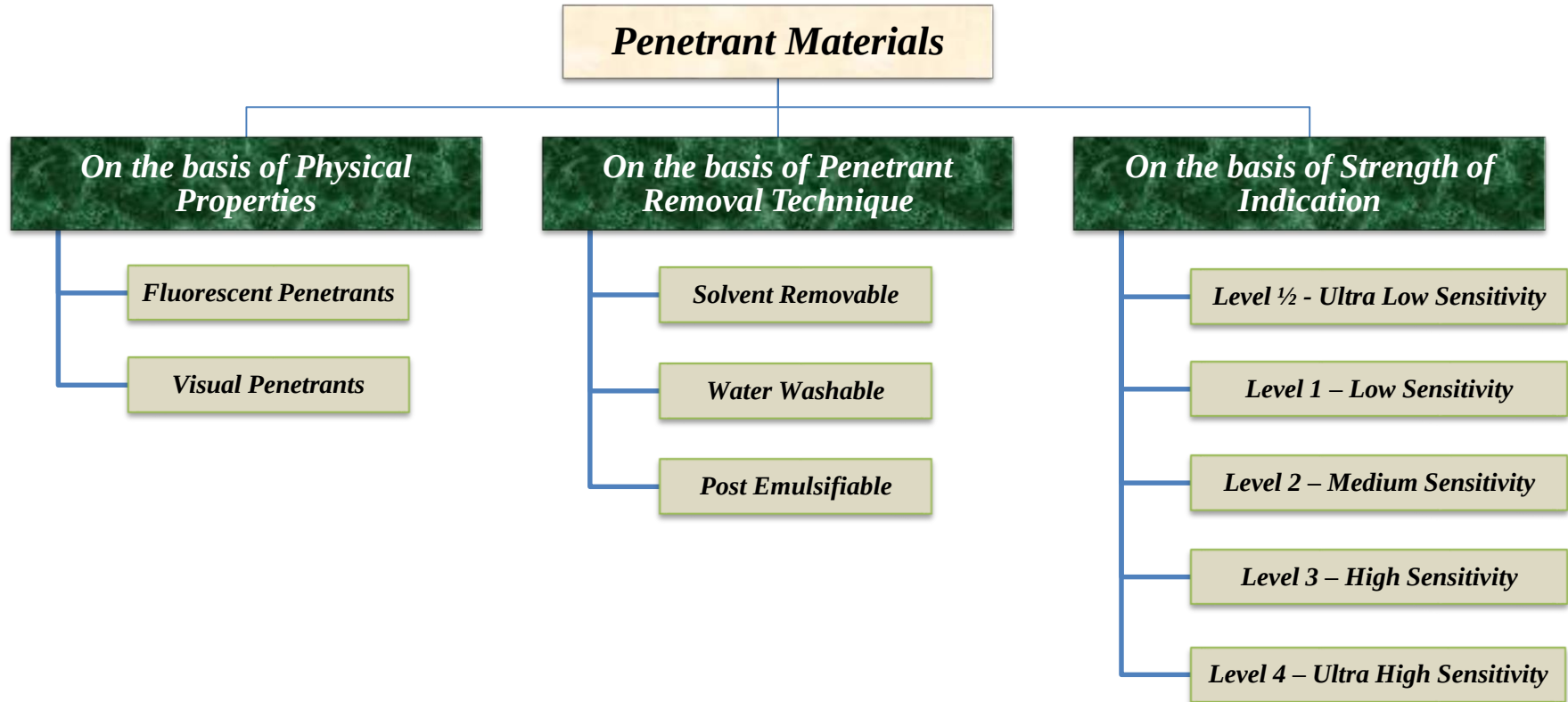
Penetrant Materials:

- The penetrants are mixtures of organic solvents, which are characterized by their ability to wet materials, spread rapidly and penetrate into minute.
- These materials used today are much more sophisticated than kerosene and whiting first used by railroad inspectors near the turn of 20th century.
- Today's penetrants are carefully formulated to produce the level of sensitivity desired by the inspector.

Characteristics
of
Liquid
Penetrants

- ❖ To perform well, a penetrant must possess a number of important characteristics.
 - ✓ It should spread easily over the surface being inspected.
 - ✓ It should be easily drawn into discontinuities by capillary action.
 - ✓ It should not be harmful to the inspector or the material being tested.
 - ✓ It should possess high indicating capability & less dwell time.
 - ✓ It should remain in fluid state.
 - ✓ It should not affect the physical and chemical properties of the testing material.
 - ✓ It should be cohesive, adhesive and relatively low in cost.

Classification of Penetrant Materials:



Classification of Penetrants on the basis of their Physical Properties:

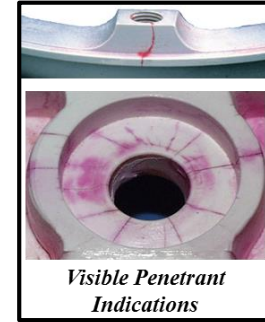
- On the basis of their physical properties, penetrants are classified as:

Fluorescent
Penetrants

Visual
Penetrants

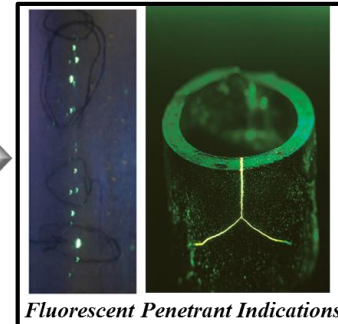
Visible Liquid Penetrants:

- They are usually **red** in colour and produces a contrasting indication against the white developer back ground.
- They do not require a darkened area and an ultraviolet light in order to make an inspection.
- They are also less vulnerable to contamination from things such as cleaning fluid that can significantly reduce the strength of a fluorescent indication.



Fluorescent Penetrants:

- They are generally **green** in colour and contain dye that glows brightly when exposed to UV lights.
- These systems are more sensitive than visible penetrant systems because the eye is drawn to the glow of the fluorescing indication.



Classification of Penetrants on the basis of Removal Technique:

- On the basis of method used to remove the excess penetrant from the part. There are four methods:

Method A :
Water Washable

Method B:
**Post-Emulsifiable,
Lipophilic**

Method C:
Solvent Removable

Method D:
**Post-Emulsifiable,
Hydrophilic**

☐ **Method A: Water Washable**

- Also called as self-emulsifying systems, can be removed from part by rinsing with water alone.
- These penetrants contain an emulsifying agent (detergent) that makes it possible to wash the penetrant from the part surface with water alone.

☐ **Method B: Post-Emulsifiable, Lipophilic**

- In this, lipophilic systems (Method B), penetrant is oil soluble and interacts with oil-based emulsifier to make removal possible.

☐ **Method C - Solvent Removable**

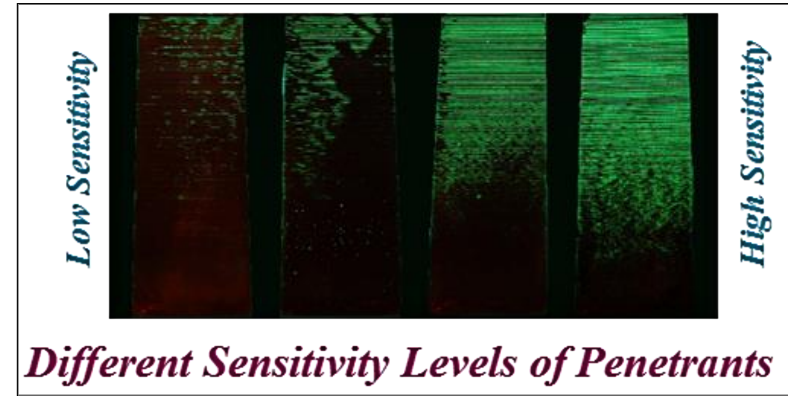
- Solvent removable penetrants require the use of a solvent to remove the penetrant from the part.

☐ **Method D - Post-Emulsifiable, Hydrophilic**

- Post-Emulsifiable, hydrophilic systems (Method D), used an emulsifier that is a water soluble detergent which lifts the excess penetrant from the surface of part with a water wash.

Classification of Penetrants on the basis of their Strength of Indication:

- Penetrants are also formulated to produce a variety of sensitivity levels.
- The higher the sensitivity level, the smaller the defect that the penetrant system is capable of detecting.
- The five sensitivity levels are:
 - ✓ *Level ½ - Ultra Low Sensitivity*
 - ✓ *Level 1 - Low Sensitivity*
 - ✓ *Level 2 - Medium Sensitivity*
 - ✓ *Level 3 - High Sensitivity*
 - ✓ *Level 4 - Ultra-High Sensitivity*

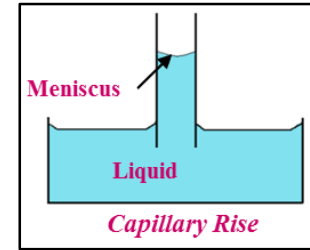


- As the sensitivity level increases, so does the number of non-relevant indications.
- Therefore, a penetrant needs to be selected that will find the defects of interest but not produce too many non-relevant indications.

Properties of Good Penetrant:

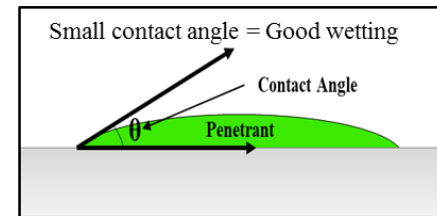
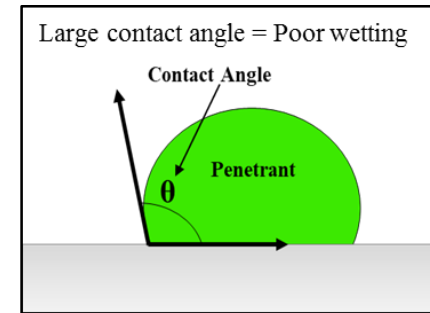
1) Capillarity:

- It is the ability of a liquid to flow in narrow spaces without the assistance of external forces. This property helps the penetrant to fill a void.



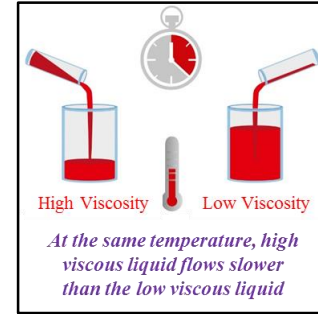
2) Surface Energy (Surface Wetting Capability):

- One of the important characteristics of a liquid penetrant material is its ability to freely wet the surface of the object being inspected.
- One way to quantify a liquid's surface wetting characteristics is to measure the **contact angle** of a drop of liquid placed on the surface of an object.
- The contact angle is the angle formed by the solid/liquid interface and the liquid/vapour interface measured from the side of the liquid.
- Liquids wet surfaces when the contact angle is less than 90 degrees.
- For a penetrant material to be effective, the contact angle should be as small as possible. In fact, the contact angle for most liquid penetrants is very close to zero degrees.



3) Viscosity:

- It is the internal resistance of a liquid to flow.
- A fluid that is highly viscous has a high resistance and flows slower than a low-viscosity fluid. e.g. Liquids such as water that flow easily, have a lower viscosity than do liquids such as honey.
- It has little effect on the ability of a penetrant material to enter a defect but it does have an effect on the speed at which the penetrant fills a defect.
- The penetrants with less viscosity fill the cracks in less time.



4) Specific Gravity:

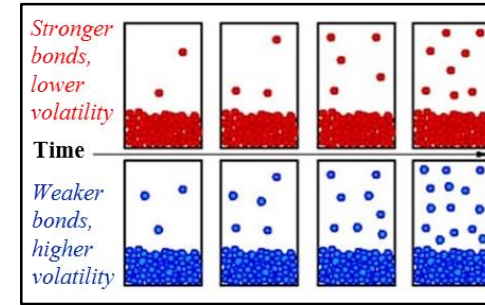
- It is the ratio of density of a substance to the density of distilled water at 40 F (4 °C).
- Most commercial penetrants have a specific gravity of less than one, primarily because they are made up of organic materials having low specific gravities.
- For this reason, water contamination sinks to the bottom of the penetrant tank.

5) Water Washable Penetrant Thermal Stability:

- It is the ability of water washable penetrants to resist physical changes under normal operating conditions.

6) Volatility:

- Volatility is characterized by the vapour pressure or boiling point of a liquid.
- It is associated with the evaporation rate of liquids and it is desirable for penetrant materials to have a low volatility i.e. a high boiling point.
- High volatility results in a loss of penetrant in open tanks.
- A high volatile material will dry on the part during the penetrant dwell, leaving a film that is difficult to remove.
- Entrapped penetrant having high volatility would also have a tendency to dry or lose its liquid properties, resulting in failure to bleed back out of a discontinuity to produce an indication.



7) Fluorescent Dye Thermal Stability:

- The dye used in fluorescent-dye penetrants lose their brightness or colour when subjected to elevated temperature. This loss is termed “heat fade”.
- Aerospace Material Specification (AMS) 2644 specifies the maximum allowable brightness loss as a function of penetrant sensitivity.
- Thermal stability is an important consideration during hot air drying before or after developer application.

8) Flash Point:

- Flash point is the temperature at which sufficient flammable vapour is given off a liquid to form an explosive mixture in air over the liquid.
- The flash point does not affect the performance of a penetrant.
- High flash points are desirable to reduce the hazard of fire.

9) Removability:

- This term describes two conflicting requirements for a penetrant:
 - a. The ability to be removed from a surface leaving little or no residual background.*
 - b. Resistance to being removed from discontinuities.*
- In order to meet the first requirement, the penetrant must maintain the dyes in solution even when in the form of a thin film on the surface of a part and without its more volatile components that have been lost during the dwell time.
- The second requirement is met by the penetrant in discontinuities resisting the removal process.



Developer:

- It's role is to pull the trapped penetrant material out of defects and spread it out on the surface of the part so it can be seen by an inspector.
- It also provide a light background to increase contrast when visual penetrant is used.
- Fine developer particles both reflect and refract the incident ultraviolet light, allowing more of it to interact with the penetrant, causing more efficient fluorescence.
- Developers also create a white background so there is a greater degree of contrast between the indication and the surrounding background.



Characteristics of Good Developer:

- It should have good absorption characteristics.
- It should be chemically inert with test material.
- It should be able to uniformly cover the surface with thin smooth coating.
- It should provide a good contrast background for bright and clean indications.
- It should be non-toxic.
- It should be easy to remove after inspection.

Classification of Developers:

- Developer classification is based on the method that the developer is applied.
- There are four forms of developers in general use:

- Water Soluble Developers*
- Dry Powder Developers*
- Water Suspensible Developers*
- Non-aqueous Developers*

Water Soluble Developers:

- They consist of a group of chemicals that are dissolved in water and form a developer layer when the water is evaporated away.
- The best method for applying water soluble developers is by spraying it on the part.
- Dipping, pouring, or brushing the solution on to the surface is sometimes used but these methods are less desirable.

❑ Dry Powder Developer:

- Dry powder developer is generally considered to be the least sensitive but it is inexpensive to use and easy to apply.
- Dry developers are white, fluffy powder that can be applied to a thoroughly dry surface in a number of ways.

Advantage:

- ❖ When a dry developer is used, indications tend to stay bright and sharp since the penetrant has a limited amount of room to spread.



Applications:

- ✓ The developer can be applied by:
 - ❖ Dipping parts in a container of developer,
 - ❖ Using puffer to dust parts with developer.
 - ❖ Using electrostatic powder spray guns.
 - ❖ Placing part in a dust cabinet where developer is blown around and allowed to settle on the part.

Limitations:

- ❖ Since dry powder developers only stick to the area where penetrant is present, the dry developer does not provide a uniform white background as the other forms of developers do.
- ❖ Having a uniform light background is very important for a visible inspection to be effective and since dry developers do not provide one, they are seldom used for visible inspections.

❑ Water Suspendable Developers:

- Water suspendable developers consist of insoluble developer particles suspended in water.
- Water suspendable developers require frequent stirring or agitation to keep the particles from settling out of suspension.
- Water suspendable developers are applied to parts in the same manner as water soluble developers.
- Parts coated with a water suspendable developer must be forced dried just as parts coated with a water soluble developers are forced dried.
- The surface of a part coated with a water suspendable developer will have a slightly translucent white coating.

❑ Non-aqueous Developers:

- Non-aqueous developers suspend the developer in a volatile solvent and are typically applied with a spray gun.
- Non-aqueous developers are commonly distributed in aerosol spray cans for portability.
- The solvent tends to pull penetrant from the indications by solvent action.
- Since the solvent is highly volatile, forced drying is not required.

Common Uses of Dye Penetrant Inspection:

- Dye penetrant inspection is one of the most widely used non-destructive evaluation methods.
- Its popularity can be attributed to two main factors: its relative ease of use and its flexibility.
- DPI offers flexibility in performing inspections because it can be applied in a large variety of applications ranging from automotive spark plugs to critical aircraft components.
- DPI can be used to inspect almost any material provided that its surface is not extremely rough or porous.
- Materials that are commonly inspected using DPI include the following:
 - Metals (aluminium, copper, steel, titanium, etc.)
 - Glass
 - Many ceramic materials
 - Rubber
 - Plastics



Types of Discontinuities that can be Detected via DPI:

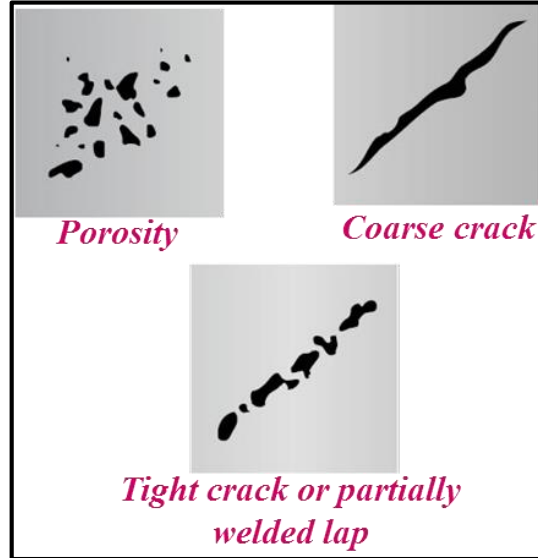
- Dye penetrant inspection can detect all discontinuities that are open to the surface.
 - ❖ **Rolled products**- cracks, seams, laminations.
 - ❖ **Castings**- cold shuts, hot tears, porosity, blow holes, shrinkage.
 - ❖ **Forgings**- cracks, laps, external bursts.
 - ❖ **Welds**- cracks, porosity, undercut, overlap, lack of fusion, lack of penetration, pin holes.
 - ❖ **Others**- Fatigue cracks, quench cracks, grinding cracks, overload and impact fractures.



Different types of defects detected by dye penetrant testing

Typical Penetrant Indications:

- The size of the indication, or accumulation of penetrant, will show the extent of defect and the brilliance will be a measure of its depth.
- Deep cracks will hold more penetrant and will be broader and more brilliant.
- Very fine openings can hold only small amounts of penetrants and will appear as fine lines.



<i>Defect</i>	<i>Penetrant Indications</i>
Casting porosity	Spherical surface indications
Casting cold shut	Dotted lines
Cracks	Straight continuous surface lines
Hot tears	Ragged line of variable width
Heat treat cracks	Multiple irregular lines
Thermal cracks	Interconnecting lines
Lack of fusion	Broken line of varying width
Fatigue cracks	Continuous line in parts
Very tight crack	Series of very small dots in continuous form

False Indications:

- It is an accumulation of penetrant caused by a drop of penetrant left on the workpiece.
- There are two conditions which may create accumulations of penetrant that are sometimes confused with the true crack and discontinuities.

1) *Indications due to inadequate removal of penetrant during rinse process or contamination from work area or hands.*



2) *Non-relevant indications caused by actual surface discontinuities that are present by design (e.g. raised lettering to identify part, press fit parts, etc.)*

- These types of indications can be identified since they are regular in form and shape.

Safety Precautions in DPI:

- When proper health and safety precautions are followed, liquid penetrant inspection operations can be completed without any harm to inspection personnel.
- Some of the most common safety concerns are:

Chemical Safety

☐ **Flammability:**

- Use exhaust fans to disperse vapours.
- Ignition sources must be avoided.

☐ **Skin Irritation:**

- Wear gloves to protect hands.
- Wear safety glasses to protect eyes from splashing.

Ultraviolet Light Safety

☐ **Lamps get hot:**

- So be cautious.

☐ **Report missing or cracked filter on lamps.**

- UV rays can cause sunburn and eye damage if filters not used or not functional.

Typical Applications of DPI:

1. Aerospace:

- ✓ Typical components that are checked by this method include turbine, rotor disc, blades, aircraft wheels, castings, forgings and welded assemblies.

2. Automobiles:

- ✓ Many automotive parts particularly aluminium, castings and forging including pistons and cylinder heads are subjected to this form of quality checks before assembly.

3. Railways:

- ✓ DPI to detect fatigue cracking is also used for the regular in service examination of the bogie frames of railway locomotive and the rolling stock.

4. Tools and dies:

- ✓ Drill bits, drill pipes, castings and drilling equipment are inspected by this method.

5. Inspection on reactors and tanks:

- ✓ Tanks, vessels, reactors, piping, dyers in the chemical and petro-chemical industries.

Advantages of DPI:

- ❖ This method has high sensitivity to small surface discontinuities.
- ❖ The method has few material limitations, i.e. metallic and non-metallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected.
- ❖ Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.
- ❖ Parts with complex geometric shapes are routinely inspected.
- ❖ Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- ❖ Aerosol spray cans make penetrant materials very portable.
- ❖ Penetrant materials and associated equipment are relatively inexpensive.

Limitations of DPI:

- Only surface breaking defects can be detected.
- Only materials with a relatively nonporous and smooth surface can be inspected.
- Pre-cleaning is critical since contaminants can mask defects.
- Metal smearing from machining, grinding, and grit or vapour blasting must be removed prior to DPI.
- The inspector must have direct access to the surface being inspected.
- Surface finish and roughness can affect inspection sensitivity.
- Multiple process operations must be performed under controlled conditions.
- Post cleaning of acceptable parts or materials is required.
- Chemical handling (due to toxicity and flammability) and proper disposal is required.

Summary:

- Dye penetrant inspection is the one of the most widely used low cost inspection method.
- It can be used to locate all kinds of surface breaking flaws in all non-porous materials (metals, plastics, or ceramics).
- Penetrants are classified on the basis of their physical properties, removal techniques, and their strength of indication.
- Developers are classified on the basis of the method of their application.
- Proper health and safety precautions must be followed while performing this test.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 08: Magnetic Particle Inspection



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



What is Magnetic Particle Inspection?

- It is a non-destructive testing process for detecting surface and shallow subsurface discontinuities in ferromagnetic materials such as iron, nickel, cobalt, and some of their alloys.

History:

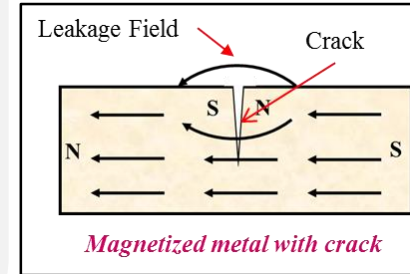
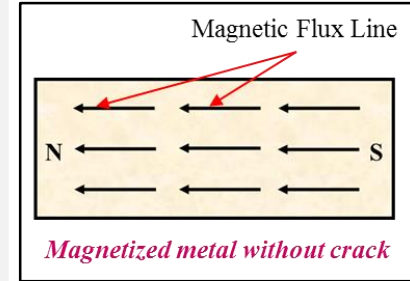
- The earliest known use of magnetism to inspect an object took place as early as 1868. Cannon barrels were checked for defects by magnetizing the barrel then sliding a magnetic compass along the barrel's length.
- In the early 1930s, magnetic particle inspection was quickly replacing the oil-and-whiting method as the method of choice by the railroad industry to inspect steam engine boilers, wheels, axles, and tracks.

- MPI is fast and relatively easy to apply, and part surface preparation is not as critical as it is for some other NDT methods.
- It uses magnetic fields and small magnetic particles (i.e. iron filings) to detect flaws in components.
- The method is used to inspect a variety of product forms including castings, forgings, and weldments.
- Many different industries use magnetic particle inspection for determining a component's fitness-for-use.

Principle of Magnetic Particle Inspection:

Magnetic Flux Leakage:

- Magnetic moments in a ferromagnetic material have the tendency to become aligned parallel to each other under the influence of a magnetic field. However, unlike the moments in a paramagnet, these moments will then remain parallel when a magnetic field is not applied.
- This phenomenon is observed below a critical temperature called as *Curie Temperature*, above which the material behaves like a paramagnetic material.
- When a homogeneous ferromagnetic material is placed in a magnetic field, it gets magnetized and forms a continuous circuit from pole to pole through the material.
- If any surface or sub-surface discontinuity is present, the magnetic flux leaks out of the material since air cannot support as much magnetic field per unit volume as metals.
- As it leaks, magnetic flux will collect ferromagnetic particles (iron powder), making the size and shape of the discontinuity easily visible.



Basic Steps for MPI:

- There are five steps for magnetic particle inspection as:

1. *Part preparation: Component pre-cleaning/degreasing and demagnetizing.*



2. *Introduction of magnetic field.*



3. *Application of fine magnetic particles on the test surface.*



4. *Examination of the component surface for defect.*



5. *Demagnetization of the component.*

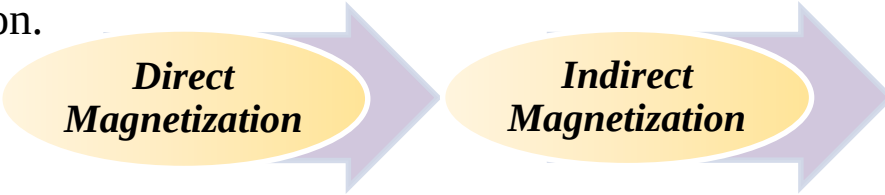
1) Part Preparation:

- When inspecting a test part with the magnetic particle method, it is essential for the particles to have an unimpeded path for migration to both strong and weak leakage fields alike.
- The part's surface should be clean and dry before starting the inspection.
- Contaminants such as oil, grease, or scale may not only prevent particles from being attracted to leakage fields, they may also interfere with interpretation of indications.
- Thin nonconductive coatings, such as paint in the order of 0.02 to 0.05 mm will not normally interfere with the formation of indications, but they must be removed at all points where electrical contact is to be made for direct magnetization.
- If the part/piece holds a residual magnetic field from a previous magnetization that will interfere with the examination, the part must be demagnetized.



2) Introduction of the Magnetic Field:

- There are a variety of methods that can be used to introduce a magnetic field in a component for evaluation using magnetic particle inspection.
- These magnetizing methods are classified as:



**Direct
Magnetization**

**Indirect
Magnetization**

a) **Direct Magnetization (Magnetization Using Direct Induction):**

- ❖ It is also called as current flow method, the magnetizing current flows through the part, thereby, completing the electric circuit.
- ❖ Magnetic field formed during this method is at right angle to the direction of current flow. Thus we can locate the defect at right angles to the applied magnetic field direction.



Precautions:

- ✓ When using the direct magnetization method, care must be taken to ensure that good electrical contact is established and maintained between the test equipment and the test component.
- ✓ Improper contact can result in arcing that may damage the component.
- ✓ It is also possible to overheat components in areas of high resistance such as the contact points and in areas of small cross-sectional area.

Types of Direct Magnetization Techniques:

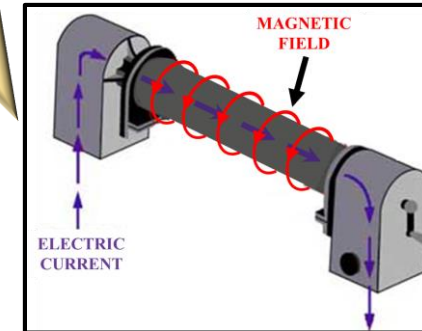
- There are two main methods through which direct magnetization is accomplished. They are:

(i) Head shot Technique

(ii) Using Prods or Clamps Technique

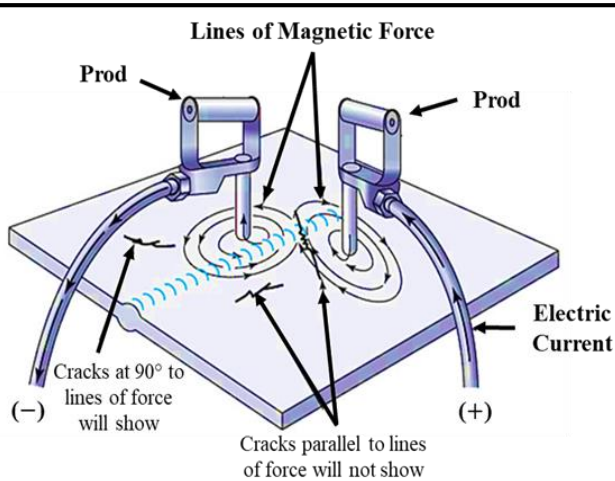
i. Head Shot Technique:

- ✓ Here magnetizing current is passed through the component directly by clamping the component between two electrical contacts.
- ✓ Magnetizing current produces circular magnetic field in and around the component that creates poles on either side of any crack or discontinuity which runs parallel to the length of the part.
- ✓ The pole attract magnetic particles, which form an indication of the discontinuity.
- ✓ When magnetizing current is stopped, a residual magnetic field will remain within the component.
- ✓ The strength of the induced magnetic field is proportional to the amount of current passed through the component.



ii. Using Prods or Clamps Technique:

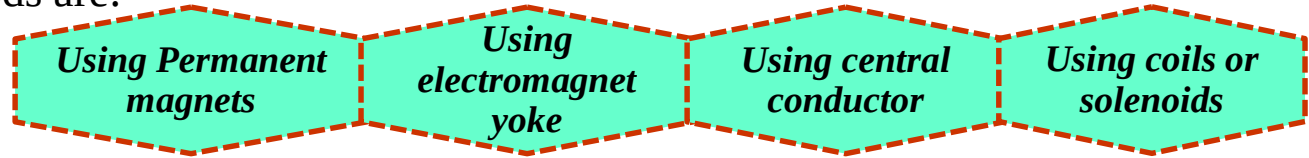
- ✓ Prods are handheld electrodes that are pressed against the surface of the component being inspected to make contact for passing electrical current through the metal.
- ✓ The passing current between the prods create a circular magnetic field around the prods that can be used in magnetic particle inspection.
- ✓ Prods are made from copper and have an insulated handle to help protect the operator.
- ✓ One of the prods has a trigger switch so that the current can be easily and quickly turned on/off.
- ✓ Sometimes two prods are connected by an insulator to facilitate one hand operation.



Weld Examination Using Prods or Clamps Technique

b) Indirect Magnetization (Magnetization Using Indirect Induction):

- ❖ It is accomplished by using a strong external magnetic field to establish a magnetic field within the component.
- ❖ There are several ways that indirect magnetization can be accomplished, some of the common and useful methods are:



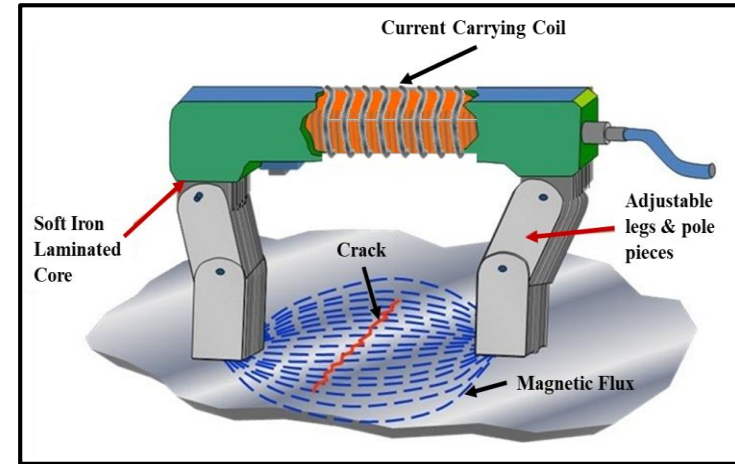
□ Using Permanent Magnets:

- Permanent magnets use is a low cost method of establishing a magnetic field in a part.
- Their use is limited due to lack of control of field strength and the difficulty of placing and removing strong permanent magnets from the component.
- These magnets are used to make inspection under water and explosive environments where electromagnets cannot be used.
- They can also be used in those congested areas where electromagnet cannot be used or where a source of electric power is not available.
- Two types of permanent magnets most commonly are: **Bar Magnets & Yoke Magnets.**



❑ Using Electromagnet Yoke:

- Electromagnets yoke use electric current to produce magnetic field for magnetic particle inspection.
- They eliminate the problems associated with permanent magnets and are used extensively in industry.
- This yoke is basically made by wrapping an electrical coil around a piece of soft iron core.
- Electromagnets only exhibit a magnetic flux when electric current is flowing around the soft iron core.
- The design of an electromagnetic yoke can be based on the use of either direct or alternating current or both.
- When the magnet is placed on the component, a magnetic field is established between the north and south poles of the magnet.
- The legs of the yoke can be either fixed or adjustable.
- Adjustable legs permit changing the contact spacing and relative angle of contact to accommodate irregularly-shaped parts.



Positioning of Electromagnetic Yoke on Test Surface:

- In general, discontinuities to be disclosed should be centrally located in the area between pole and pieces and oriented perpendicular to an imaginary line connecting them.
- Here are some examples to know, how we can use magnetization yoke to make better magnetic particle inspection.



Good Practice



Bad Practice



Good Practice



Bad Practice



Good Practice



Bad Practice



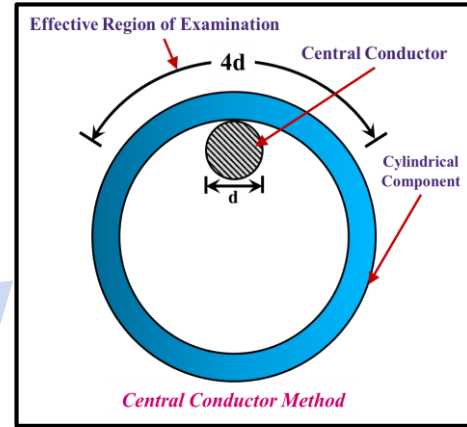
Good Practice



Bad Practice

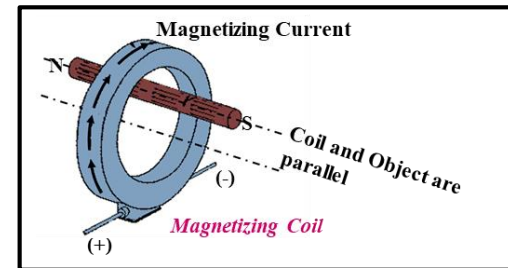
❑ Using Central Conductor:

- Another way of indirectly inducing a magnetic field in a material is by using the magnetic field of a current carrying conductor.
- A circular magnetic field can be established in cylindrical components by using a central conductor.
- In this technique, a conductor carrying high amperage current are passed through the cylindrical components which induces a circular magnetic field in the component to reveal radial and longitudinal defects.
- The effective region of examination when using an offset central conductor is equal to four times the diameter of the conductor as indicated.



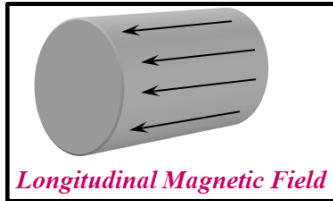
❑ Using Coils or Solenoids:

- When the length of a component is several times larger than its diameter, then we can produce longitudinal magnetic field using coil.
- In this method, the component is placed longitudinally in the concentrated magnetic field that fills the centre of a coil.



Direction of the Magnetic Field:

- The basic principle of magnetization is to produce magnetic lines of force across the expected direction of cracks.
- Two general types of magnetic fields may be established within the specimen:
 1. *Longitudinal Magnetization*
 2. *Circular Magnetization*

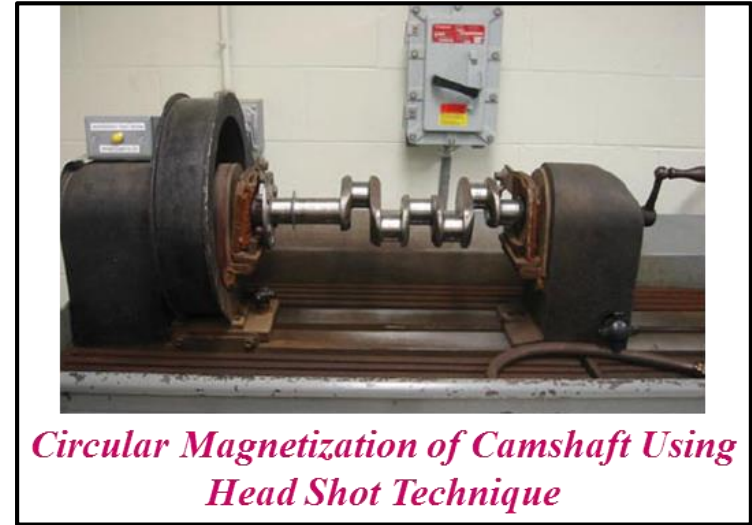
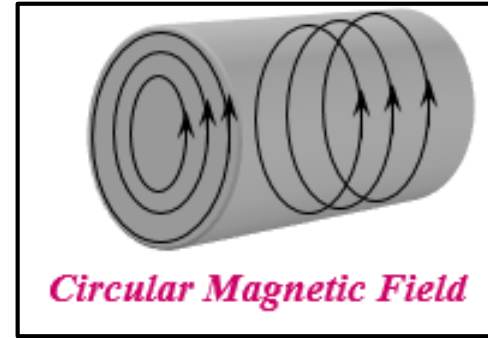


1. Longitudinal Magnetization:

- ✓ It has magnetic lines of force that run parallel to the long axis of the part.
- ✓ Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid.
- ✓ Flexible coil method is useful for large or irregularly shaped parts for which standard solenoids are not available.
- ✓ It can also be accomplished using permanent magnets or electromagnets.

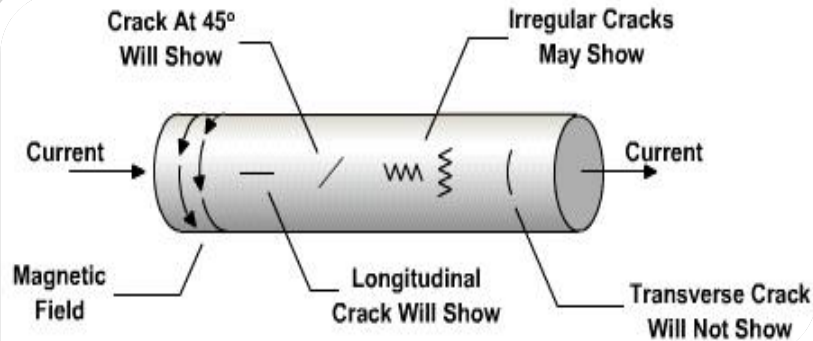
2. Circular Magnetization:

- ✓ It has magnetic lines of force that run circumferentially around the perimeter of a part.
- ✓ A circular magnetic field is induced in an article by either passing current through the component or by passing current through a conductor surrounded by the component.
- ✓ This type of magnetization will locate defects running approximately parallel to the axis of the part.



Magnetic Field Orientation and Flaw Detectability:

- Orientation of the crack relative to the magnetic lines of force determines if the crack can or cannot be detected.
- An orientation of 45 to 90 degrees between the magnetic field and the defect is necessary to form an indication.
- Since defects may occur in various and unknown directions, each part is normally magnetized in two directions at right angles to each other.

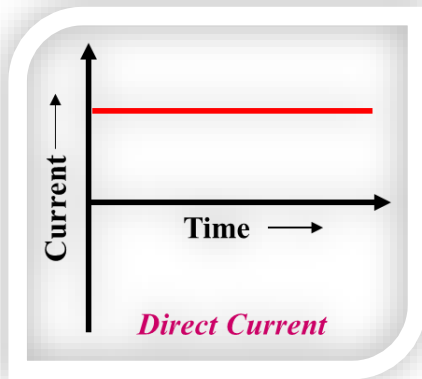


Example:

With circular magnetization, discontinuity that have a significant dimension in the direction of the current (longitudinal defects) are detectable, while transverse-type defects will not be detectable.

Magnetizing Current:

- Electric current used to establish the magnetic field in components during magnetic particle inspection is known as magnetizing current.
- Current flow is often modified to provide the appropriate field within the part.
- The types of magnetizing currents commonly used are:
 - a) Direct Current (DC)
 - b) Alternating Current (AC)
 - c) Rectified Alternating Current

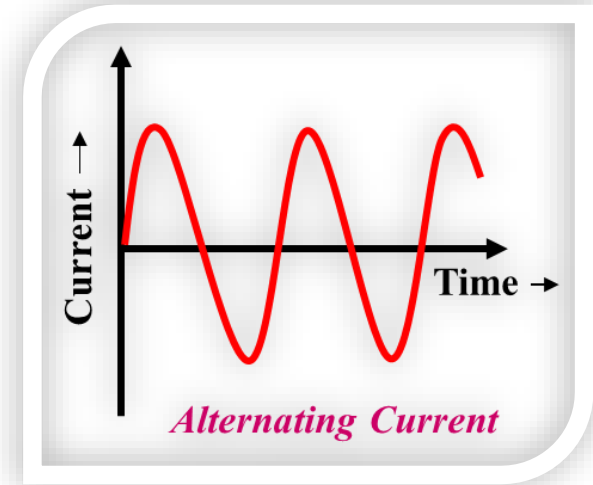


a) Direct Current (DC):

- ✓ Direct current flows continuously in one direction at a constant voltage.
- ✓ DC is very desirable when inspecting for subsurface defects because DC generates a magnetic field that penetrates deeper into the material.
- ✓ In ferromagnetic materials, the magnetic field produced by DC generally penetrates the entire cross-section of the component.
- ✓ Conversely, the field produced using alternating current is concentrated in a thin layer at the surface of the component.

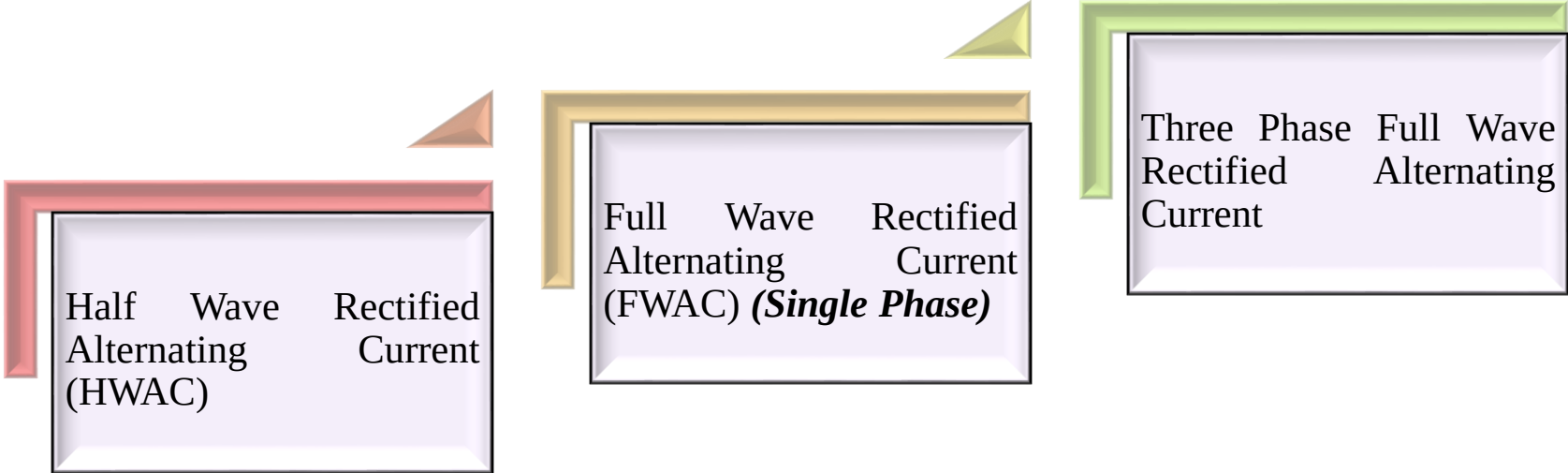
b) Alternating Current (AC):

- ✓ Alternating current reverses in direction at a rate of 50 or 60 cycles per second.
- ✓ Since AC is readily available in most facilities, it is convenient to make use of it for magnetic particle inspection.
- ✓ When AC is used to induce a magnetic field in ferromagnetic materials, the magnetic field will be limited to narrow region at the surface of the component.
- ✓ This phenomenon is known as the "skin effect" and occurs because the changing magnetic field generates eddy currents in the test object.
- ✓ The eddy currents produce a magnetic field that opposes the primary field, thus reducing the net magnetic flux below the surface. Therefore, it is recommended that AC be used only when the inspection is limited to surface defects.



c) Rectified Alternating Current:

- ✓ With the use of rectifiers, the reversing AC can be converted to a one directional current, which is known as rectified alternating current.
- ✓ The three commonly used types of rectified current are:



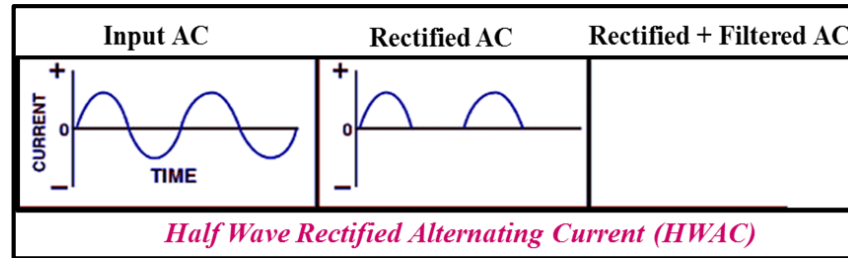
Half Wave Rectified
Alternating Current
(HWAC)

Full Wave Rectified
Alternating Current
(FWAC) (*Single Phase*)

Three Phase Full Wave
Rectified Alternating
Current

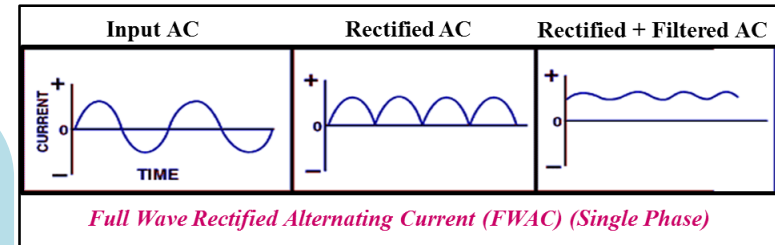
Half Wave Rectified Alternating Current (HWAC):

- When single phase alternating current is passed through a rectifier, current is allowed to flow in only one direction.
- The reverse half of each cycle is blocked out so that a one directional, pulsating current is produced.
- The HWAC repeats at same rate as the unrectified current. Since half of the current is blocked out, the amperage is half of the unaltered AC.
- This type of current is often referred to as half wave DC or pulsating DC.
- The pulsation of the HWAC helps magnetic particle indications form by vibrating the particles and giving them added mobility. This added mobility is especially important when using dry particles.
- The pulsation is reported to significantly improve inspection sensitivity. HWAC is most often used to power electromagnetic yokes.



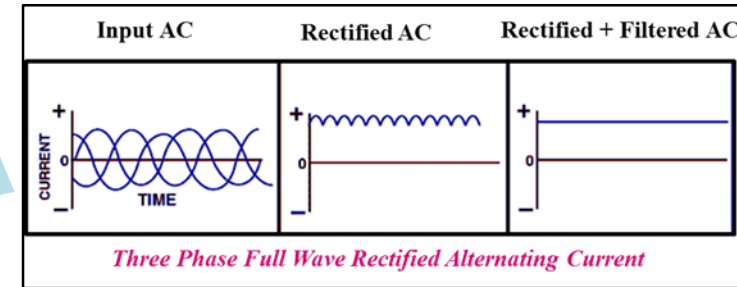
Full Wave Rectified Alternating Current (FWAC) (Single Phase):

- Full wave rectification inverts the negative current to positive current rather than blocking it out.
- This produces a pulsating DC with no interval between the pulses.
- Filtering is usually performed to soften the sharp polarity switching in the rectified current.
- While particle mobility is not as good as half-wave AC due to the reduction in pulsation, the depth of the subsurface magnetic field is improved.



Three Phase Full Wave Rectified Alternating Current:

- Three phase current is often used to power industrial equipment because it has more favourable power transmission and line loading characteristics.
- This type of electrical current is also highly desirable for magnetic particle testing because when it is rectified and filtered, the resulting current very closely resembles direct current.



3) Application of Magnetic Particle:

❖ **Particle Characteristics:** Particles used in MPI are made of finely divided ferromagnetic materials, have the following characteristics:

- **High Magnetic Permeability:**
 - It is important because it makes the particles attract easily to small magnetic leakage fields from discontinuities.
- **Low Retentivity:**
 - It is important because the particles themselves never become strongly magnetized so they do not stick to each other or the surface of the part.
- **Others:**
 - Other properties of importance that affect the sensitivity of the MPI are the **size, shape, density, mobility, and visibility or contrast** of the particles.

❖ There are two basic forms of magnetic particles used in magnetic particle inspection (MPI):

- a) Dry Magnetic Particles
- b) Wet Magnetic Particles

a) Dry Magnetic Particles:

- Dry particles are primarily used for the examination of welds and castings where the detection of discontinuities lying slightly below the surface is considered important.
- They are provided in powder form and available in red, black, yellow, and grey colours.
- Magnetic properties, particle size and shape, and coating method are similar in all colours making the particles equally efficient.
- Choice of powder is then determined primarily by which powder will give the best contrast and visibility on the parts being examined and the degree of sensitivity desired.

Advantages:

- ✓ Excellent for locating discontinuities which are slightly below the surface.
- ✓ Easy to use for large objects and for field examinations with portable equipment.
- ✓ Good mobility when used with alternating current or HWDC.
- ✓ Not as messy as the wet particles, and
- ✓ Equipment usually less expensive.



Limitations:

- ✓ Not as sensitive as the wet method for very fine and shallow cracks.
- ✓ Not easy to cover all surfaces properly, especially of irregularly-shaped or large parts.
- ✓ Slower than the wet particles for large numbers of small parts.
- ✓ Difficult to adapt to an automated test system.

b) Wet Magnetic Particles:

- Magnetic particles are also supplied in a wet suspension such as water or oil.
- These particles are available in two forms: **visible** and **fluorescent** magnetic particles.
- When exposed to near ultraviolet light (black light) fluorescent dye coated magnetic particles glow with a highly visible yellow-green colour.
- Fluorescent particles are particularly useful for corners, key ways and deep holes type discontinuities.

Advantages:

- ✓ This method is more sensitive than dry because the suspension provides the particles with more mobility and makes it possible for smaller particles to be used since dust and adherence to surface contamination is reduced or eliminated.
- ✓ It quickly and thoroughly covers all surfaces of irregularly-shaped parts, large or small, with magnetic particles.
- ✓ It is the fastest and most thorough method for the examination of large numbers of small parts.
- ✓ It is easy to measure and control the concentration of particles in the suspension, which makes for uniformity and accurate reproducibility of results.
- ✓ It is readily adaptable to automated examination.

Limitations:

- Usually wet particles are as reliable of finding discontinuities lying below the surface as dry particles.
- It is messy to work with, especially when used in the field testing.
- A recirculation system is required to keep the particles in suspension.
- It sometimes presents a post-examination cleaning problem.

Application of Fine Magnetic Particles on the Test Surface:

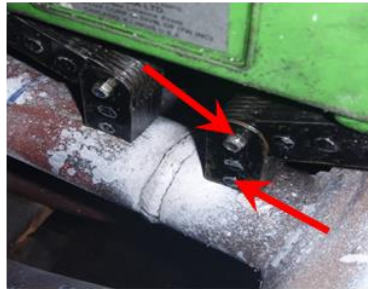
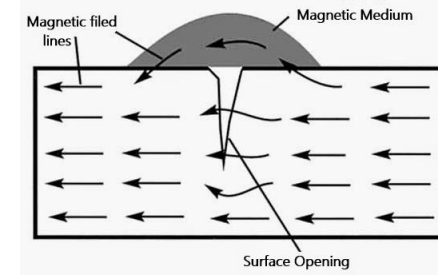
- ***Dry Particles Application:*** Fine magnetic particle in dry powder form are dusted over the test surface.
- ***Wet Particles Application:*** Fine magnetic particles suspended in kerosene or any other liquid are sprayed over the test surface after magnetization.

4) Examination of the Surface:

- When fine particles of magnetic material are applied on the surface of test material, the leakage field attracts particles which forms a outline of the discontinuity and indicate the location, size, extent and shape of the discontinuity.
- Visible particles clusters formed at specimen surface are viewed under white light, whereas fluorescent particles are viewed under black light.

Examples:

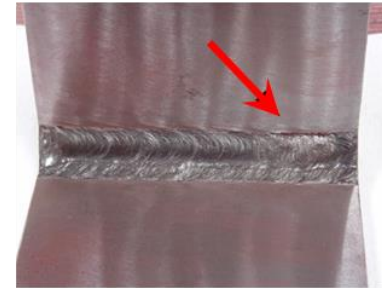
❖ Visible Wet/Dry Particle Method



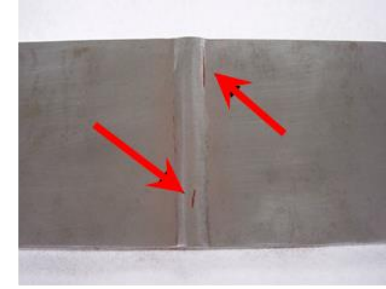
Surface Defect in Gas Pipe Weld



Crack in Seal Weld of Boiler Tube to Steam Drum



Lack of Fusion in SMAW Weld

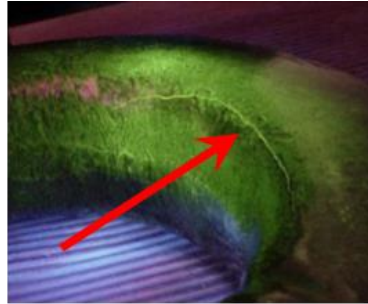


Throat and Toe Cracks in Partially Ground Weld

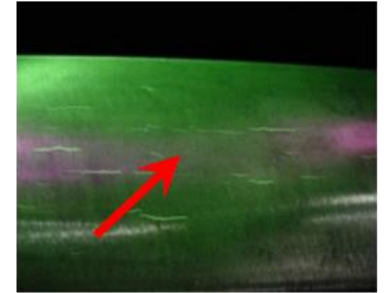
❖ Fluorescent Wet Particle Method



Crane Hook with Service Induced Crack



Drive Shaft with Heat Treatment Induced Cracks



Gear with Service Induced Crack



Large Bolt with Service Induced Crack



5) Demagnetization:

- Parts inspected by the magnetic particle method may sometimes have an objectionable residual magnetic field that may interfere with subsequent manufacturing operations or service of the component.

Retained magnetic field depends upon:

Magnetic characteristics of component.

Geometry of the component.

Direction of the magnetization.

Strength of the magnetic field.

Effects of Residual Magnetism:

- ✓ It affect machining by causing cuttings to cling to a component.
- ✓ Interfere with navigational instruments that are sensitive to magnetic fields if placed in close proximity.
- ✓ Create a condition known as "arc blow" in the welding process. Arc blow may cause the weld arc to wonder or filler metal to be repelled from the weld.
- ✓ Cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Methods of Demagnetization:

- There are two methods of demagnetization as:

Heating Method:

- ✓ This random orientation of magnetic domains can be achieved most effectively by heating the material above its curie temperature.
- ✓ When part is heated above its curie temperature, it loses its magnetic properties.
- ✓ When it is cooled back down, it will go through a reverse transformation and will contain no residual magnetic field.
- ✓ The material should also be placed with its long axis in an east-west orientation to avoid any influence of Earth's magnetic field.

Electrical Method:

- ✓ Subjecting the component to a reversing and decreasing magnetic field will return the dipoles to a nearly random orientation throughout the material.
- ✓ To demagnetize a part, the current or magnetic field needed has to be equal to or greater than the current or magnetic field used to magnetize the part.
- ✓ The current or magnetic field is then slowly reduced to zero, leaving the part demagnetized.

Advantages, Limitations & Applications of Magnetic Particle Inspection:

Advantages:

- ✓ Rapid and economical compared to other NDT methods.
- ✓ Staff can be trained quite rapidly to operate a procedure.
- ✓ It can detect both surface and near sub-surface discontinuity.
- ✓ It can inspect parts with irregular shapes easily.
- ✓ Pre-cleaning of components is not as critical as it is for some other inspection methods.
- ✓ Inspection and indications are fast and visible directly on the specimen surface.
- ✓ Very portable method especially when used with battery powered equipment.

Limitations:

- ✓ It can only be used on ferromagnetic materials. Unable to inspect non-ferrous materials such as aluminium, magnesium or most stainless steels.
- ✓ It is only effective for seeking surface breaking or near-surface defects.
- ✓ Components or materials must be magnetized in at least two directions for complete coverage.
- ✓ Components or materials often must be demagnetized after magnetic particle testing.
- ✓ Weldments with different magnetic characteristics of base metal and weld metal are difficult to inspect.
- ✓ Post cleaning, and post demagnetization is often necessary.

Applications:

- Industries that use MPI are structural steel, automotive, petrochemical, power generation, and aerospace industries.
- Underwater inspection is another area where MPI may be used to test items such as offshore structures and underwater pipelines.

Summary:

- Magnetic particle inspection is a fast and relatively easy NDT method for surface/subsurface flaw inspection in ferromagnetic materials.
- It is based on the magnetic flux leakage caused by material discontinuities, which collects magnetic particles (either dry or in a wet suspension) to form indications.
- Different types of direct/indirect methods are used to magnetize the component to perform the inspection.
- After conducting a magnetic particle inspection, it is usually necessary to demagnetize the component as it may interfere with manufacturing processes or service.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 09: Eddy Current Inspection



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology

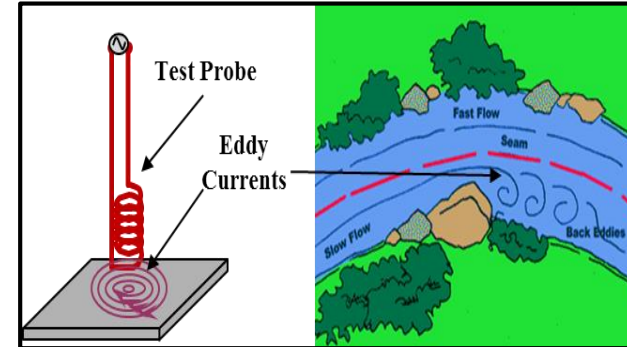


Introduction:

- Eddy current inspection has its origins with Michael Faraday's discovery of electromagnetic induction in 1831.
- Its development as a non-destructive testing technique for industrial applications was carried out during World War II in Germany.
- Eddy current testing (ECT) is widely used in aerospace industry and in other manufacturing and service environments that require inspection of thin metal for potential safety-related or quality-related problems.

What is Eddy Current?

- ❖ Eddy currents are electrical currents induced within a conductor by a varying magnetic field.
- ❖ They get their name from “eddies” that are formed when a liquid or gas flows in a circular path around obstacles when conditions are right.



Properties of Eddy Currents:

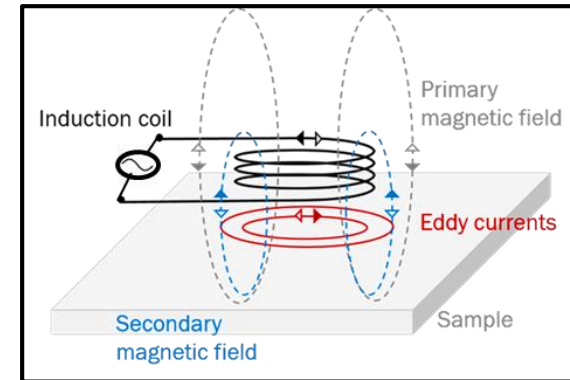
- ✓ They flow in closed loops within conductor.
- ✓ They flow in a plane that is parallel to coil winding or material surface.
- ✓ They attenuate and lag in phase with depth.

Basic Principle of Eddy Current Testing (ECT):

- Eddy current testing works on the principle of electromagnetic induction to detect flaws in conductive materials.

Electromagnetic Induction:

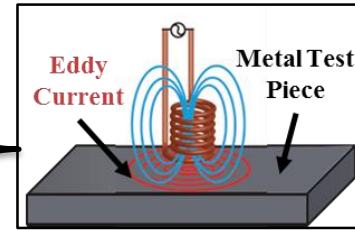
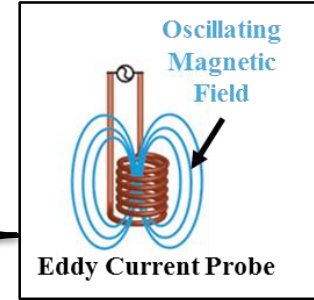
- ❖ When the magnetic flux through a conductor changes, induced currents are set up in close paths on the surface of the conductor.
- ❖ These currents are in a direction perpendicular to the magnetic flux and are called Eddy Current.



How It Works?

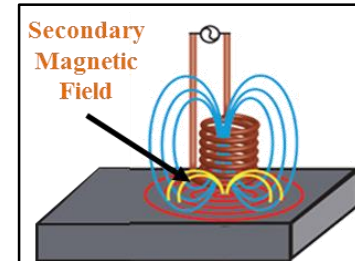
Step-1: Generation of Eddy Currents

- In order to generate eddy currents for an inspection a “probe” is used.
- Inside the probe is a length of electrical conductor which is formed into a coil.
- Alternating current is passed through the coil, which generates an oscillating magnetic field.
- The probe and its magnetic field are brought close to a metal test piece.
- A circular flow of electrons known as an Eddy Current will begin to move through the metal.



Step-2: Secondary magnetic field is set up in opposite direction

- Eddy currents flowing in the material will generate their own “secondary” magnetic field which will oppose the coil’s “primary” magnetic field.

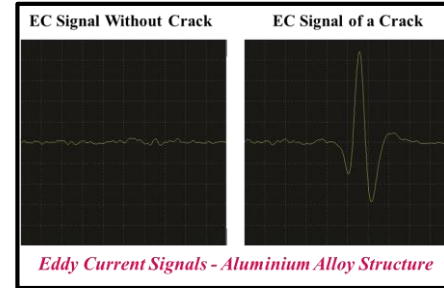


Step-3: Impedance of the coil is changed

- Changes in metal thickness or defects like near-surface cracking will interrupt or alter the amplitude and pattern of the eddy current and the resulting magnetic field.
- This in turn affects movement of electrons in coil by varying the electrical impedance of the coil.

Step-4: Change in impedance is analysed

- Eddy current instrument plots changes in the impedance amplitude and phase angle, which can be used by a trained operator to identify changes in the test piece.



Factors Affecting Eddy Current Response:

Electromagnetic Factors:

- σ : Electrical conductivity of the sample.
- μ : Magnetic permeability of the sample.
- f : Excitation frequency.

Geometric Factors:

- **Coil parameters:** loop area, number of turns, diameter of wire.
- **Lift-off:** Proximity of excitation or pickup coil to the sample (implies coupling efficiency).
- **Sample Geometry:** Thickness compared to skin depth, shape, lateral dimensions.
- Probe proximity to sample edges.

Eddy Current Density and Depth of Penetration:

- Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil.
- Eddy current density decreases exponentially with depth. This phenomenon is known as the **Skin Effect**.

What causes the Skin Effect?

- ❖ Skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases.

Factors Affecting Depth of Penetration:

- Frequency of the excitation current.
- Electrical conductivity of the specimen.
- Magnetic permeability of the specimen.

Standard Depth of Penetration:

- The depth that the eddy currents are only $1/e$, or about 37% as strong as they are on the surface is known as the standard depth of penetration or skin depth.
- It can be calculated by using following equation:

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

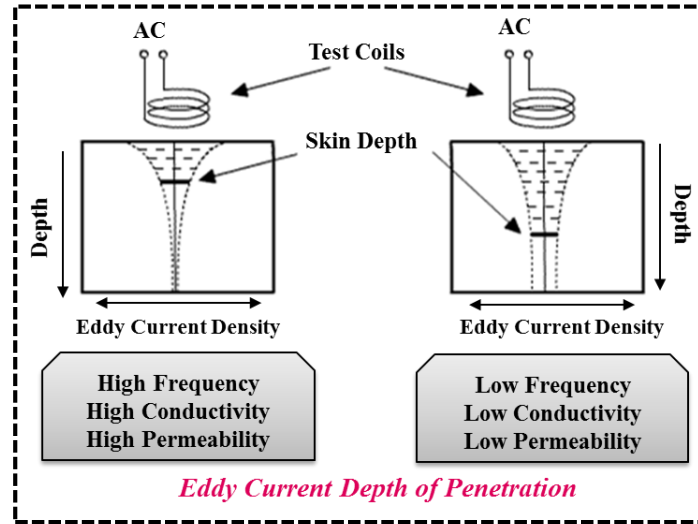
Where:

δ = Standard depth of penetration (m)

f = Test frequency (Hz)

μ = Magnetic permeability (H/m)

σ = Electrical Conductivity (S/m)



Working with this Equation:

- ✓ If relative permeability (μ_r) is given, it must be converted to an absolute permeability (μ) as: $\mu = \mu_r \mu_0$
where, $\mu_0 = 4\pi \times 10^{-7}$ H/m (permeability of free space).
- ✓ As per the **International Annealed Copper Standard (IACS)**, electrical conductivity values are often expressed as a percent of the conductivity of pure annealed copper measured at 25°C, which can be converted to siemens/meter as:

$$\sigma_{\text{material}} = \% \text{ IACS} \times \sigma_{\text{copper}} \quad \text{Where, } \sigma_{\text{copper}} = 5.8 \times 10^7 \text{ S/m}$$

Eddy Current Equipment:

- Equipment for eddy current inspection are very diversified and proper equipment selection is important if accurate inspection data is desired for a particular application.
- As a minimum, at least three basic pieces of equipment are needed for any eddy current examination:

1. Instrumentation

2. Probes

3. Reference Standards

1. Instrumentation

- Eddy current instruments are available in a large variety of configurations and they are commonly classified by the type of display used to present the data.
- The common display types are:
 - a) Analog Meter
 - b) Digital Meter
 - c) Eddy Scope(Impedance Plane Display)

a) Analog Meters:

- ✓ They are used for many different inspection applications such as crack detection, material thickness measurements, nonconductive coating measurements or conductive coating measurements.

b) Digital Meters:

- ✓ They are designed to examine conductivity of test component or nonconductive coating thickness.
- ✓ A digital meter contains an analogue-to-digital converter (to change the input voltage to a number) and a digital readout to display this number
- ✓ These meters tend to have slightly higher accuracy than analog devices.

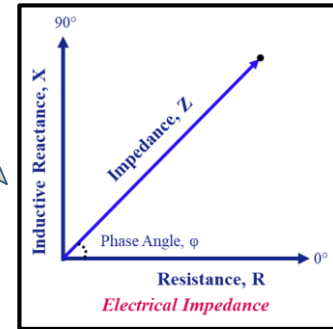


c) Eddy Scopes (Impedance Plane Display):

- ✓ Eddy scopes are another category of instrumentation and they present the inspection data in the form of an impedance plane diagram.

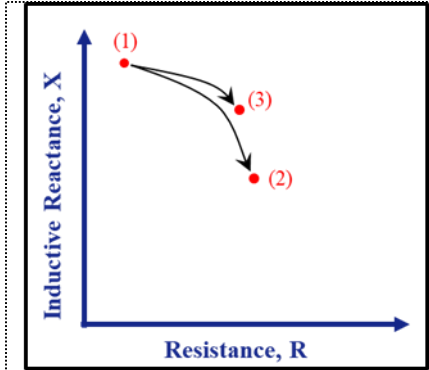
On the impedance diagram, the total impedance is displayed by plotting its resistance component and inductive reactance component at 90° to each other.

- **Resistance:** It is the opposition offered by a substance to the flow of current.
- **Inductive Reactance:** It is the opposite reaction of the coil against the alternating current (changing current) flowing through it.



Impedance Plane Trajectory of a Coil Over a Nonferromagnetic Specimen With and Without Discontinuity:

- If the eddy current probe is balanced in air and then placed on a non-ferromagnetic specimen:
 - ✓ The **resistance** component will **increase** (because eddy currents are being generated in the specimen and this takes energy away from the coil, which shows up as resistance)
 - ✓ The **inductive reactance** of the coil **decreases** (because the magnetic field created by the eddy currents opposes the coil's magnetic field and the net effect is a weaker magnetic field to produce inductance).
- The presence of discontinuity or inhomogeneity in the test specimen causes a reduction as well as a redistribution of the eddy currents; consequently, the changes in the coil impedance are reduced.

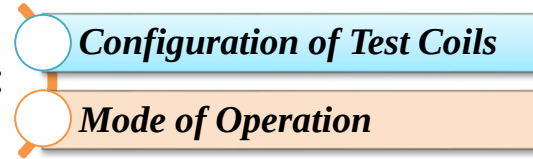


- (1) Coil in air
- (2) Coil over specimen with no discontinuities
- (3) Coil over specimen with a discontinuity



2. Eddy Current Probes:

- Eddy current probes are available in a large variety of shapes and sizes.
- One of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications.
- Eddy current probes are classified on the basis of:



Classification of Eddy Current Probes on the basis of Configuration:

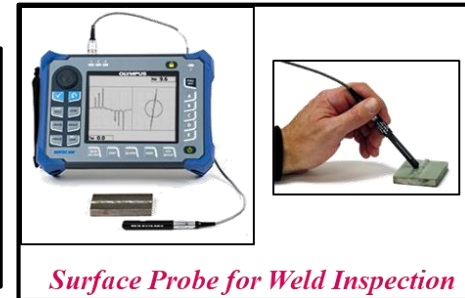
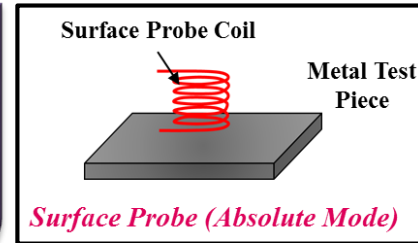
- The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest.
- Some of the common classifications of probes based on their configuration include:
 - i. *Surface Probe*
 - ii. *Bolt Hole Probes*
 - iii. *Inside Diameter or Internal Bobbin Probes*
 - iv. *Outside Diameter or Encircling Probes*

i. Surface Probes:

- Surface probe or Pancake probe, usually a spring mounted flat probe or a pointed pencil type probe, allows determining the exact location of a defect.
- The probe may be hand held, may be mounted on automated scanners or may even be rotated around to get e.g. a helical scan in tube/rod inspections.
- Usually ferrite cores (absolute cylindrical as well as split-D differential types) and shields are used for enhanced sensitivity and resolution.
- This coil configuration is good for detecting surface discontinuities that are oriented perpendicular to the test surface.
- Discontinuities, such as delamination's, that are in a parallel plane to the test surface will likely go undetected with this coil configuration.

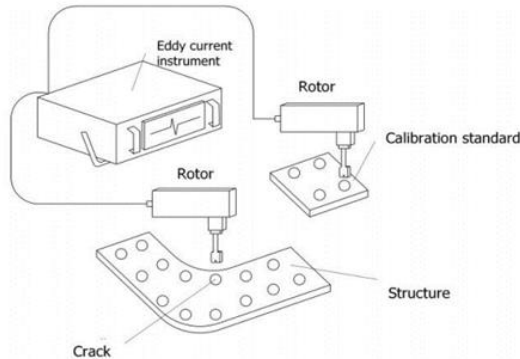
Applications:

- ✓ Crack detection
- ✓ Weld inspection
- ✓ Detection of corrosion/exfoliation in hidden layers



ii. Bolt Hole Probes:

- They are intended exclusively for bolt hole testing with manual probe guidance.
- The main application field for these probes lies in testing bores on aircraft.
- They have a surface coil that is mounted inside a housing that matches the diameter of the hole being inspected.
- The probe is inserted in the hole and the scanner rotates the probe within the hole.



Bolt Hole Eddy Current Inspection Equipment

Contain holes with EDM (Electrical Discharge Machining) notches for instrument calibration



Reference Standards



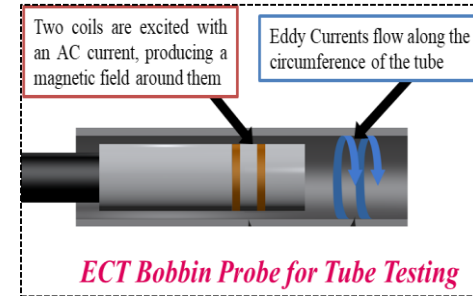
Bolt Hole Probes

iii. Inside Diameter (ID) or Internal Bobbin Probes:

- They consist of a coil arrangement in the form of a winding over a bobbin, which passes through components such as tubes and scans the entire inside surface in one-go.
- The ID probes have a housing that keep the probe centered in the product and the coil(s) orientation somewhat constant relative to the test surface.
- The directional properties of these probes are identical to encircling probes.

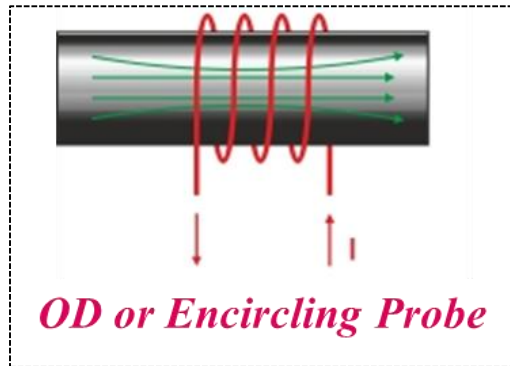
Applications:

- ✓ High-speed multi-frequency inspection of heat exchanger tubes in-situ for detection of cracks, wall thinning and corrosion in tubes as well as under support plate regions.
- ✓ In some instances, bobbin type probes are employed for inspection of bolt holes.
- ✓ Hollow products, such as pipes, to inspect from the inside out.



iv. Outside Diameter (OD) or Encircling Probes:

- They are similar to ID probes except that the coil(s) encircle the material to inspect from the outside in.
- In an encircling probe the coil is in the form of a solenoid into which the component is placed.
- In this arrangement, the entire outside circumferential surface of the component covered by the coil is scanned at a time, giving high-inspection speeds.
- These probes may not detect circumferential defects as the eddy currents flow parallel to them without getting distorted.



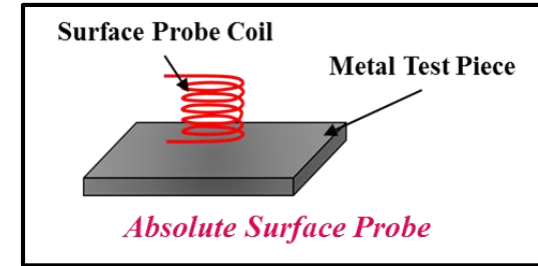
Applications:

- Popular industrial application of encircling probes is high-speed inspection of tubes from outside during the manufacturing stages.
- Encircling probes are used to inspect solid products, such as rods, tubes and wires.

Classification of Eddy Current Probes on the basis of Mode of Operation:

- Mode of operation refers to the way the coil or coils are wired and interface with the test equipment.
- The mode of operation of a probe generally falls into one of four categories:

- Absolute Mode Probe*
- Differential Mode Probe*
- Reflection Mode Probe*
- Hybrid Mode Probe*



i. Absolute Mode Probe:

- Absolute probes generally have a single test coil that is used to generate the eddy currents and sense changes in the eddy current field.
- Absolute probes provide an absolute voltage signal.

Applications:

• Absolute coils can be used for:

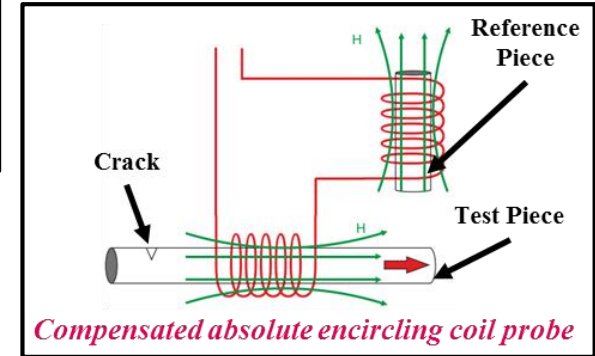
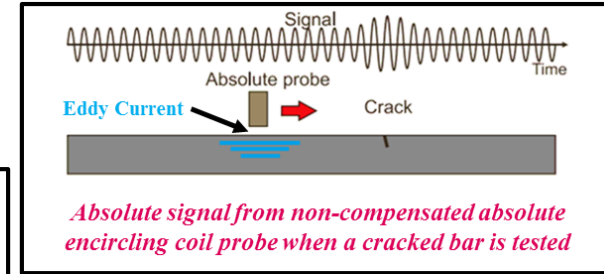
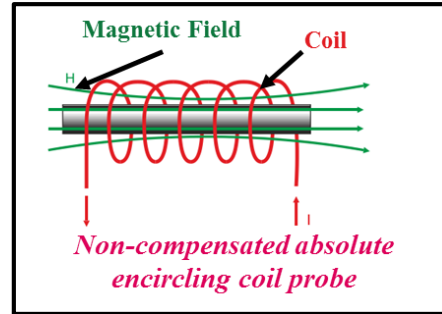
- Flaw detection
- Conductivity measurements
- Lift-off measurements
- Thickness measurements

Important Consideration for Absolute Mode Probes:

- Absolute probes are sensitive to things such as conductivity, permeability lift-off and temperature.
- Steps must be taken to minimize these variables when they are not important to the inspection being performed.

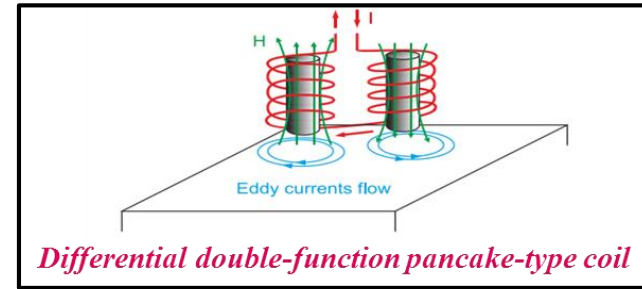
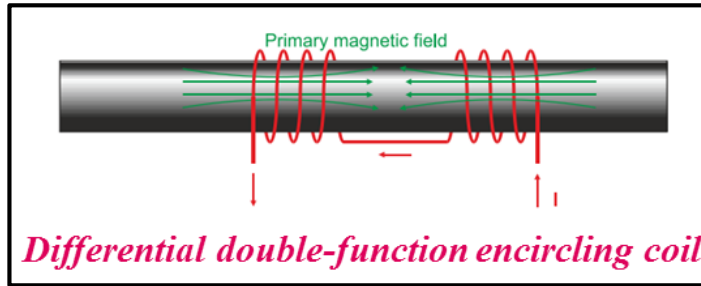
Example:

- ✓ Commercially available absolute probes have a voltage compensation using an additional reference coil that compensates for ambient temperature variations.
- ✓ A null voltage signal is measured when there is no defect which increases the instrument's dynamic range.
- ✓ Furthermore, they are less sensitive to temperature changes than non-compensated probes.



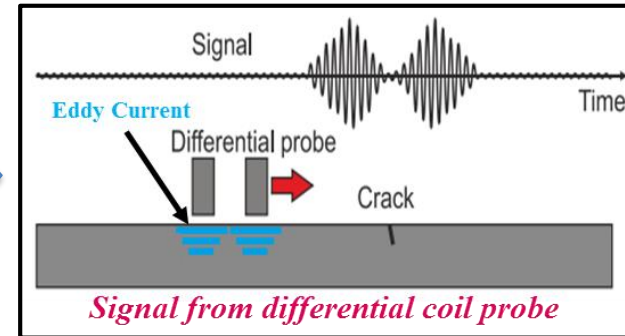
ii. Differential Mode Probe:

- Differential probes consist of two coils that compare two adjacent parts of the inspected material.
- The detecting coils are wound in the opposite directions to one another in order to equalize the induced voltages originated by the excitation primary field.



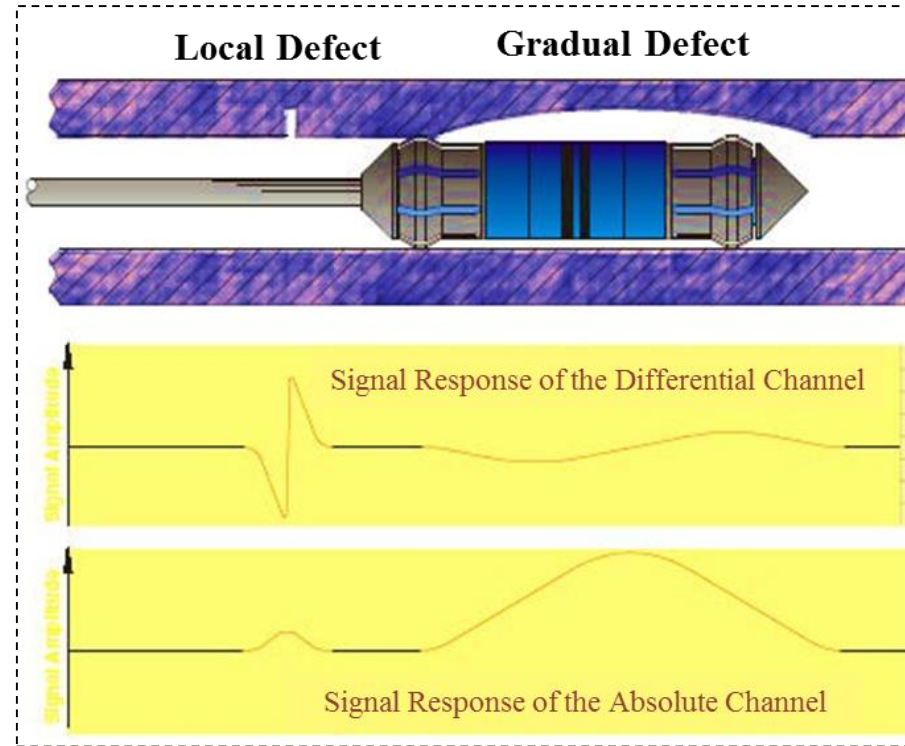
Signal From Differential Probe:

- ✓ The output voltage of the differential coil probe is zero when there is no crack inside the probe.
- ✓ Cracks in the test material, which moves at a constant speed, alter the balance, and two pulses in the voltage signal are detected.



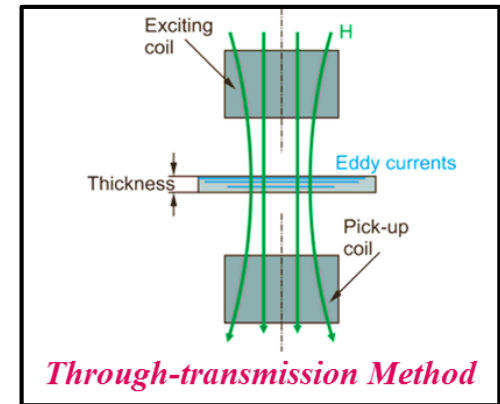
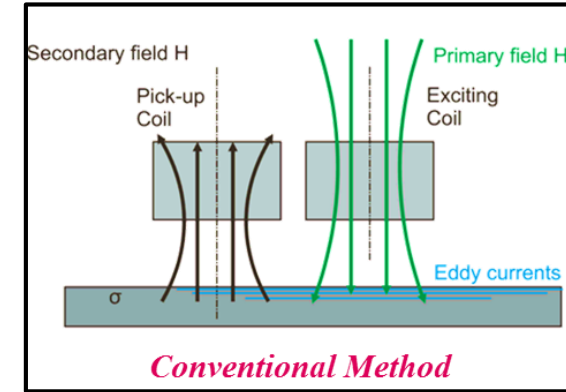
Eddy Current Signal Responses to Local and Gradual Defects:

- Differential coils have the advantage of being able to detect very small discontinuities.
- However, differential coils do not detect gradual dimensional or composition variations of the test piece, as the coils are typically very close.



iii. Reflection Probe:

- Reflection probes have two coils similar to a differential probe, but one coil is used to excite the eddy currents and the other is used to sense changes in the test material.
- Probes of this arrangement are often referred to as send-receive or driver-pickup probes.
- The advantage of reflection probes is that the driver and pickup coils can be separately optimized for their intended purpose.
- The driver coil can be made so as to produce a strong and uniform flux field in the vicinity of the pickup coil, while the pickup coil can be made very small so that it will be sensitive to very small defects.
- The through-transmission method is sometimes used when complete penetration of plates and tube walls is required.

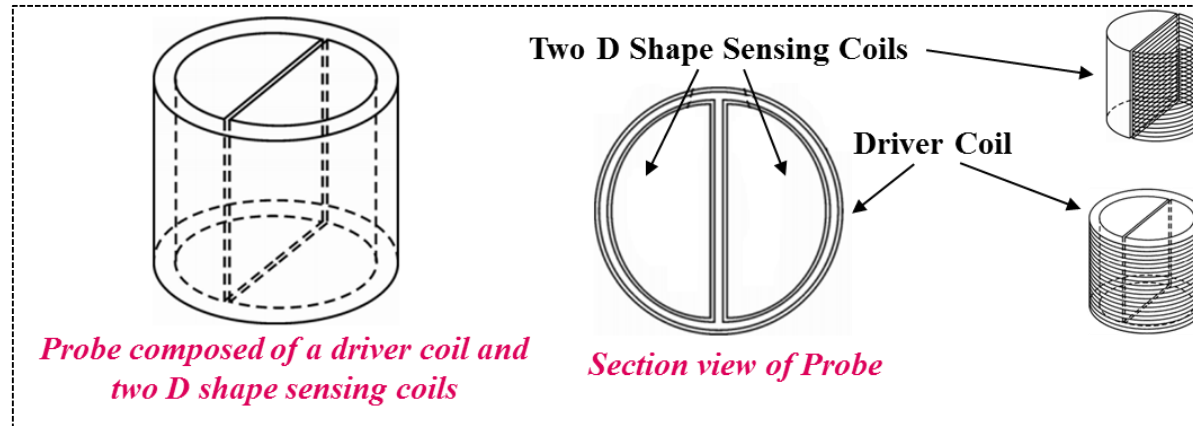


iv. Hybrid Probe:

- These eddy current probes are specially designed for a specific inspection application and they work on two or more than two different operating modes.
- This type of probe is very sensitive to surface cracks.

✓ **Example: Split D, Differential Probe**

- It has a driver coil that surrounds two D shaped sensing coils.
- It operates in the reflection mode but additionally, its sensing coils operate in the differential mode.



Selection of Eddy Current Probes:

- Probes selection is critical in acquiring adequate inspection data.

Several factors to consider include:

- *Material penetration requirements (surface vs. subsurface)*
- *Sensitivity requirements*
- *Type of probe connections on eddy current instrument*
- *Probe and instrument impedance matching (will probe work with instrument)*
- *Probe size*
- *Probe type (absolute, differential, reflection or hybrid)*

Some Tips for Selection of Eddy Current Probes:

- Surface probes for plates and encircling probes for tubes, bars.
- Small diameter probes for shallow and fine defects on smooth surfaces (smaller probes penetrate less).
- Large diameter probes for sub-surface defects and rough surfaces.
- Differential coils are used for temperature compensation and drift.
- Probes with wear resistant coatings and ceramic insulation are used for high temperature applications.

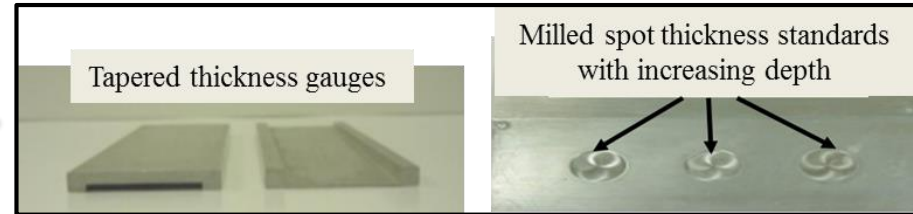
Reference Standards:

- In order to give the eddy current inspector useful data while conducting an inspection, signals generated from the test specimen must be compared with known values.
- In almost all cases, eddy current inspection equipment are configured using reference standards.
- Reference standards are typically manufactured from the same or very similar material as the test specimen.
- Many different types of standards exist for due to the variety of eddy current inspections performed.

Examples:

Material thickness standards:

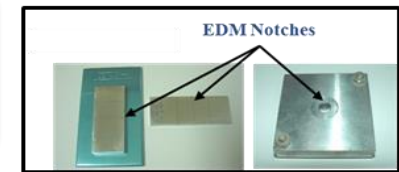
- Material thickness standards used to help determine material thinning caused by corrosion or erosion.



Non-conductive Coating Standards:

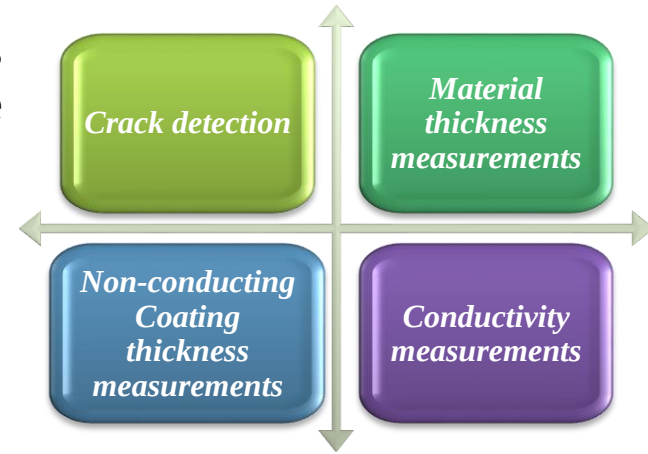
- Nonconductive coating (paint) standard with various thickness of paint on aluminium substrate.

Crack Standards:



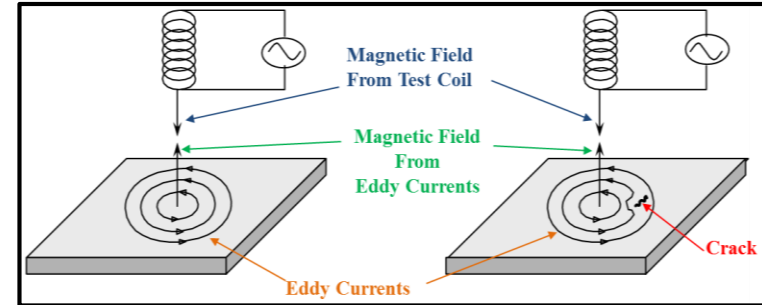
Applications of Eddy Current Inspection:

- One of the major advantages of eddy current as an NDT tool is the variety of inspections and measurements that can be performed.
- In the proper circumstances, eddy currents can be used for: →



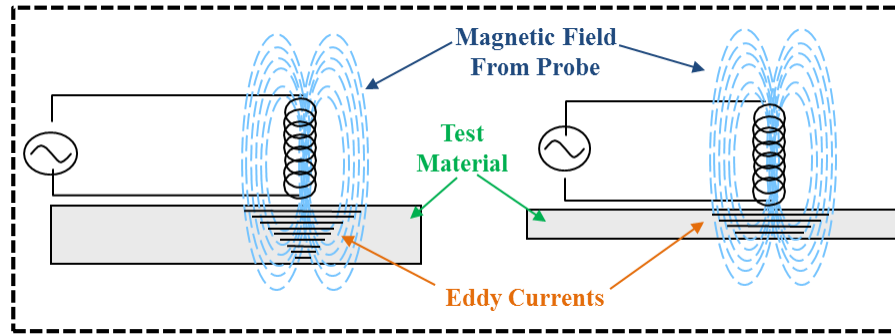
1) Crack Detection:

- ✓ It is the primary uses of eddy current inspection.
- ✓ Cracks cause a disruption in the circular flow patterns of the eddy currents and weaken their strength.
- ✓ This change in strength at the crack location can be detected.



2) Material Thickness Measurement:

- ✓ Thickness measurements are possible with eddy current inspection within certain limitations.
- ✓ Only a certain amount of eddy currents can form in a given volume of material.
- ✓ Therefore, thicker materials will support more eddy currents than thinner materials.
- ✓ The strength (amount) of eddy currents can be measured and related to the material thickness.

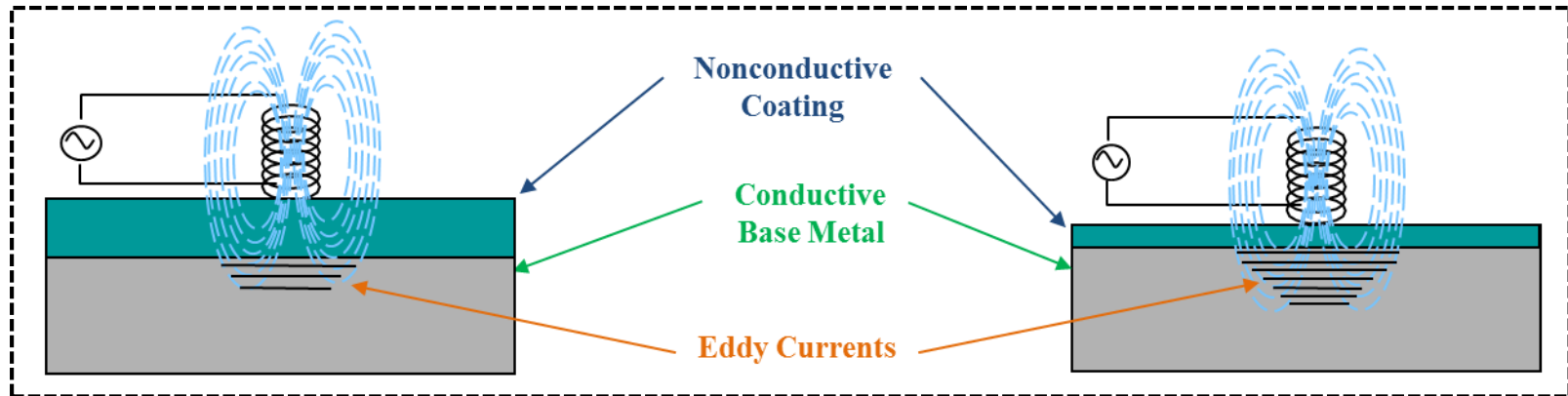


Industrial Applications:

- Eddy current inspection is used in aviation industries to detect material loss due to corrosion and erosion.
- It is used to inspect tubing at power generation and petrochemical facilities for corrosion and erosion.

3) Non-conducting Coating Measurement:

- ✓ Nonconductive coatings on electrically conductive substrates can be measured very accurately with eddy current inspection.
- ✓ The coating displaces the eddy current probe from the conductive base material and this weakens the strength of the eddy currents.
- ✓ This reduction in strength can be measured and related to coating thickness.



4) Conductivity Measurements:

- ✓ This technique involves nulling an absolute probe in air and placing the probe in contact with the sample surface.
- ✓ For nonmagnetic materials, the change in impedance of coil can be correlated directly to the conductivity of the material and hence conductivity of material can be measured.

Applications of Conductivity Measurement Technique:

- The value of the electrical conductivity of a metal depends on several factors like chemical composition and the stress state of its crystalline structure.
- So, electrical conductivity information can be used for:
 - *Material identification.*
 - *Sorting magnetic materials from non-magnetic materials.*
 - *Heat damage detection.*
 - *Case depth determination.*
 - *Heat treatment monitoring.*

Some important points to consider for conductivity measurements:

- It is important to control factors that can affect the results such as inspection temperature and the part geometry.
- Conductivity changes with temperature so measurements should be made at a constant temperature.
- Thickness of specimen should generally be greater than three standard depths of penetration.

Advantages & Limitations of ECT:

Advantages:

- Sensitive to small cracks and other defects.
- Detects surface and near surface defects.
- Inspection gives immediate results.
- Equipment is very portable.
- Method can be used for much more than flaw detection.
- Minimum part preparation is required.
- Test probe does not need to contact the part.
- Inspects complex shapes and sizes of conductive materials.

Limitations:

- Only conductive materials can be inspected.
- Surface must be accessible to the probe.
- Skill and training required is more extensive than other techniques.
- Surface finish and roughness may interfere.
- Reference standards needed for setup.
- Depth of penetration is limited.
- Flaws such as delamination's that lie parallel to the probe coil winding and probe scan direction are undetectable.

Summary:

- Eddy-current testing uses the principle of electromagnetic induction, to detect and characterize surface and sub-surface flaws in conductive materials.
- Eddy current probes used for inspection can be custom designed for a wide variety of applications.
- A variety of inspections and measurements (e.g. crack detection, thickness and conductivity measurements) can be performed using this method.
- It is widely used in automotive and aircraft manufacturing, and it is an integral part of inspection and maintenance in the power generation and aircraft industries.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 10: Ultrasonic Inspection



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Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology

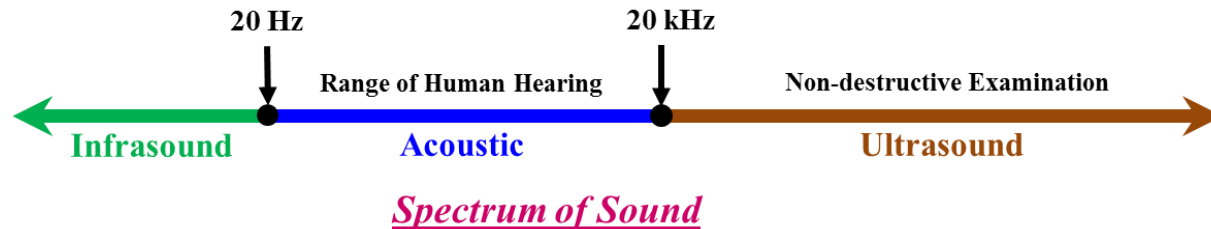


Introduction:

- Ultrasonic Inspection is a non-destructive test method that uses ultrasonic waves to conduct examinations and make measurements.
- Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more.

What are Ultrasonic Waves?

- ❖ Ultrasonic waves are high (“ultra”) frequency sound (“sonic”) waves.
- ❖ They vibrate at a frequency above the upper audible limit of human hearing i.e. 20,000 vibrations per second, or 20 kHz.



Properties of Ultrasonic Waves:

- Ultrasonic waves are no different from 'normal' (audible) sound in its physical properties, except in that humans cannot hear it.
- They have the following properties:
 - ✓ *Ultrasonic waves cannot travel through vacuum.*
 - ✓ *These waves travel with speed of sound in a given medium.*
 - ✓ *Their velocity remains constant in homogeneous media.*
 - ✓ *They are reflected and refracted just like light waves.*
 - ✓ *Their velocity mainly depends on the density and Young's modulus of material.*
 - ✓ *Speed of ultrasonic waves is more in more dense media: $v_{gas} < v_{liquid} < v_{solid}$*

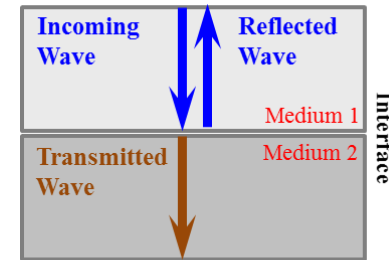
Example:



Principle of Ultrasonic Inspection:

Acoustic Impedance:

- Acoustic impedance (Z) of a material is defined as the product of its density (ρ) and acoustic velocity (V):
$$Z = \rho V$$
- Ultrasound travels in a very straight line and get reflected when it strikes an interface between materials with different speeds of sound (acoustic impedance).
- An interface between materials with a larger difference in acoustic impedance reflects ultrasonic waves more strongly.
- Interface with smaller difference in acoustic impedance reflects them less strongly and lets part of them travel through.



Wave Propagation at an Interface

The fraction of the incident wave intensity that is reflected can be calculated as:

$$R = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1} \right]^2$$

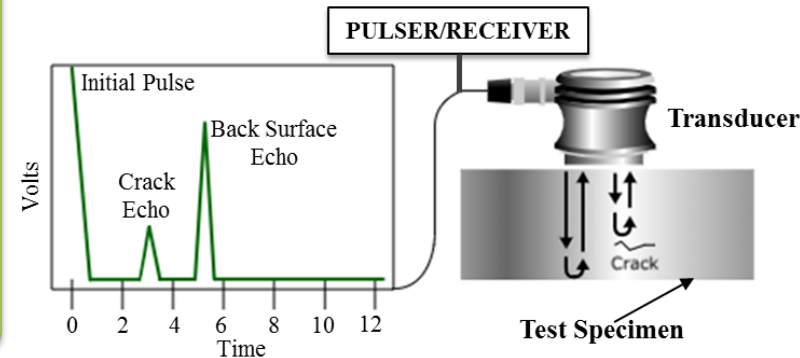
Where, Z_1 and Z_2 are the acoustic impedances of medium 1 and 2 respectively.

How it works?

- A pulser/receiver is an electronic device that is used to produce high voltage electrical pulses.
- Driven by the pulser, the transducer generates high frequency ultrasonic energy.
- The sound energy is introduced and propagates through the materials in the form of waves.
- When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface.
- Reflected wave signal is transformed into an electrical signal by transducer and is displayed on a screen.

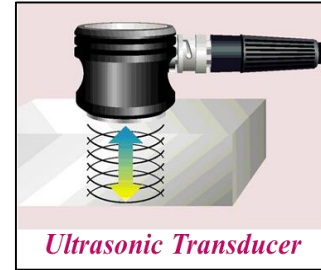
Plot of Electrical Signal vs Time:

- ✓ Signal travel time can be directly related to the distance that the signal travelled.
- ✓ From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.



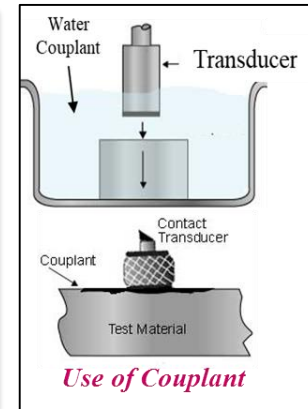
Ultrasonic Transducers:

- These are also called Probe or search unit which generate and receive ultrasound of all frequencies and intensity.
- Transducers for flaw detection come in a wide variety of sizes, frequencies, and case styles, but most have a common internal structure.
- In selecting a transducer for a given application, it is important to choose the desired frequency, bandwidth, size and in some cases focusing which optimizes the inspection capabilities.



Use of Couplant Material:

- Couplant material (usually liquid) is used to facilitate the transmission of ultrasonic energy from the transducer into the test specimen.
- It is necessary because the acoustic impedance mismatch between air and test specimen is large.
- The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained.

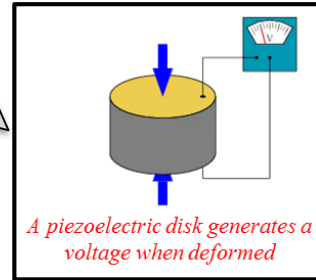


Working Principle of Transducer:

- The active element of the transducer is a thin disk of piezoelectric ceramic or piezocomposite that works on the phenomenon of piezoelectricity.

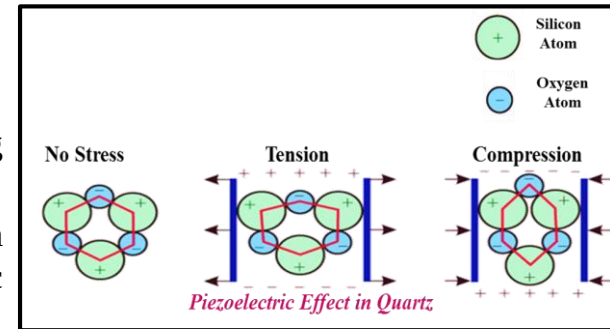
What is Piezoelectricity or Piezoelectric Effect?

- When crystals of some materials are subjected to a mechanical pressure in a certain direction, charges of opposite sign develop on their faces, normal to the direction of the applied pressure.
- This phenomenon is known as the piezoelectric effect.
- It is a reversible process: means electrical signal can be converted into mechanical vibrations.



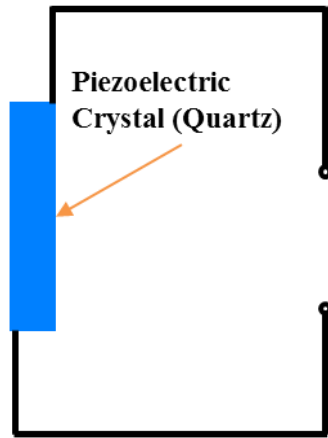
What causes Piezoelectric Effect?

- This effect works because of the movement of atoms in the crystal's molecules.
- Piezoelectric crystals are composed of positive and negative ions in an alternating fashion.
- Tension and compression, push and pull these positive and negative away from either other, creating an energy gradient across the crystal and allowing an electric current to flow.

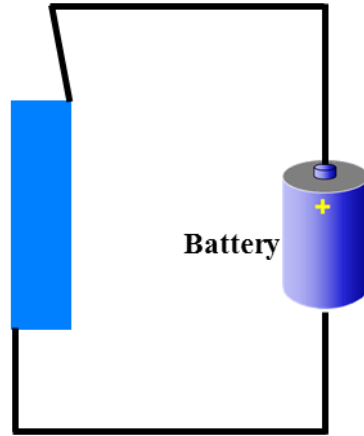


Ultrasound Generation with Transducer:

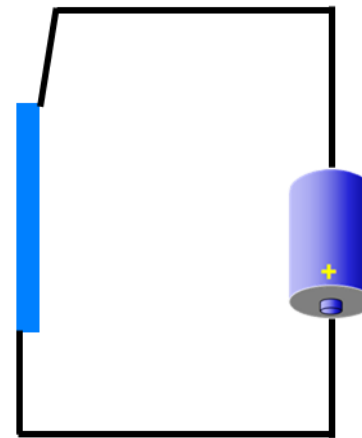
- A piezoelectric element in the transducer converts electrical energy into mechanical vibrations.



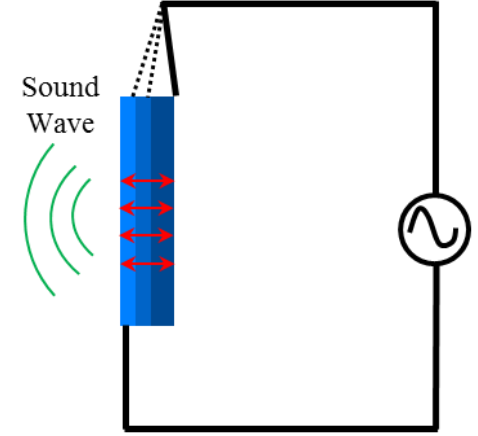
Piezoelectric crystal in its un-deformed state.



The crystal gets thicker, due to distortion of the crystal lattice.



The effect inverses with change in polarity.



An alternating voltage generates crystal vibrations.

Ultrasonic Wave Propagation:

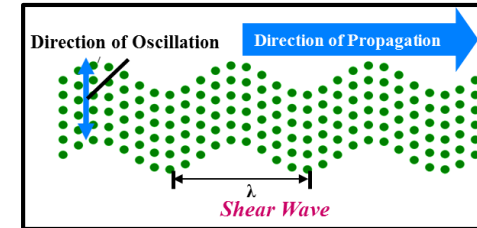
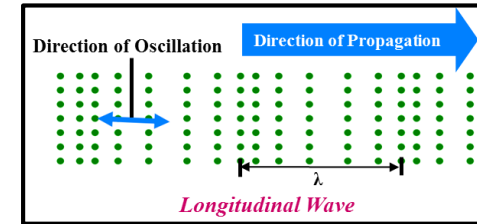
- Ultrasonic waves propagate through a medium due to vibratory or oscillatory motions of its particles.
- In solids, molecules can support vibrations in multiple directions, hence, a number of wave modes are possible.
- Two predominant types of waves, or wave modes generated within a material with ultrasonic waves are:

➤ Longitudinal Waves (L-waves):

- ✓ L-waves compress and decompress the material in the direction of motion, much like sound waves in air.
- ✓ They propagate in all kind of materials.

➤ Shear Waves (S-waves):

- ✓ S-waves vibrate particles at right angles compared to the motion of the ultrasonic wave.
- ✓ They only propagate in solid bodies.
- ✓ The velocity of shear waves through a material is approximately half that of the longitudinal waves.



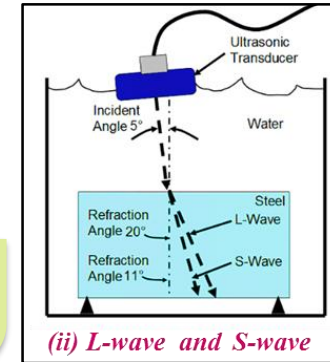
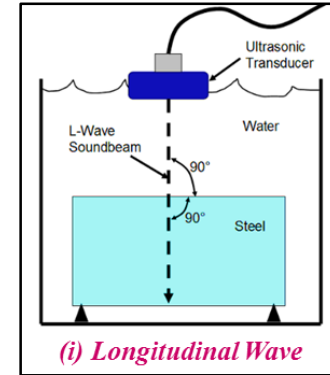
Ultrasonic Wave Mode Conversion:

- The angle in which the ultrasonic wave enters the material determines whether longitudinal, shear, or both waves are produced.

Example:

- ❖ Ultrasonic transducer transmits an ultrasonic wave through water into a block of steel.
 - i. When the direction of the ultrasonic wave is at 90° angle with the surface of the steel block.
 - ✓ No refraction occurs and the L-wave is preserved.
 - ii. When the transducer is rotated at an angle (5° in this case).
 - ✓ The longitudinal from the transducer is converted into two modes, longitudinal and shear, and both wave modes are refracted.
 - ✓ L-waves and S-waves have different angles of refraction because they have dissimilar velocities within the same material.

Angles that create two wave modes are not appropriate because they cause the ultrasonic transducer to receive multiple echoes, making it difficult to analyse the data.

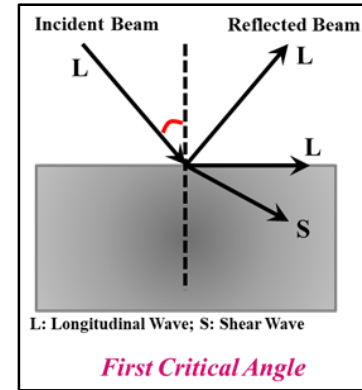


Critical Angle:

- Critical angle is one of the parameter used to avoid the problem of two wave mode generation.

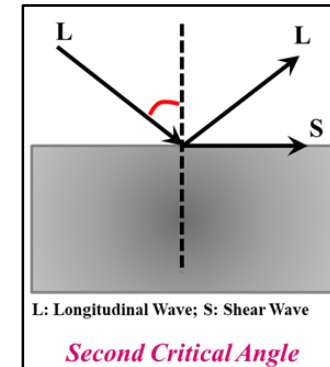
i. First Critical Angle:

- As the angle of the ultrasonic transducer continues to increase, L-waves move closer to the surface of the test specimen.
- The angle at which the L-wave is parallel with the surface of the test specimen is referred to as the first critical angle.
- This angle is useful for two reasons:
 - i. Only one wave mode is echoed back to the transducer, making it easy to interpret the data.
 - ii. Also, this angle gives the test system the ability to look at surfaces that are not parallel to the front surface, such as welds.



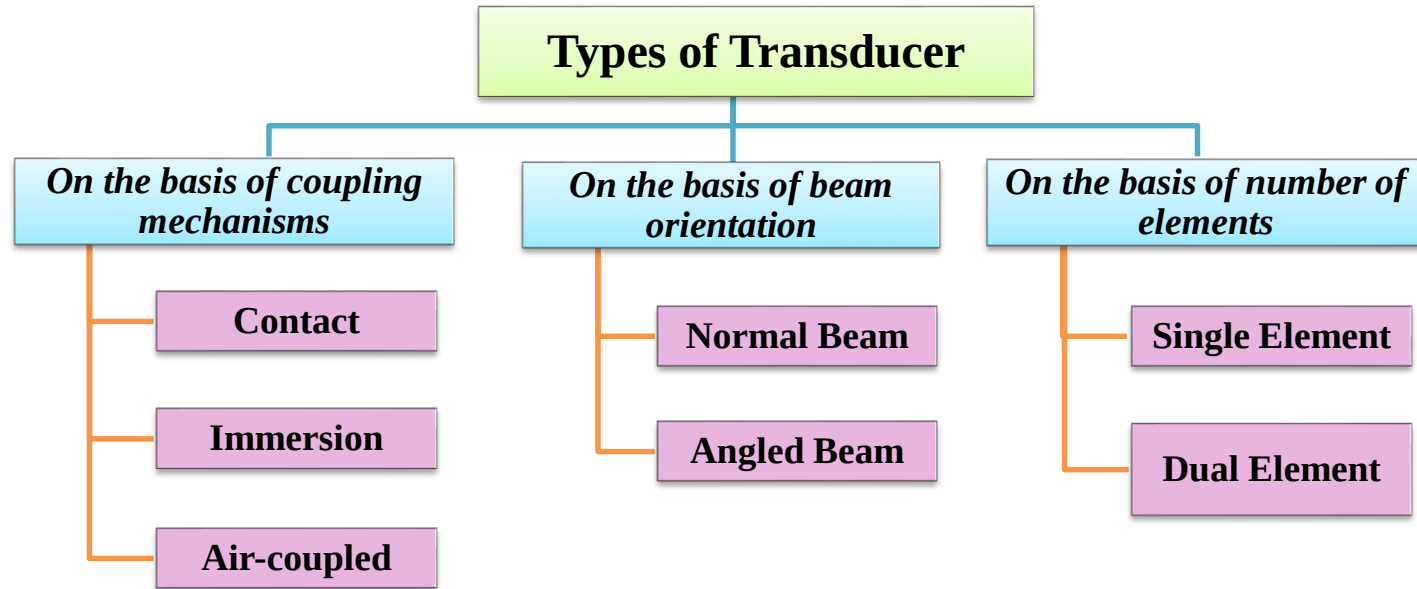
ii. Second Critical Angle:

- The second critical angle is an incident angle that makes the angle of refraction for the shear wave 90° .
- At this point, all of the wave energy is reflected or refracted into a surface following shear wave or shear creep wave.



Classification of Transducers (Probes):

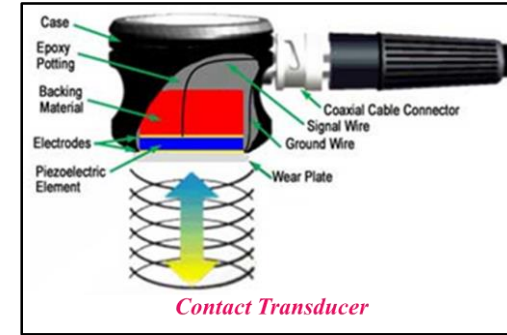
- Piezoelectric transducers can be classified on the basis of coupling mechanism, the beam orientation, the environment where used, and in other ways.
- Some of the most common classifications are:



Classification of Transducer on the Basis of Coupling Mechanisms:

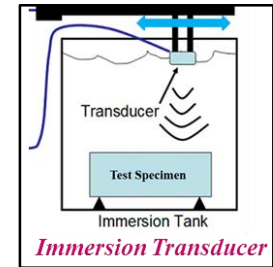
a) Contact Transducer:

- They appear to come into direct contact with the test specimen.
- They require some form of liquid or dry couplant to adequately couple the ultrasound to and from the test specimen.



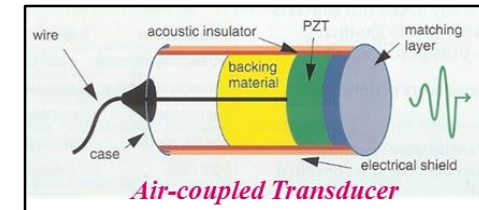
b) Immersion Transducer:

- Immersion transducers operate in a scanning tank where the specimen and the transducer are fully immersed with in the fluid (typically water).



c) Air-coupled Transducer:

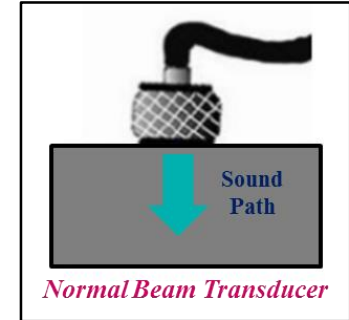
- Air-coupled transducers require a special layer of material (impedance matching layer) to help send a pulse through air to the sample.
- This layer should have an impedance that is intermediate between the acoustic impedances of the transducer and the air.



Classification of Transducer on the Basis of Beam Orientation:

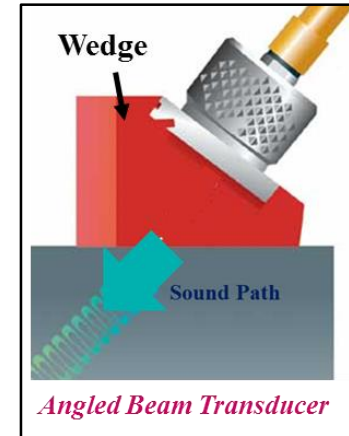
a) Normal Beam Transducer:

- Normal beam transducers transmit a wave normal to the face of the transducer.



b) Angled Beam Transducer:

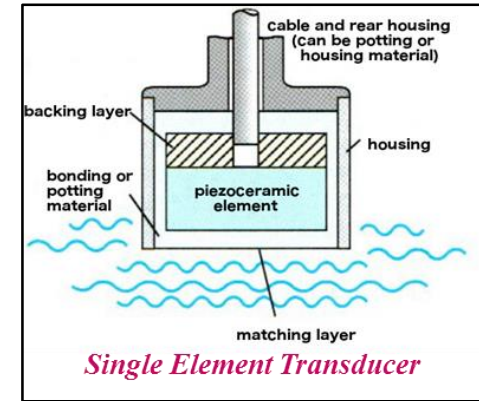
- Angled beam transducers transmit a wave at an angle (not normal) to the face of the transducer.
- Angled beam or refracting transducers are usually just longitudinal normal-beam transducers attached to a wedge (often made of plastic).
- Wedge angles are designed to operate between the first and second critical angle, to create only a mode-converted shear wave.



Classification of Transducer on the Basis of Number of Elements:

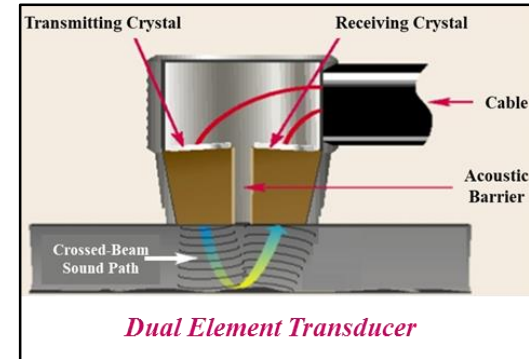
a) Single Element Transducer:

- Single element transducer contain one active ceramic element.
- This often results in reduced cost and simplicity in design.



b) Dual Elements Transducer:

- Dual-element transducers contain separate transmitter and receiver elements housed in a common case.
- This arrangement improves near surface resolution because the second transducer does not need to complete a transmit function before listening for echoes.
- Dual elements are commonly employed in thickness gauging of thin materials.



Basic Test Techniques:

- Ultrasonic testing is a very versatile inspection method and inspections can be accomplished in a number of different ways.
- It depends on the nature of product, manufacturing process, surface condition, geometry and accessibility of the scanning area.

Classifications of Test Techniques:

Ultrasonic inspection techniques are commonly divided into three primary classifications as follows:

a) Pulse-echo and Through Transmission Technique:

- (Relates to whether reflected or transmitted energy is used).

b) Contact and Immersion Technique:

- (Relates to the method of coupling the transducer to the test article).

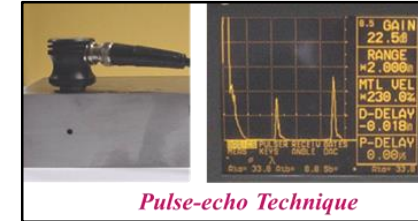
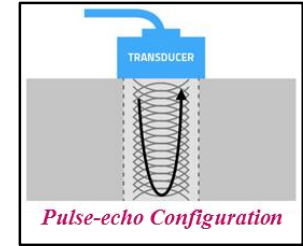
c) Normal Beam and Angle Beam Technique:

- (Relates to the angle that the sound energy enters the test article).



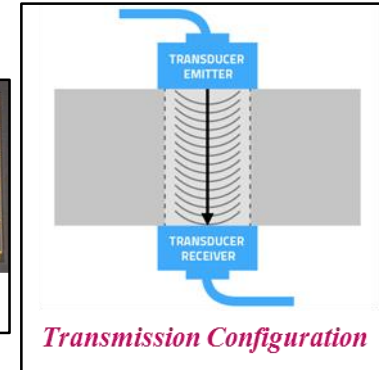
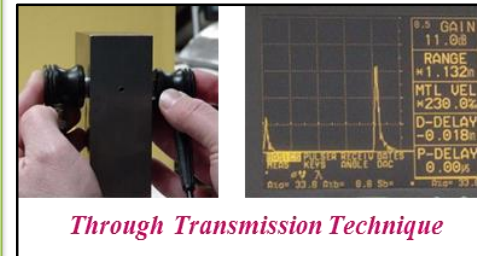
Pulse-echo Technique:

- Pulses of ultrasonic waves (by the transducer) are transmitted into the material under test.
- Reflected waves (or echo) by discontinuities are received by the same or other transducer and displayed on the CRT.
- The relative size and depth of the discontinuity in term of amplitude and appropriately calibrated form are displayed on the CRT.
- The **pulse-echo technique** allows testing when access to only one side of the material is possible.



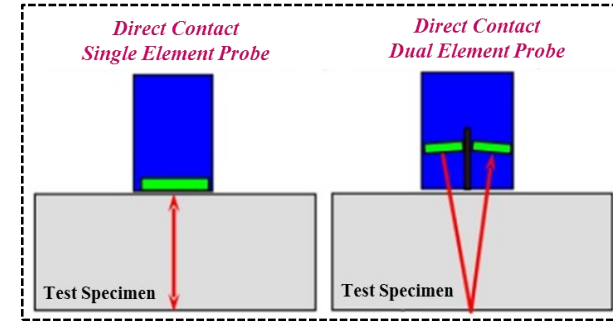
Through Transmission Technique:

- Two transducers located on opposite sides of the test specimen are used.
- One transducer acts as a transmitter and other as a receiver.
- **Through transmission** is useful in detecting discontinuities that are not good reflectors, and when signal strength is weak.



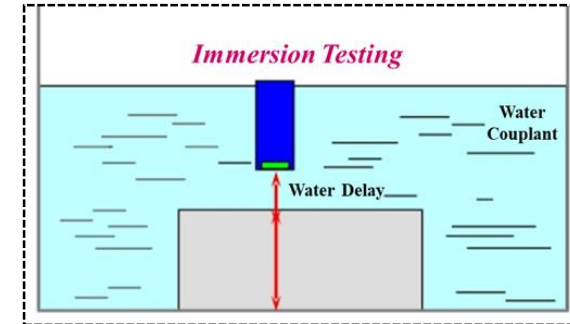
Contact Mode Testing:

- In contact mode of testing, the transducer is kept in contact with the test object with a couplant.
- A thin film of oil, glycerine or water is generally used as couplant between the transducer and the test surface.
- It is commonly used for manual inspection.



Immersion Technique:

- In immersion testing, the specimen and the transducer are immersed in a water bath.
- This arrangement allows better movement of the transducer while maintaining consistent coupling (i.e. water).
- Immersion testing is employed to achieve high speed and automatic scanning with enhanced flaw detection efficiency.



Normal Beam Inspection:

- In normal beam testing, the sound beam is introduced into the test article at 90° to the surface.
- Location of a discontinuity in a part or structure is found by accurately measuring the transit time of ultrasonic pulse.
- The results are expressed by using the following well-known relationship:

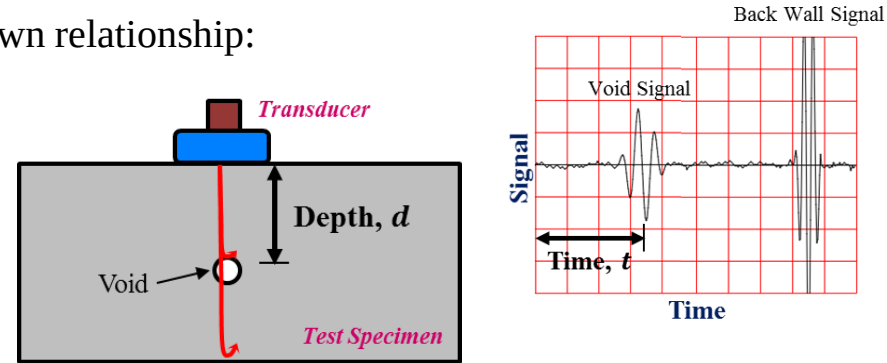
$$d = \frac{v \times t}{2}$$

Where,

d = distance from the surface to the discontinuity in the test piece,

v = the velocity of sound waves in the material,

t = is the measured round-trip transit time.

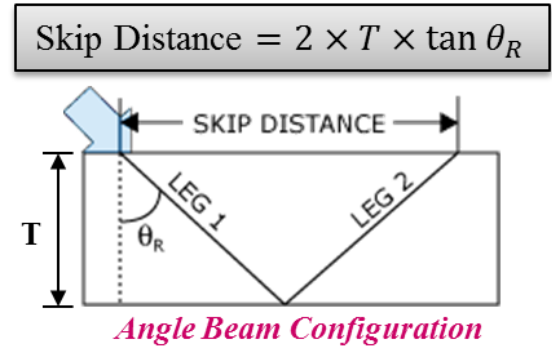


Angle Beam Inspection:

- In angle beam testing, the sound beam is introduced into the test article at some angle other than 90°.
- This technique is typically used to introduce a refracted shear wave into the test material.
- An angled sound path allows the sound beam to come in from the side, thereby improving detectability of flaws in and around welded areas.

Angle Beam Inspection Calculations:

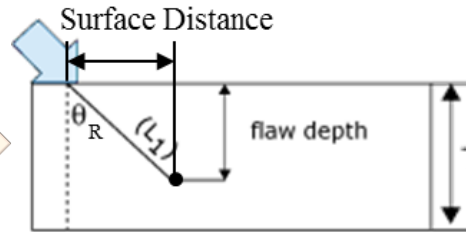
- ✓ **Nodes** - Surface points where sound waves reflect.
- ✓ **Skip Distance** - Surface distance of two successive nodes.
- ✓ **Leg 1 (L_1)** - Sound path in material to 1st node.
- ✓ **Leg 2 (L_2)** - Sound path in material from 1st to 2nd node.
- ✓ θ_R - Angle of Refraction and T - Material Thickness



Flaw Location (1st Leg):

$$\text{Surface Distance} = \sin \theta_R \times L_1$$

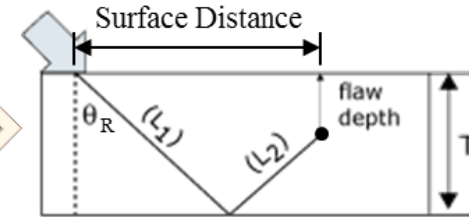
$$\text{Depth} = \cos \theta_R \times L_2$$



Flaw Location (2nd Leg):

$$\text{Surface Distance} = \sin \theta_R \times (L_1 + L_2)$$

$$\text{Depth} = 2T - \cos \theta_R \times (L_1 + L_2)$$



Data Presentation:

- Information from ultrasonic testing can be presented in a number of differing formats.
- The three most common formats are: 
 - A-scan
 - B-scan
 - C-scan

A-scan Presentation

B-scan Presentation

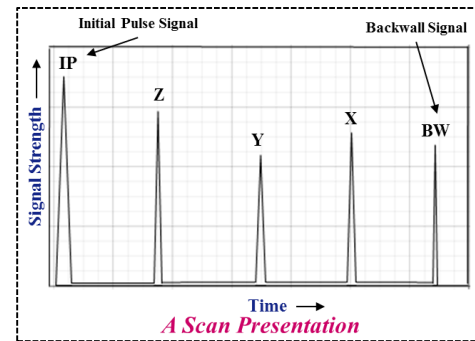
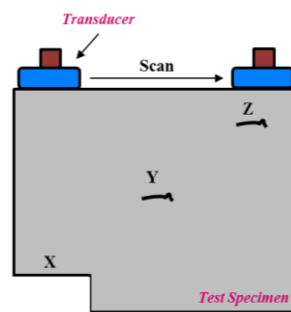
C-scan Presentation

Data Presentation: A-scan:

- A-scan presentation displays the amount of received ultrasonic energy as a function of time.
- The relative amount of received energy is plotted along the vertical axis and the elapsed time is displayed along the horizontal axis.
- Relative discontinuity size can be estimated by comparing the signal amplitude to that from a known reflector.
- Reflector depth can be determined by the position of the signal on the horizontal sweep.

Example:

- ✓ Initial pulse generated by transducer is represented by the signal **IP**, which is near time zero.
- ✓ As transducer is scanned along the surface of part, four other signals are likely to appear at different times on the screen.

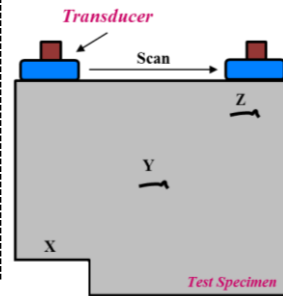
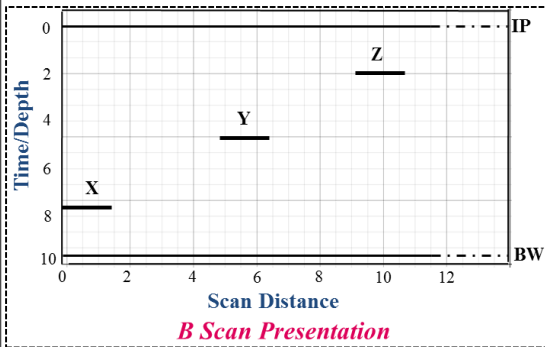


Data Presentation: B-scan

- B-scan presentation is a profile view (cross-sectional) of a test specimen.
- In the B-scan, the **time-of-flight** (travel time) of the sound energy is displayed along the vertical axis and the **linear position of the transducer** is displayed along the horizontal axis.
- From the B-scan, depth of the reflector and its approximate linear dimensions in the scan direction can be determined.
- It almost represent a photographic type of image of the defect.

Scanning Procedure:

- The B-scan is typically produced by establishing a trigger gate on the A-scan.
- Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan.



Example:

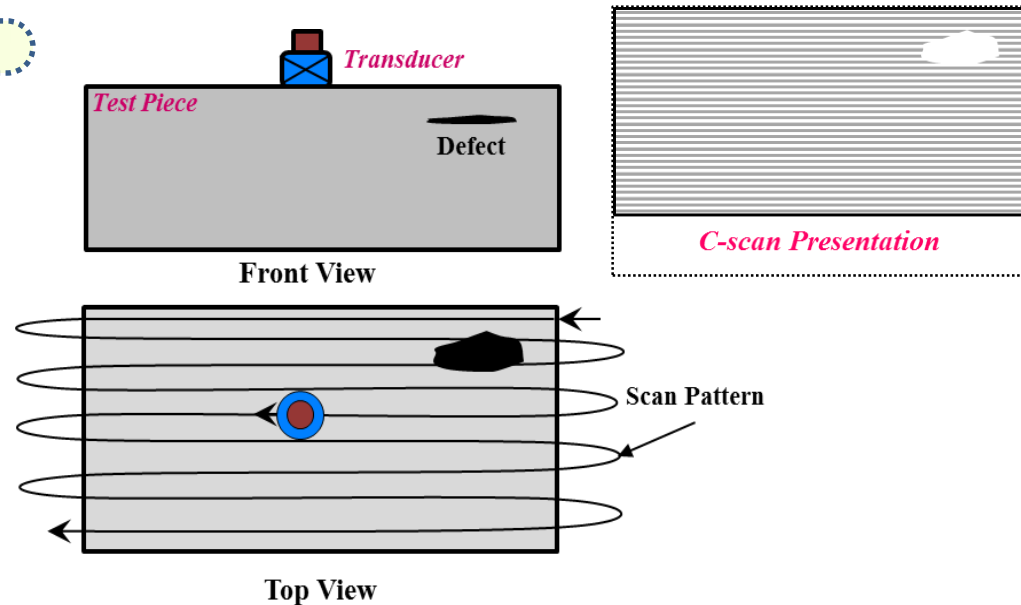
- ✓ In the given B-scan, line X is produced as the transducer is scanned over the reduced thickness portion of the specimen.
- ✓ When transducer moves to right of this section, the backwall line BW is produced.
- ✓ When transducer is over flaws Y and Z, lines that are similar to length of flaws and at similar depths within the material are drawn on B-scan.

Data Presentation: C-scan

- It displays a plan type view of the test specimen and discontinuities by mechanically or electrically scanning a X-Y plane.
- C-scan presentations are produced with an automated data acquisition system, such as in immersion scanning.
- Use of A-scan in conjunction with C-scan is necessary when depth determination is desired.

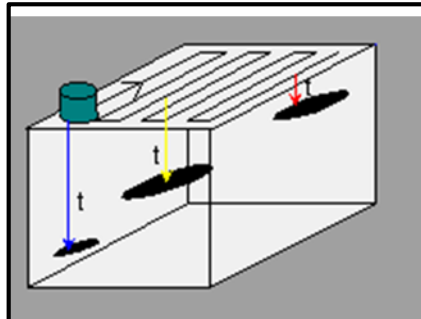
Scanning Procedure:

- ✓ Typically, a data collection gate is established on the A-scan and amplitude of the signal is recorded at regular intervals as transducer is scanned over the test piece.
- ✓ Relative signal amplitude is displayed as a shade of gray or a colour for each of the positions where data was recorded.
- ✓ C-scan presentation provides an image of the features that reflect and scatter sound within and on surfaces of the test piece.



Data Presentation: D-scan

- It displays the through thickness view showing a cross-section of the test object perpendicular to the scanning surface.
- The D- scan is similar to the C-scan, but the echo time of flight (depth) in relation to probe position is recorded.
- Actually the D-scan is a '3-D visualization' of the object.

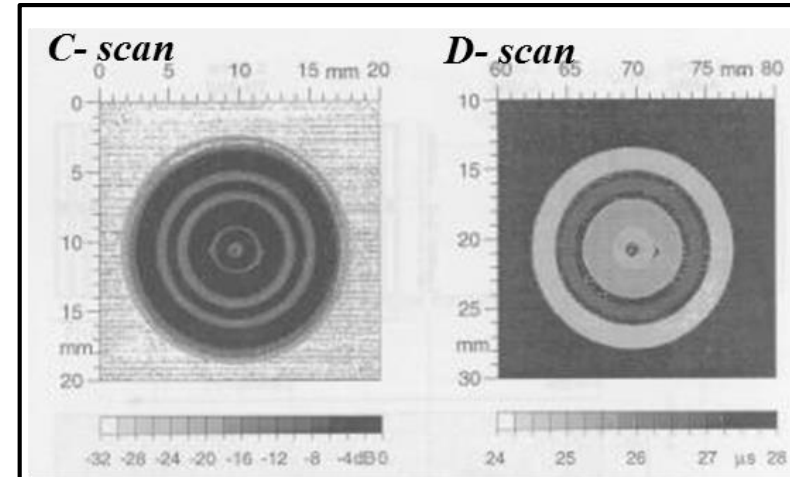


Probe Movement

Presentation represents top view of time of flight data



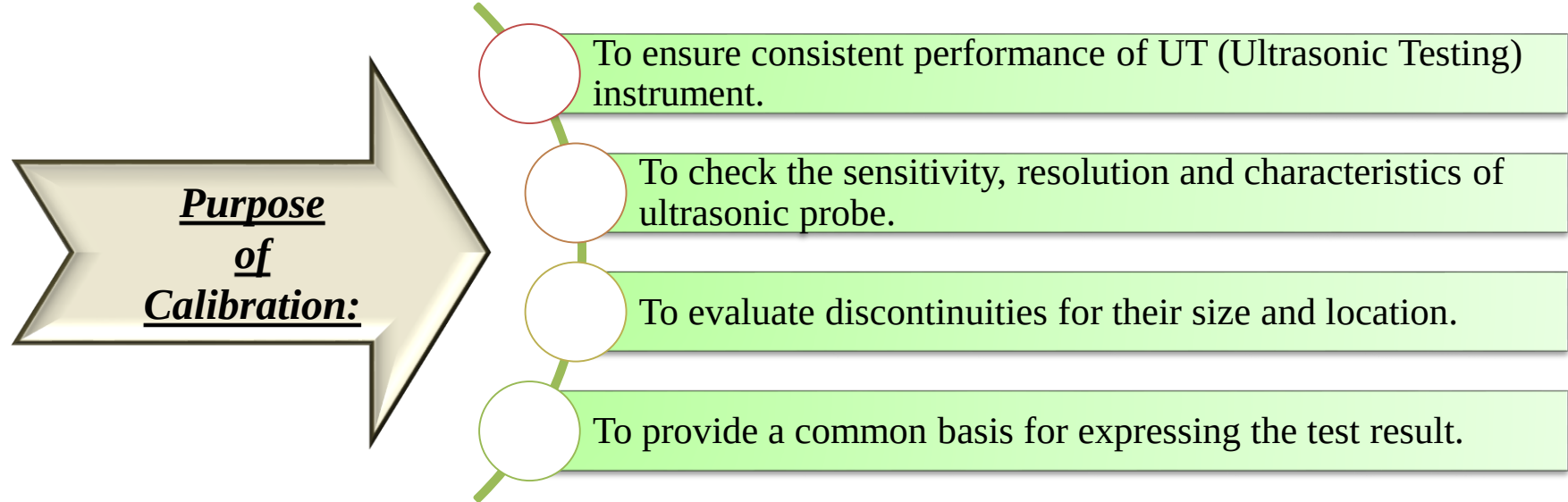
D-scan Presentation



*C- And D-scan Image of a Membrane
Tested in Immersion Technique*

Calibration Standards:

- Calibration is a operation of configuring the ultrasonic test equipment to known values.
- This provides the inspector with a means of comparing test signals to known measurements.
- Calibration standards are typically manufactured from materials of the same acoustic properties as those of the test articles.



Calibration Standards (Ultrasonic Reference Blocks):

Calibration Blocks for Parallel Inspection :

a) Thickness Calibration Standards:

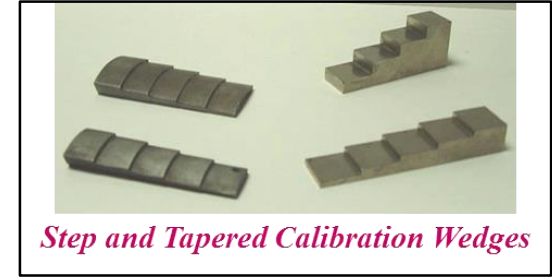
- ✓ Thickness calibration standards may be flat or curved for pipe and tubing applications, consisting of simple variations in material thickness.

b) Distance/Area Amplitude Standards:

- ✓ Distance/Area Amplitude standards utilize flat bottom holes or side drilled holes to establish known reflector size with changes in sound path from the entry surface.

c) NAVSHIPS Test Block:

- ✓ Used for distance amplitude correction, sensitivity levels and flaw depth information.

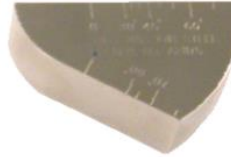


Calibration Blocks for Non-parallel Inspection:

- There are also calibration standards for use in angle beam inspections when flaws are not parallel to entry surface.
- These standards utilized side drilled holes, notches, and geometric configuration to establish time distance and amplitude relationships.



IIW Type 1 Calibration Block



ROMPAS Calibration Block



Distance Calibration (DC) Block



Sensitivity Calibration (SC) Block



Distance/Sensitivity Calibration (DSC) Block

Qualification Standards:

- Qualification standards are used to assess the proficiency/qualification of equipment or NDT personnel for specific codes and standards.

☐ IOW Beam Profile Block:

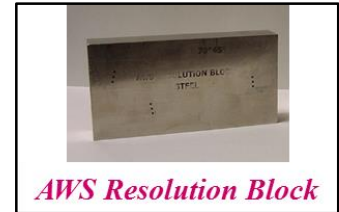
- ✓ Used for beam profile measurement of angle beam transducers and measurement of transducer angles.

☐ AWS Resolution Block:

- ✓ Used for checking resolution capabilities of angle beam transducers.

☐ DS Test Block:

- ✓ Used to check the horizontal linearity and the dB accuracy as per requirements of AWS.



Applications:

Applications for which ultrasonic testing is employed include:

- ✓ Flaw detection (cracks, inclusions, porosity, etc.).
- ✓ Erosion & corrosion thickness gauging.
- ✓ Assessment of bond integrity in adhesively joined and brazed components.
- ✓ Estimation of void content in composites and plastics.
- ✓ Measurement of case hardening depth in steels.
- ✓ Estimation of grain size in metals.

Some of the typical examples are:



Railway Track Inspection



Weld Inspection



Testing of Composite Structure for Laminar Flaws



Ultrasonic Testing of Metal Bars

Advantage & Limitations of Ultrasonic Testing:

Advantages:

- Sensitive to small discontinuities both surface and internal.
- Depth of penetration for flaw detection or measurement is superior to other methods.
- Only single-sided access is needed when pulse-echo technique is used.
- High accuracy in determining reflector position and estimating size and shape.
- Volumetric scanning ability of objects.
- Electronic equipment provides instantaneous results.
- Detailed images can be produced with automated systems.
- Ultrasonic inspection can be used to know not only that a flaw exists, but also the severity of the damage.

Limitations:

- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- Normally requires a coupling medium to promote transfer of sound energy into test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.

Summary:

- Ultrasonic testing (UT) uses high frequency sound energy to conduct examinations and make measurements.
- The sound energy reflected due to any discontinuity is detected and accordingly its position, shape and size is determined.
- A typical UT inspection system consists of pulser/receiver, transducer, and display devices.
- Transducer is used to convert electrical energy into mechanical energy (vibrational energy) and vice versa.
- Computers can be programmed to inspect large, complex shaped components, with one or multiple transducers collecting information.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 11: Acoustic Emission Inspection



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



Introduction to Acoustic Emission Method:

Acoustic Emission Inspection:

- It is considered as quite unique among the non-destructive testing methods.
- **Materials “talk” when they are in trouble:** Many materials make an audible noise when they fail (paper, wood, cloth etc.).
- Using Acoustic Emission equipment we can “listen” to the sounds of cracks growing, fibers breaking and many other modes of active damage in the stressed material.
- In contrast to other NDT methods, Acoustic Emission Testing (AET) is usually applied during loading, while most others are applied before or after loading of a structure.



*How AEI is
used ?*

- ✓ It is often used to detect a failure at a very early stage, long before a structure completely fails.
- ✓ Unlike conventional ultrasonic testing, AE tools are designed for monitoring acoustic emissions produced by the material during failure or stress, and not on the material's effect on externally generated waves.

Characteristics of Acoustic Emission Inspection Compared with Other Methods:

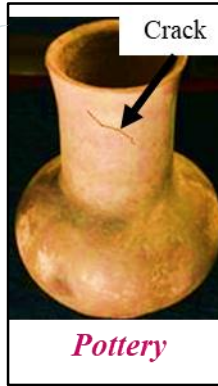
- Acoustic emission inspection has many features that distinguish it so sharply from other methods:

<i>Acoustic Emission</i>	<i>Other NDT Methods</i>
• Detects movement of defects	• Detects geometric form of defects
• Require stress	• Do not require stress
• Each loading is unique	• Inspection is directly repeatable
• More material-sensitive	• Less material-sensitive
• Less geometry-sensitive	• More geometry-sensitive
• Requires access only at sensors	• Require access to whole area of inspection
• Tests whole structure at once	• Scan local regions in sequence
• Main problems: noise related	• Main problems: geometry related

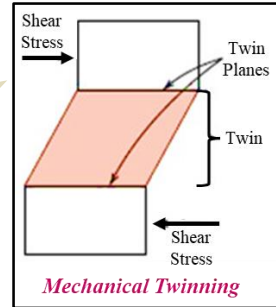
- AE inspection method is particularly useful when used in combination with other NDT methods.

A Brief History of AE Testing:

- Word '**crack**' is onomatopoeic ("sounds like") being based on a description of a sound that material makes as it fails.
- Probably the first practical use of AET was by **pottery** makers. As early as 6500 BC, potters were known to listen for audible sounds during the cooling of their ceramics, to assess the quality of their products.



- In metal working, the term "tin cry" (audible emissions produced by the **mechanical twinning** of pure tin during plastic deformation) was coined around 3,700 BC.



- 60 years ago, **Josef Kaiser** showed that metals also make very low amplitude sound as they fail.
- Today, AE is widely used in materials research programs, for corrective Maintenance of machinery and assessment of structural integrity.
- In 1960's, research at **Boeing** identified that by detecting signals with sensors resonant at high frequency (up to 90 kHz) it was possible to clearly see incipient aero engine failure.

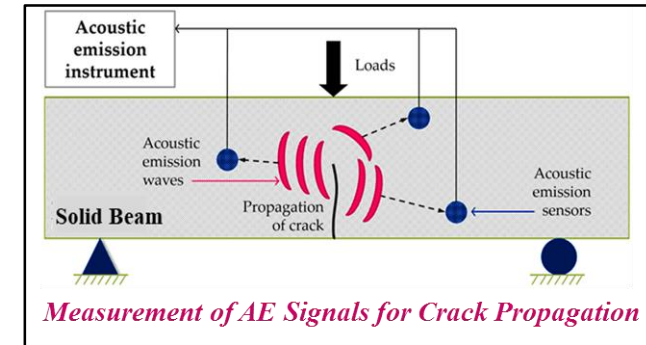
Principle of Acoustic Emission Inspection:

Acoustic Emission (AE):

- It is the phenomenon of radiation of acoustic (elastic) waves in solids that occurs when a material undergoes irreversible changes in its internal structure.

How It Works?

- When crack formation or plastic deformation occurs due to aging, temperature gradients or external mechanical forces, accumulated elastic energy in material or on its surface is released rapidly.
- This results in the generation of elastic or stress waves within the material.
- Understanding the physical nature of AE waves helps to detect, locate and characterize the damage.
- The waves generated by sources of AE are of practical interest in structural health monitoring (SHM), quality control, system feedback, process monitoring and other fields.
- AE method is considered to be a “*passive*” non-destructive technique, because it usually identifies defects only while they develop during the test.



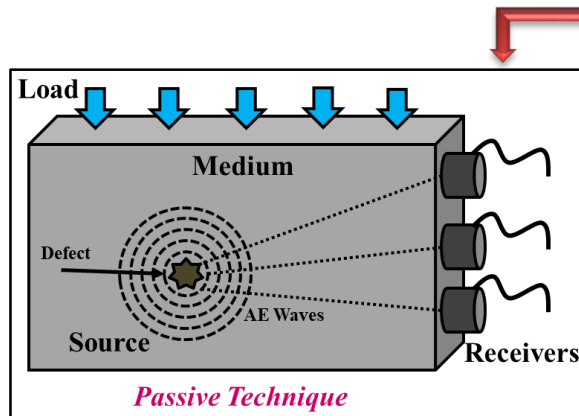
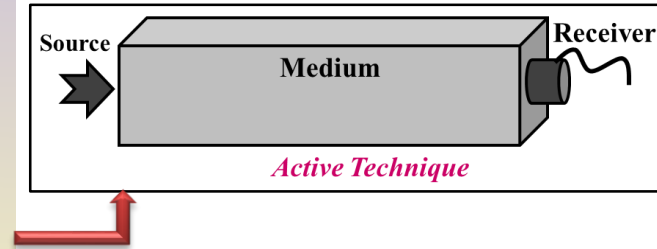
Comparison of Two Different Kinds of NDT Techniques:

Active Techniques:

- The source emitting the waves is generally applied externally to the material in active methods.

Example: Ultrasonic Inspection

- ✓ It detects the defect in a specimen using an artificially generated source signal and receiver.



Passive Techniques:

- In passive methods, sources are within the material; no input signal is required from the operator.

Example: Acoustic Emission Inspection

- ✓ It detects the elastic waves radiated by a growing fracture.
- ✓ Sources of acoustic emissions can have widely varying characteristics due to significant differences in the source signals.

Acoustic Emission Instrumentation:

- Acoustic emission testing can be performed in the field with portable instruments or in a stationary laboratory setting.
- Typical AE apparatus consist of the following components:

- **Sensors:**

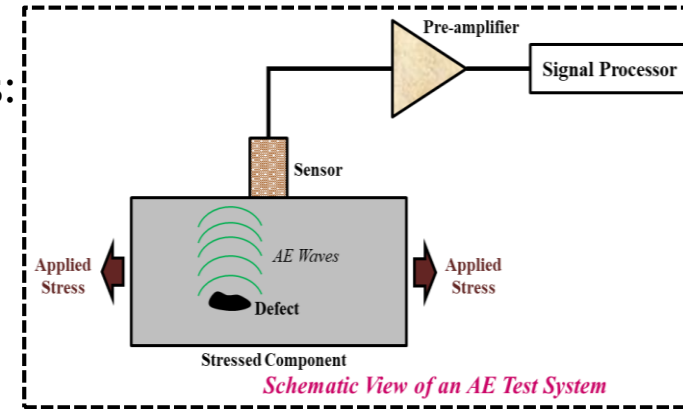
- ✓ Used to detect AE events.
- ✓ Contact type sensor (a piezoelectric element in a protective housing) is normally employed.

- **Preamplifiers:**

- ✓ Amplifies initial signal.

- **Signal Processor:**

- ✓ Performs filtration, data analysis and charting.



Installation of Sensors on Structure:

- The sensor is coupled to the test piece with a fluid couplant.
- Type of installation and choice of couplant material is defined by a specifics of application such as:
 - Glue (superglue type) is commonly used for piping inspections.
 - Magnets usually used to hold sensors on metal pressure vessels. Grease and oil then used as a couplant.
 - Bands used for mechanical attachment of sensors in long term applications.
 - Waveguides (welded or mechanically attached) used in high temperature applications.
 - Rolling sensors are used for inspection rotating structures.
 - Special Pb blankets used to protect sensors in nuclear industry.



AE Sensor attached with magnet



Pb Blanket in Nuclear Applications



Waveguide



Rolling Sensor

Characteristics of Acoustic Emission Waves:

- Fracture in material takes place with the release of stored strain energy, which is consumed by nucleating new external surfaces (cracks) and emitting elastic waves, which are defined as AE waves.
- AE waves are not sonic waves, but elastic waves in a solid.
- Radiation pattern is same as ultrasonic waves i.e. they radiate energy in all directions.
- AE waves are generally broad band and the received frequencies cover a wide range from audible to 1200 kHz.

Types of AE Signal:

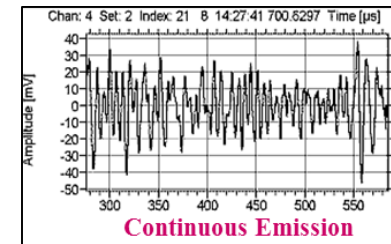
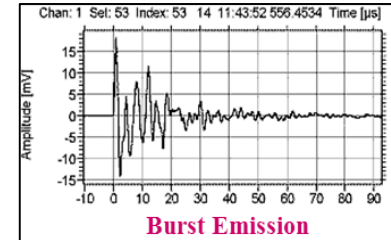
Two types of AE signals are detected in AE sensors:

i. Burst Type AE Signal:

- ✓ They are transient signals generated due to yielding, deformation, dissolution, solidification, cracking, and fracture failure of materials.

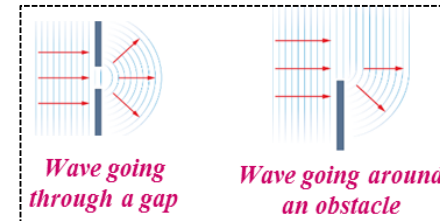
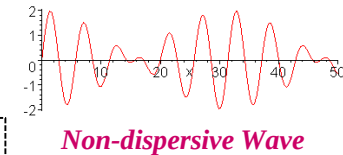
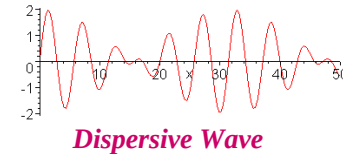
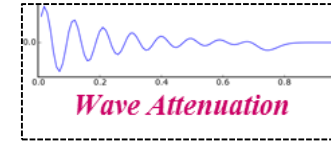
ii. Continuous AE Signal:

- ✓ They are generated when multiple transients overlap so that they cannot be distinguished and the envelope of the signal amplitudes becomes constant.
- ✓ It is detected due to friction and leakage on the crack surface.



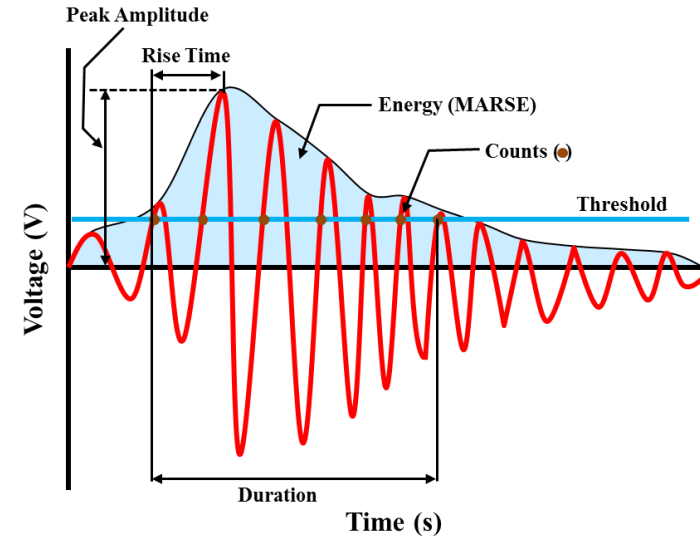
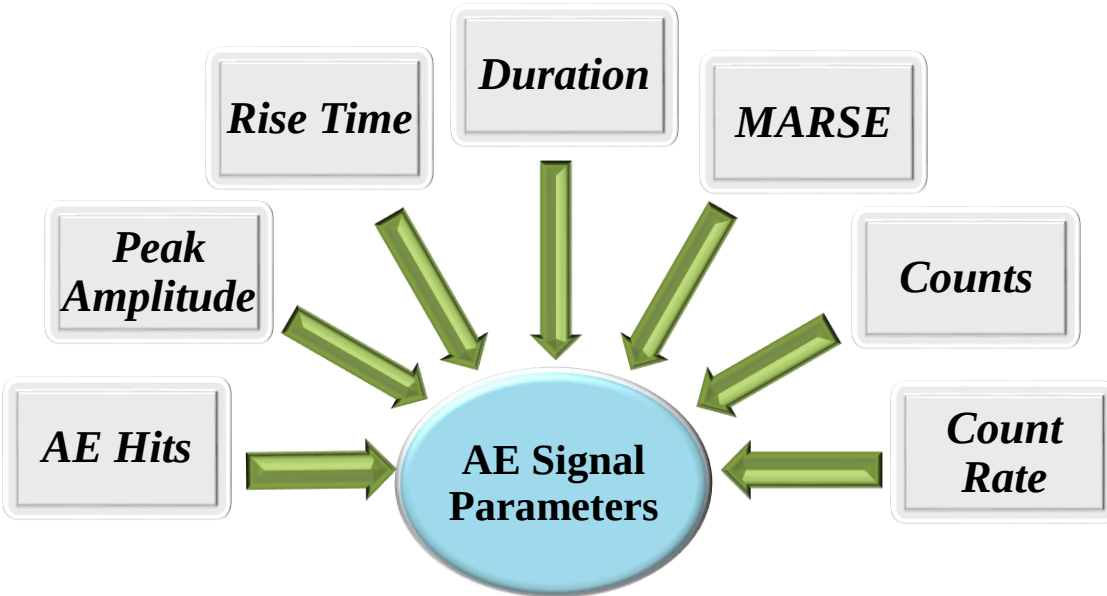
Wave Propagation:

- The following phenomena take place as AE waves propagate along the structure:
 - ✓ **Attenuation:** The decrease in AE amplitude as a stress wave propagate along a structure due to energy loss mechanisms, from dispersion, diffraction or scattering.
 - ✓ **Dispersion:** A phenomenon caused by the frequency dependence of speed for waves. Sound waves are composed of different frequencies hence the speed of the wave differs for different frequency spectrums.
 - ✓ **Diffraction:** The spreading or bending of waves passing through an aperture or around the edge of a barrier.
 - ✓ **Scattering:** The dispersion, deflection of waves encountering a discontinuity in the material such as holes, sharp edges, cracks inclusions etc.



AE Signal Parameters:

- They are features of an AE waveform, which are frequently used during the analysis of AE data.
- For locating or characterizing the type of damage within the material, different parameters of AE signal are evaluated.



AE Waveform Features

- **AE Hits:**
 - These are transient portions of the measured AE waveform which satisfy a given detection criterion.
 - Purpose of the detection criterion is to detect the presence of transient AE and discriminate it from background noise, or continuous AE.
 - In earlier figure, the waveform corresponds to one “hit”.
- **Peak Amplitude:**
 - It is the greatest measured voltage or maximum amplitude in a waveform.
 - This is an important parameter in acoustic emission inspection because it determines the detectability of the signal.
 - Signals with amplitudes below the operator-defined, minimum threshold will not be recorded.
- **Rise Time:**
 - The time from the first threshold crossing to the maximum amplitude of the signal.
 - This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor.
- **Duration:**
 - Time from the first threshold crossing to the end of the last threshold crossing of the signal.
 - Duration can be used to identify different types of sources and to filter out noise.

- **MARSE (Measured Area under the Rectified Signal Envelope):**
 - MARSE is the measure of the area under the envelope of the rectified linear voltage time signal from the transducer.
 - MARSE is sensitive to the duration and amplitude of the signal, but does not use counts or user defined thresholds and operating frequencies.
- **Counts:**
 - Counts refers to the number of pulses emitted by the measurement circuitry that exceeds the threshold
 - Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts.
 - While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal.
- **Count Rate:**
 - The number of times the signal amplitude has exceeded the threshold in a specified period of time.

Background Noise:

- It significantly affects the result of AE testing and need to be considered and controlled.

❖ Types of Noise:

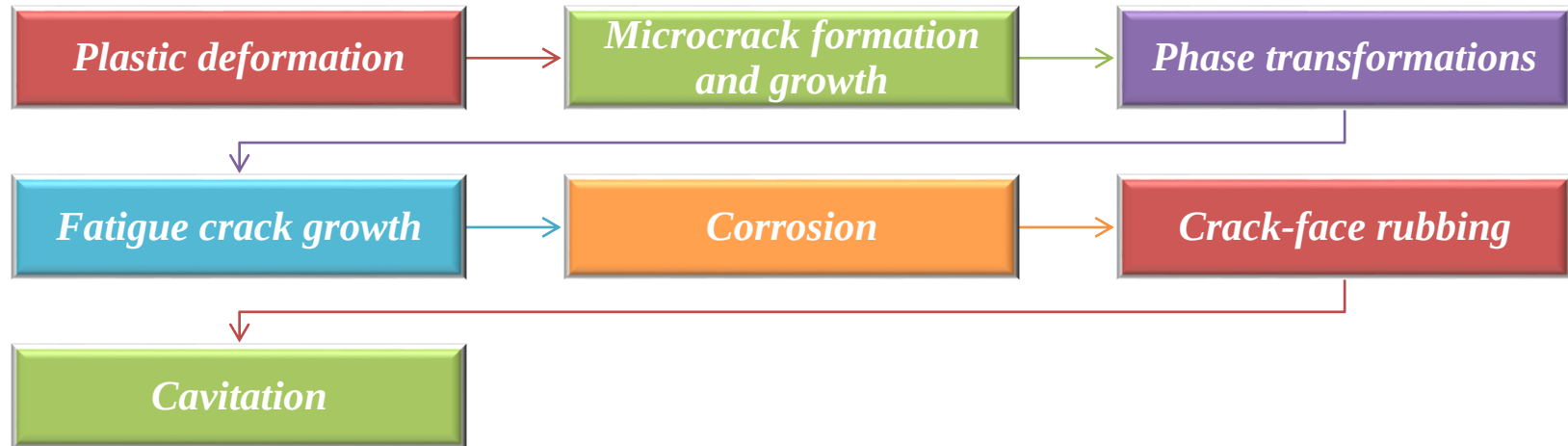
- **Hydraulic Noise:** Cavitation's, turbulent flows, boiling of fluids and leaks.
- **Mechanical Noise:** Movement of mechanical parts in contact with the structure e.g. fretting of pressure vessels against their supports caused by elastic expansion under pressure.
- **Cyclic Noise:** Repetitive noise such as that from reciprocating or rotating machinery.
- **Electro-magnetic Noise:** It causes the disruption of operation of an electronic device when it is in the vicinity of an electromagnetic field.

❖ Control of Noise Sources:

- ✓ **Rise Time Discriminator:** There is significant difference between rise time of mechanical noise and acoustic emission.
- ✓ **Frequency Discriminator:** Frequency of mechanical noise is usually lower than an acoustic emission burst from cracks.
- ✓ **Floating or Smart Threshold:** Varies with time as a function of noise output, used to distinguish between background noise and acoustic emission events under conditions of high, varying background noise.

AE Source Mechanisms in Metals:

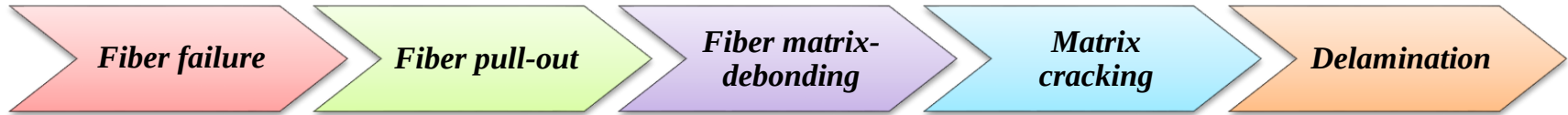
- AE can originate from any mechanisms which causes a rapid release of elastic energy.
- Sources of AE in metallic structures which have been identified in the past are:



- AE sources can also originate from external stimuli like impact of an external body on the structure under investigation or rubbing of joints, bolts and frames.

AE Source Mechanisms in Composites:

- Due to the fact that their material compositions are so different from one another, composite materials have AE sources which are not shared by metals.
- Plastic deformation and phase transformation do not occur in composites.
- AE sources experienced by composites but not metals are:



Analysis of AE Signals:

- Signals originated from a loaded structure are identified as desired and undesired signals on the basis of following:
 - ❖ **Desired Signal:**
 - Which are released directly from the damage mechanisms in a tested structure
 - Which contribute positively towards the detection of damage.
 - ❖ **Undesired Signal:**
 - Any signal (electrical or acoustic) that interferes with the reception, interpretation, or processing of desired signals.

Factors that Tend to Increase/Decrease the Amplitude of AE:

<i>Increase</i>	<i>Decrease</i>
• High strength	• Low strength
• High strain rate	• Low strain rate
• Low temperature	• High temperature
• Anisotropy	• Isotropy
• Heterogeneity	• Homogeneity
• Thick sections	• Thin sections
• Brittle failure (cleavage)	• Ductile failure (shear)
• Material containing discontinuities	• Material without discontinuities
• Martensitic phase transformations	• Diffusion controlled phase transformations
• Crack propagation	• Plastic deformation
• Cast materials	• Wrought materials
• Large grain size	• Small grain size
• Mechanically induced twinning	• Thermally induced twinning

Source Location Concepts:

- Locating the source of acoustic emissions is often accomplished by one of three methods:

- I. Linear Location Technique
- II. Point Location Technique
- III. Zonal Location Technique

I. Linear Location Technique:

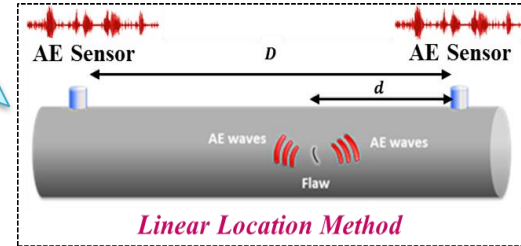
- It is a time difference method commonly used to locate AE source on linear structures such as pipes.
- It is based on the arrival time difference between two sensors for known velocity.
- Sound velocity is evaluated by generating signals at known distances.



Distance of AE source from first hit sensor (d) is given by:

$$d = \frac{1}{2} (D - \Delta T \times V)$$

Where, D = distance between sensors, V = wave velocity, ΔT = time difference of wave arrivals between two sensors.



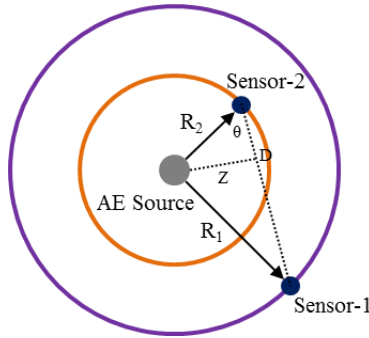
II. Point Location Technique:

- In order for point location of AE source to be justified, signals must be detected in a minimum number of sensors: two for linear, three for planar, four for volumetric.
- Accurate arrival times must also be available.
- Arrival times are often found by using peak amplitude or the first threshold crossing.
- The velocity of wave propagation and exact position of the sensors are necessary criteria as well.
- Equations can then be derived using sensor array geometry or more complex algebra to locate more specific points of interest.

Two Dimensional Source Location:

- For location of an AE source on a plane two sensors are used.

D = distance between sensor-1 and 2,
 $\Delta T_{1,2}$ = time difference between sensor-1 and 2,
 V = wave velocity,
 R_1 = distance between sensor-1 and source,
 R_2 = distance between sensor-2 and source,
 θ = angle between R_2 and D ,
 Z = line perpendicular to D .



We have, $R_1 - R_2 = V \times \Delta T_{1,2}$

$$Z = R_2 \sin \theta$$

$$Z^2 = R_1^2 - (D - R_2 \cos \theta)^2$$

$$\Rightarrow R_2^2 \sin^2 \theta = R_1^2 - D^2 + 2DR_2 \cos \theta - R_2^2 \cos^2 \theta$$

$$\Rightarrow R_2^2 = R_1^2 - D^2 + 2DR_2 \cos \theta$$

$$\Rightarrow R_2^2 + D^2 - 2DR_2 \cos \theta = R_1^2$$

Substituting for $R_1 = R_2 + V \times \Delta T_{1,2}$,

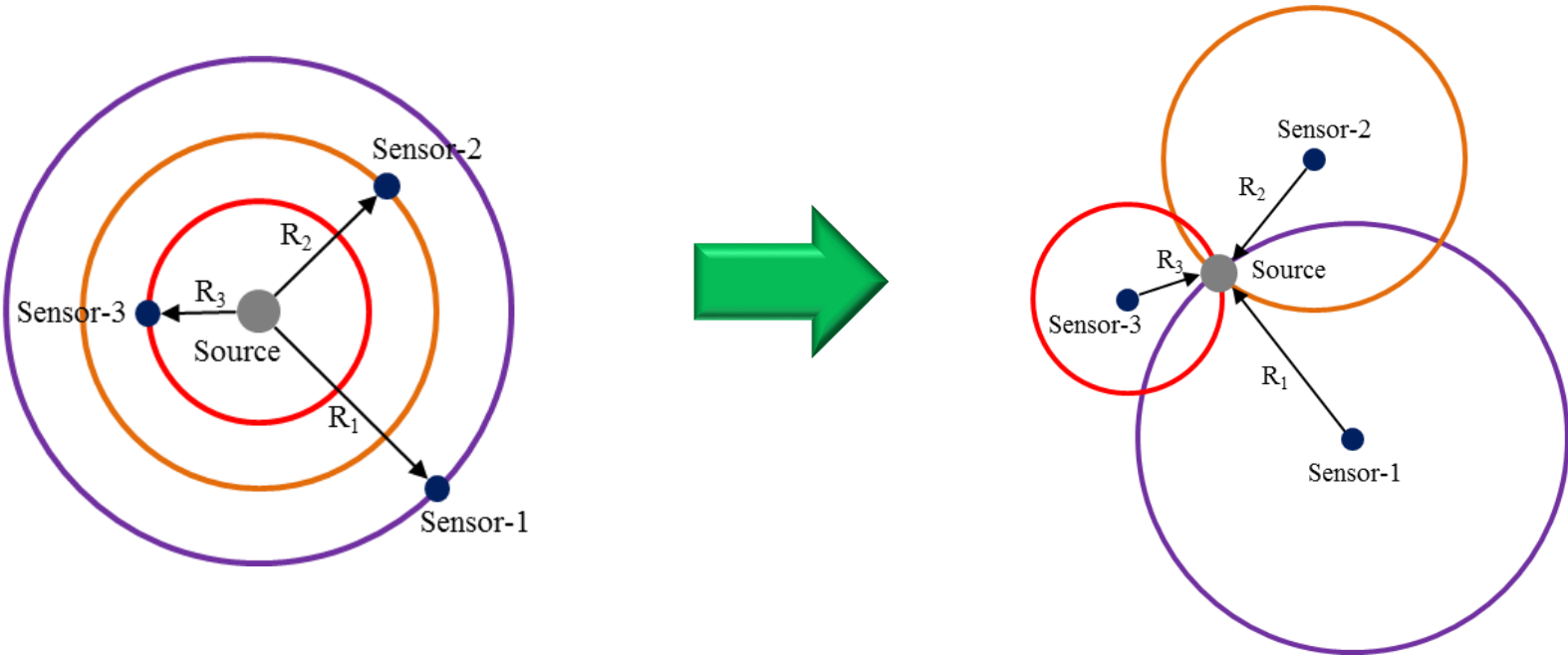
$$R_2^2 + D^2 - 2DR_2 \cos \theta = R_2^2 + V^2 \Delta T_{1,2}^2 + 2R_2 \cdot V \cdot \Delta T_{1,2}$$

$$\Rightarrow D^2 - V^2 \Delta T_{1,2}^2 = 2DR_2 \cos \theta + 2R_2 \cdot V \cdot \Delta T_{1,2}$$

$$\Rightarrow R_2 = \frac{1}{2} \left(\frac{D^2 - V^2 \Delta T_{1,2}^2}{D \cos \theta + V \Delta T_{1,2}} \right)$$

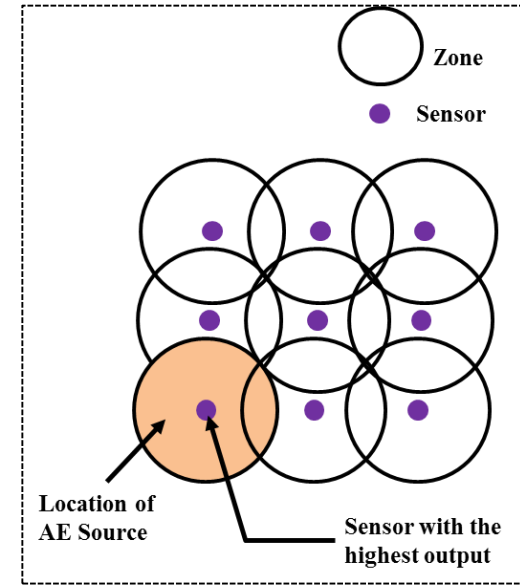
Source is situated on a curve represented by above equation, which is a hyperbola.

- Three sensors are used to locate a source to a point by intersecting two hyperbolae using the same technique as two sensors.
- If the distances R_1 , R_2 and R_3 are known, then the point of intersection of three circles of respective radius and centered at the location of the sensors will be the location of the source.



III. Zonal Location Technique:

- It aims to trace the AE source to a specific zone or region around a sensor.
- Zones can be lengths, areas or volumes depending on the dimensions of the array.
- It is based on the principle that the sensor with the highest amplitude or energy output will be closest to the source.
- With additional sensors added, a sequence of signals can be detected giving a more accurate result using time differences and attenuation characteristics of the wave.



The source can be assumed to be within the region and less than halfway between sensors.

Activity of AE Sources in Structural Loading:

- AE signals generated under different loading patterns can provide valuable information concerning the structural integrity of a material.
- Relationship between the loading history and AE events in a particular interval is described by two effects:

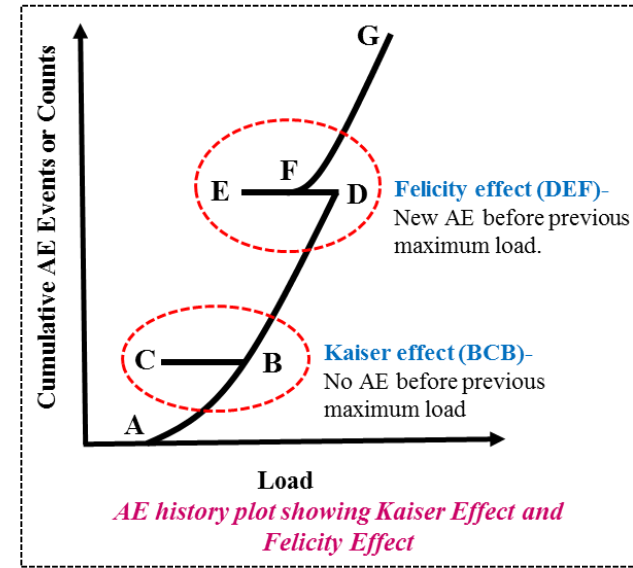
a) Kaiser Effect:

- It is the absence of detectable AE at a fixed sensitivity level, until previously applied stress levels are exceeded.

b) Felicity Effect:

- It is the presence of AE, detectable at a fixed predetermined sensitivity level at stress levels below those previously applied.
- This effect is used in testing of fiberglass vessels and storage tanks.
- It can be quantified using the Felicity Ratio, which is defined as:

$$\text{Felicity Ratio} = \frac{\text{Load at which emission begins again (F)}}{\text{Previous maximum applied load (D)}}$$



Advantages and Disadvantages of AET:

Advantages of AE Testing:

- Damage processes in materials being tested can be observed during the entire load history, without any disturbance to the specimen.
- The sensors can be fixed to the surface of the specimen for the duration of the test and do not have to be moved for scanning the whole structure point by point.
- Access to both sides of an object, which is necessary for all through-transmission methods, is not required in AET.

Disadvantages of AE Testing:

- A particular test is not perfectly reproducible due to the nature of signal source, e.g. the sudden and sometimes random formation of a crack.
- Energy released by AE signals are usually several magnitudes smaller compared to signals used in ultrasonic techniques. This requires much more sensitive sensors as well as reliable amplifiers and pre-amplifiers.
- It also has problems related to the influence of ambient noise, the attenuation of signals and resulting low signal-to-noise ratio.
- It requires sophisticated data processing techniques to detect acoustic emissions, to localize them and to apply other advanced techniques or inversions.



Applications:

- Acoustic emission is a very versatile, non-invasive way to gather information about a material or structure.
 - It is applied to inspect and monitor pipelines, pressure vessels, storage tanks, bridges, aircraft, and bucket trucks, and a variety of composite and ceramic components.
 - A few examples of AET applications, where AE techniques are used for are: 
- ❖ In-process weld monitoring.
 - ❖ Detecting tool touch and tool wear during automatic machining.
 - ❖ Detecting wear and loss of lubrication in rotating equipment, and tribological studies.
 - ❖ Detecting loose parts and loose particles.
 - ❖ Detecting and monitoring leaks, cavitation, and flow.
 - ❖ Monitoring chemical reactions, including corrosion processes, liquid-solid transformations, and phase transformations.

Summary:

- The acoustic emission inspection is a reliable, extensively used and well-established dynamic NDT method.
- It detects the acoustic (elastic) waves produced due to different modes of active damage within the stressed material to receive a warning long before it completely fails.
- The three major applications of AE techniques are:
 1. Source location – determine the locations where an event source occurred.
 2. Material mechanical performance – evaluate and characterize materials or structures.
 3. Health monitoring – monitor the safe operation of a structure.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 12: Radiography Inspection



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Introduction:

- Term radiography usually implies a radiographic process that produces a permanent image on film or paper.
- Radiography is a non-destructive inspection technique where many types of manufactured components can be examined to verify the internal structure and integrity of the specimen.
- Radiography has seen expanded usage in industry to inspect not only welds and castings, but to radiographically inspect items such as airbags and canned food products.
- The objects which can be examined can range in sizes and shapes from micro-miniature electronic parts to mammoth missiles or power plant structures.

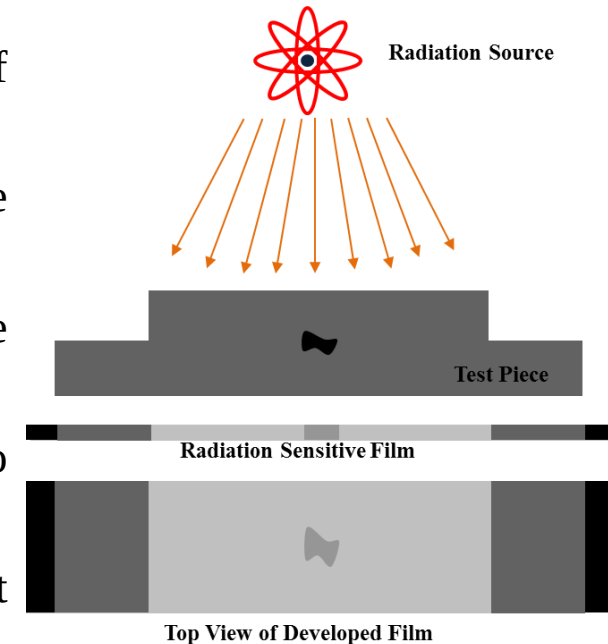
History of Radiography:

- Radiography started with the discovery of **X-rays** by **W. C. Roentgen** in 1895, and **radioactivity** by **Becquerel** in 1896.
- By using radioactive sources such as radium, far higher photon energy could be obtained than those from normal X-ray generators.
- Soon X-rays and gamma rays found various applications.
- These rays were put to use very early, before the dangers of ionizing radiation were discovered.
- After Word War II new isotopes such as caesium-137, iridium-192 and cobalt-60 became available for industrial radiography, and the use of radium and radon decreased.



Basic Principle of Radiography:

- The part is placed between the radiation source and a piece of film.
- The part will stop some of the radiation. Thicker and more dense area will stop more of the radiation.
- The unabsorbed radiation exposes the film emulsion, similar to the way light exposes the film in photography.
- Development of the film produces an image that is two dimensional shadow picture of the object.
- Variations in the density, thickness or composition of the object being inspected, causes variations in the development of film.



Evaluation of the radiograph is based on a comparison of the differences in the photographic density with known characteristics of the object itself or defects present in the test object.


More exposure

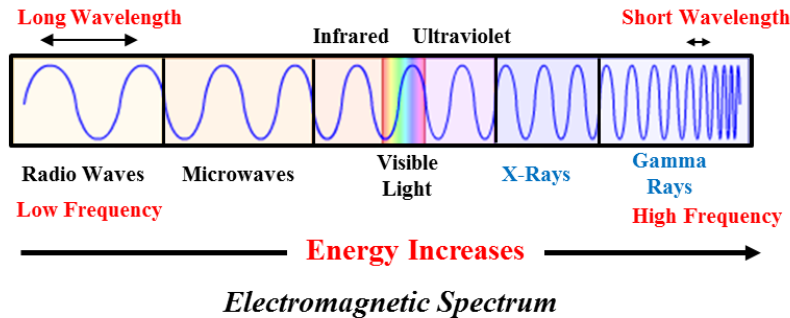

Less exposure

Essential Elements for Radiography Testing:

1. A source of penetrating radiation, such as an X-ray machine.
2. The object to be radiographed, such as a weldment or casting.
3. A recording or viewing device, usually photographic film enclosed in a light tight holder.
4. A qualified radiographer trained to produce a satisfactory exposure.
5. A person skilled in the interpretation of radiographs.

Penetrating Radiation:

- The radiation used in Radiography testing are: *X-rays and Gamma rays*.
- They are a form of electromagnetic radiation, similar to visible light.
- Unlike light, however, they have higher energy (shorter wavelength) and the ability to penetrate, travel through, and exit various materials such as carbon steel and other metals.
- When the components are subjected to radiography, these radiations travel and are transmitted through them in different amounts by different materials, depending upon their radiological densities.
- Radiological density is determined by both the density and the atomic number (the number of protons in an atom's nucleus) of the material being imaged.



Spectrum Table of X-rays and Gamma Rays

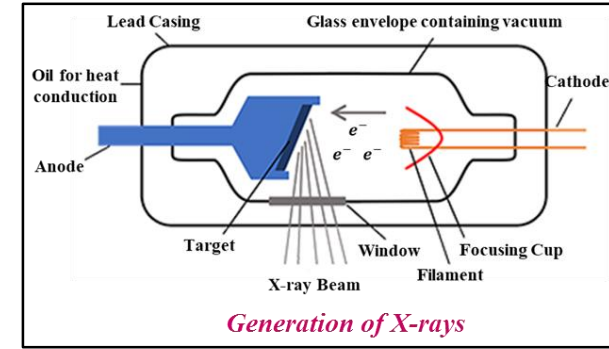
	Wavelength	Frequency (Hz)	Photon Energy (eV)
X-Rays	0.01 – 10 nm	3×10^{16} Hz to 3×10^{19} Hz	120 eV – 120 keV
Gamma Rays	Less than 0.01 nm	More than 10^{19} Hz	More than 100 keV

X-rays:

- They are form of electromagnetic radiation having wavelength ranging from 0.01 to 10 nm.

Production of X-rays:

- X-rays are produced when fast moving electrons emitting from heated filament by thermionic emission, are suddenly brought to rest by colliding with matter.
- Electrons are accelerated through a potential difference and directed towards a target material.
- When these electrons strike on target with very high velocity, X-rays are produced at the point of impact and radiate in all directions.
- The kinetic energy of the accelerated electrons can be converted in three different ways:
 - A very small fraction, i.e. less than 1%, is converted into X-radiation.
 - Approximately 99% of energy of electrons is converted into heat by increasing the thermal vibration of the atoms of the target.
 - Some of the electrons have sufficient energy to eject orbital electrons from the atoms of the target material which are ionised.



Mechanism of X-ray Generation:

- There are two different atomic processes that can produce X-ray photons:

- Bremsstrahlung
- K-shell Emission

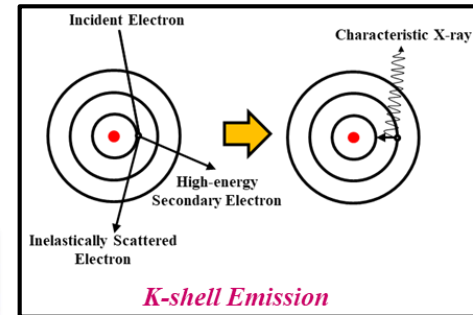
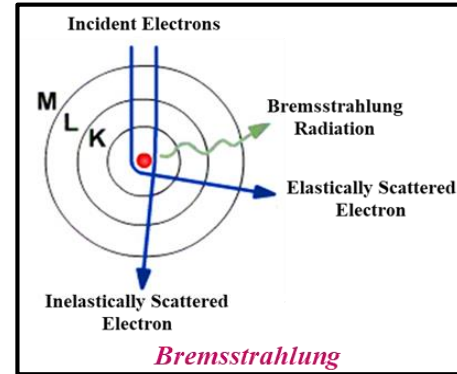
i. Bremsstrahlung:

- Bremsstrahlung is a German term meaning “braking radiation”.
- In this process, a high speed electron traveling in a material is slowed or completely stopped by the forces of any atom it encounters.

ii. K-shell Emission:

- When incoming electron give enough energy to knock K-shell electron out of its energy state, then electron of higher energy can fall into the K shell.
- The energy lost by the falling electrons shows up in an emitted X-ray photon.
- Meanwhile, higher energy electrons fall into the vacated energy state in the outer shell, and so on.
- K-shell emission produces higher-intensity x-rays than Bremsstrahlung, and the x-ray photon comes out at a single wavelength.

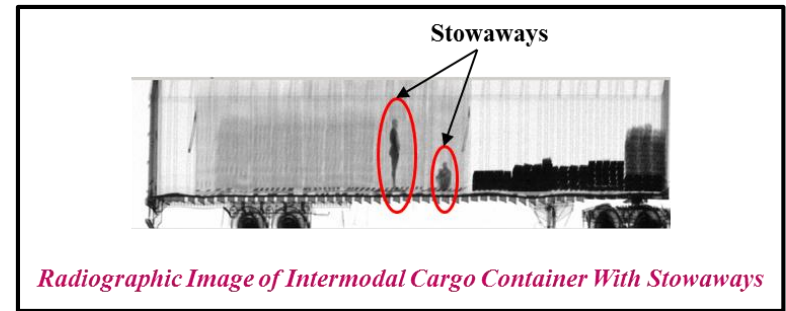
Both atomic processes can occur in the heavy atoms of tungsten, which is often the material chosen for the target or anode of the x-ray tube.



High Energy X-Radiation:

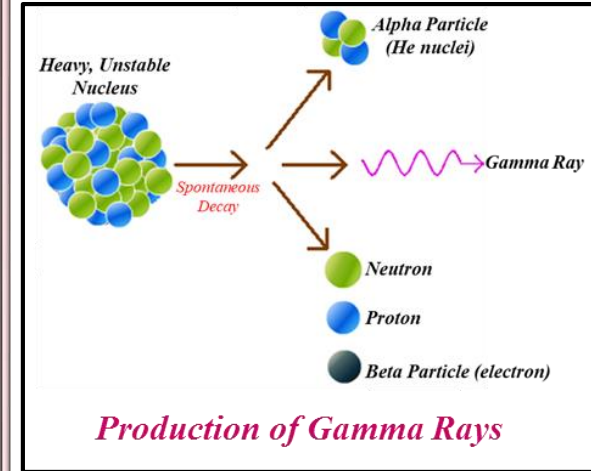
- Examination of thicker sections is carried out using high energy X-rays whose energy value is 1MeV or more.
- Using high energy X-rays, possibility of large distance to thickness ratios with correspondingly low geometrical distortion, short exposure times and high production rate can be achieved.
- Also, small focal spot size and reduced amount of high angle scattered X-ray reaching the film result in radiographs with good contrast, excellent penetrameter sensitivity and good resolution.

Example: High-energy X-ray radiography is currently used to scan intermodal freight cargo containers in many countries.



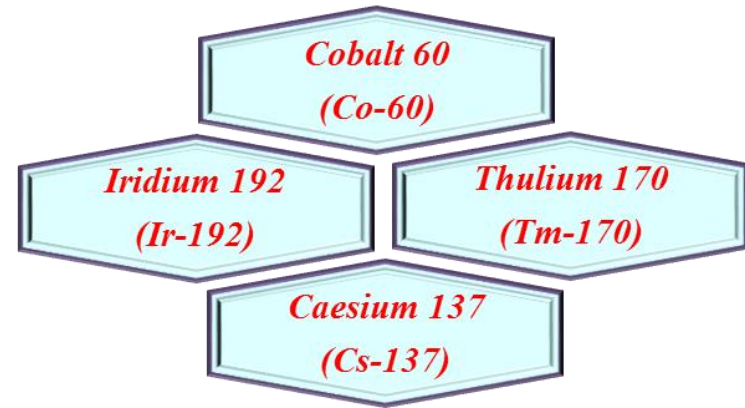
Gamma Rays:

- They are the electromagnetic radiation of the shortest wavelength and highest energy.
- They are identical to X-Rays, except that X-Rays are artificially produced and Gamma rays are naturally occurring.
- Gamma rays are emitted from an unstable nucleus.
- Each isotope with unstable nucleus will have characteristic nuclear energy levels and intensities for the emitted radiation.
- In contra-distinction to X-ray machines which emit a broad band of wavelengths gamma ray sources emit one or few discrete wavelengths.
- The gamma ray energy levels remain constant for a particular isotope but the intensity decays with time as indicated by the half time.



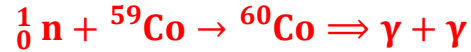
Gamma Ray Sources:

- Most of the radioactive material used in industrial radiography are artificially produced by subjecting stable material to a source of neutrons in a special nuclear reactor.
- In this activation process, an extra neutron is introduced to the atoms of the source material.
- As the material rids itself of the neutron, energy is released in the form of gamma rays.
- Selection of radioisotopes for the purpose of radiography is usually done on the basis of:
 - ✓ Half life
 - ✓ Intensity of gamma rays produced
 - ✓ Cost of production
- The four most popular radiographic sources are:



Production of Gamma Ray Isotopes:

- Co-60, Ir-192 and Th-170 are produced by (n, γ) reaction; e.g. for Co-60



- Cs-137 is separated out from the fission products of the irradiated reactor fuel.

Important Characteristics of Most Popular Radiographic Sources:

Characteristics	Cobalt-60	Iridium-192	Caesium-137	Thulium-170
Half life	5.27 yrs.	74.3 days	30.1 yrs.	129 days
Energy (MeV)	1.33-1.17	0.3-0.6	0.66	0.08-0.05
Radiation output (Rhm/Ci)	1.35	0.55	0.34	0.003
Size (dia.mm)	2.5	2.5	10	2.5
Steel thickness which can be radiographed	200 mm	75 mm	40-100 mm	10 mm

Common Properties of X-rays and Gamma Rays:

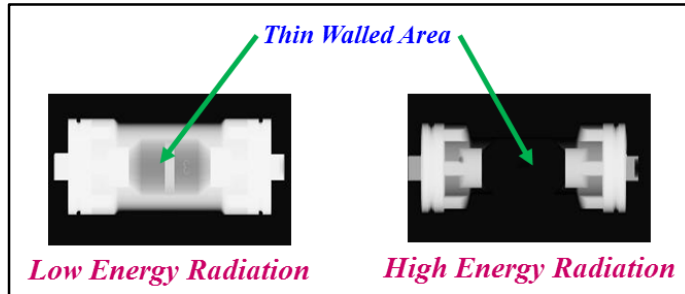
- They are not detected by human senses (cannot be seen, heard, felt, etc.).
- They travel in straight lines at the speed of light.
- Their paths cannot be changed by electrical or magnetic fields.
- They can be diffracted to a small degree at interfaces between two different materials.
- They pass through matter until they have a chance encounter with an atomic particle.
- Their degree of penetration depends on their energy and the matter they are traveling through.
- They have enough energy to ionize matter and can damage or destroy living cells.

Important Factors for Proper Imaging

Energy of the Penetrating Radiation

- Energy of the radiation affects its penetrating power.
- Higher energy radiation can penetrate thicker and more dense materials.
- Radiation energy and/or exposure time must be controlled to properly image the region of interest.

Example:



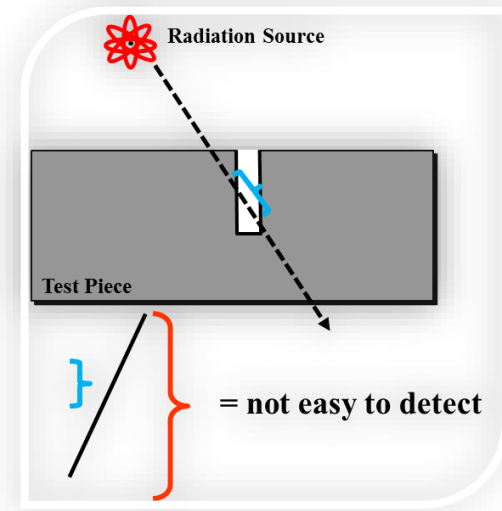
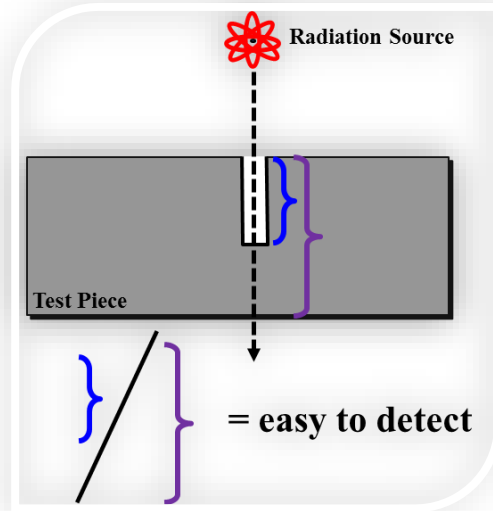
Geometric Factors of the Inspection System

Following geometric conditions must fulfil for sharpest true shadow of the object:

- Source size should be as small as possible.
- Source should be as far as possible from object.
- The film should be closest to the object.
- X-rays should be directed perpendicular to the recording surface.
- Plane of the object and film should be parallel.
- The volumetric extension of the defect or **flaw orientation** should be parallel to the direction of projection (*Explained on next slide*).

Flaw Orientation:

- Radiography has sensitivity limitations when detecting cracks.
- Penetrating radiations “see” a crack as a thickness variation and the larger the variation, the easier the crack is to detect.
- When the path of the rays is not parallel to a crack, the thickness variation is less and the crack may not be visible.



Imaging Modalities:

- Several different imaging methods are available to display the final image in industrial radiography:
 - Film Radiography.
 - Digital Radiography - It includes:

Computed Radiography (CR)



Real-time Radiography (RTR)



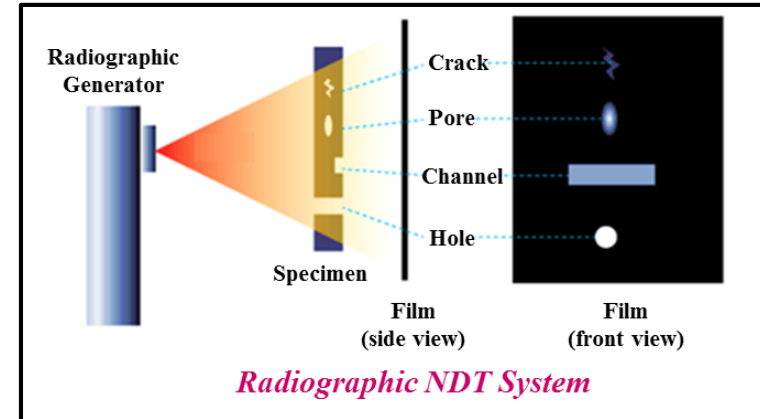
Direct Radiographic Imaging (DR)



Computed Tomography (CT)

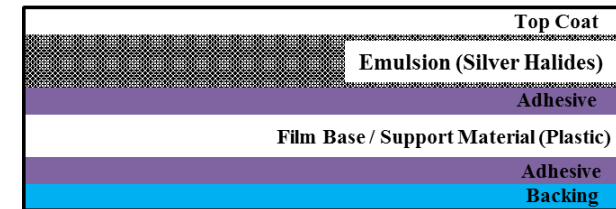
Film Radiography:

- It is most widely used and oldest imaging mediums in industrial radiography is radiographic film.
- In this method, a two-dimensional latent image from the projected radiation is produced on a sheet of film that has been exposed to the unabsorbed radiation passing through the test piece.
- Film must be protected from visible light. Light, just like x-rays and gamma rays, can expose film, hence it is loaded in a “light proof” cassette in a darkroom.
- This cassette is then placed on the specimen opposite the source of radiation.
- In order for the image to be viewed, the film must be “developed” in a darkroom. The process is very similar to photographic film development.
- Film processing can either be performed manually in open tanks or in an automatic processor.
- Once developed, the film is typically referred to as a “radiograph.”



Structure of Radiographic Film:

- Composition of radiographic film is similar to that of a photographic film and contains several layers:
 - Top Coat Layer:**
 - To prevent emulsion from scratches, pressure or contamination during use.
 - Emulsion Layer:**
 - Radiation sensitive emulsion layer is coated on transparent film base.
 - The emulsion consists of gelatin containing light sensitive silver halide crystals such as AgBr and AgCl.
 - The light sensitive crystals change shape when exposed to light, which are then converted to a dark metallic silver, giving us the image that we see.
 - Adhesive Layer:**
 - To achieve firm attachment of the emulsion and backing layer with film base.
 - Film Base:**
 - To provide support for emulsion layer & to transmit light to view image.
 - Backing Layer:**
 - To prevent film curling due to swelling of emulsion during processing.
 - To prevent reflection of stray light from the film support material back into the light-sensitive area.



Cross Section of Single Sided Emulsion Film

Digital Radiography:

- One of the newest forms of radiographic imaging is “Digital Radiography”.
- Requiring no film, digital radiographic images are captured using either special phosphor screens or flat panels containing micro-electronic sensors.
- No darkrooms are needed to process film, and captured images can be digitally enhanced for increased detail.
- Images are also easily archived (stored) when in digital form.
- There are a number of forms of digital radiographic imaging including:

i) Real-time Radiography (RTR)



ii) Computed Radiography (CR)



iii) Direct Radiography (DR)



iv) Computed Tomography (CT)

i. Real Time Radiography (RTR):

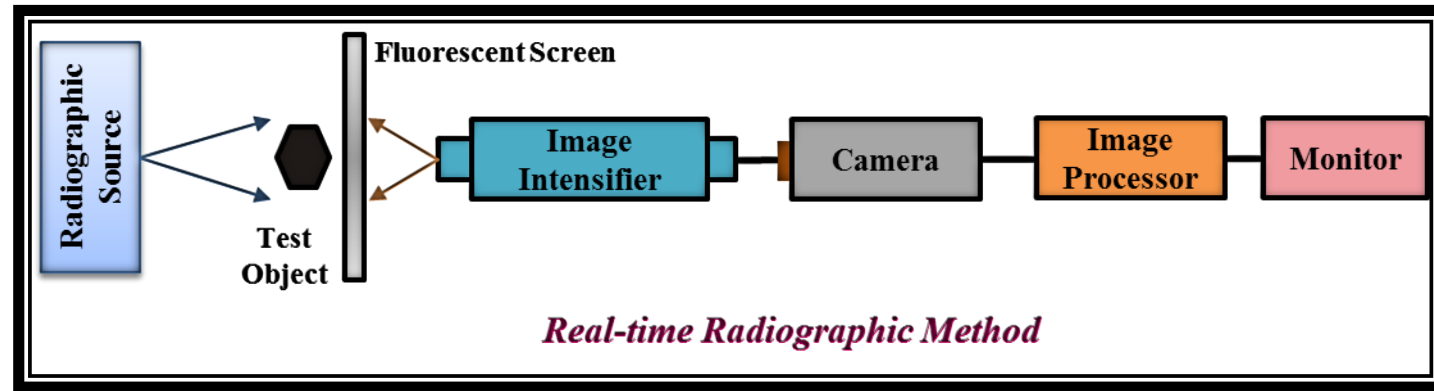
- RTR or real-time radiography, is a non-destructive test (NDT) method whereby an image is produced electronically rather than on film so that very little lag time occurs between the item being exposed to radiation and the resulting image.
- Because image acquisition is almost instantaneous, radiographic images can be viewed as the part is moved and rotated.

Advantages:

- Manipulating the part can be advantageous for several reasons:
 - It may be possible to image the entire component with one exposure.
 - Viewing the internal structure of the part from different angular prospective can provide additional data for analysis.
 - Time of inspection can often be reduced.

Working Procedure of Real-time Radiography:

- ✓ Fluorescent screen uses materials that fluoresce when struck by radiation and produces luminescence during the period of irradiation coming from the test object.
- ✓ Image intensifier converts x-rays/gamma rays coming from fluorescent screen into visible light at higher intensity.
- ✓ A special camera, which is very sensitive to a variety of different light intensities, captures the light output of the image intensifying screen.
- ✓ The captured image is then processed and viewed on the display device (monitor).

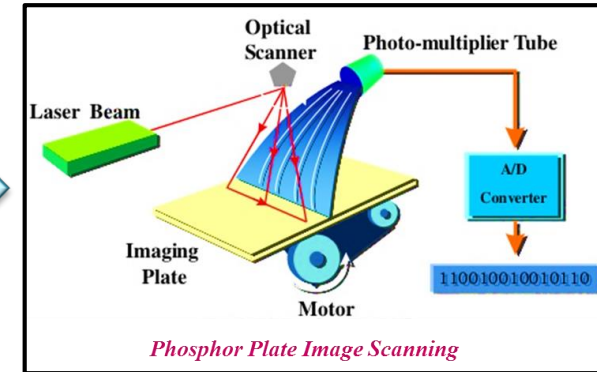


ii. Computed Radiography (CR):

- It uses a phosphor imaging plate that replaces film in conventional radiography techniques.
- CR requires several extra steps compared to direct radiography:
 - ✓ First, it indirectly captures the image of a component on a phosphor plate,
 - ✓ Then converts the image into a digital signal that can be visualized on a computer monitor.
- Image quality is fair but can be enhanced using appropriate tools and techniques (*i.e. adjusting contrast, brightness, etc. without compromising integrity*).
- It's important to know how tools, such as adjusting contrast, effect the image.
- Care should also be taken to make sure minor defects are not hidden after enhancements are made.

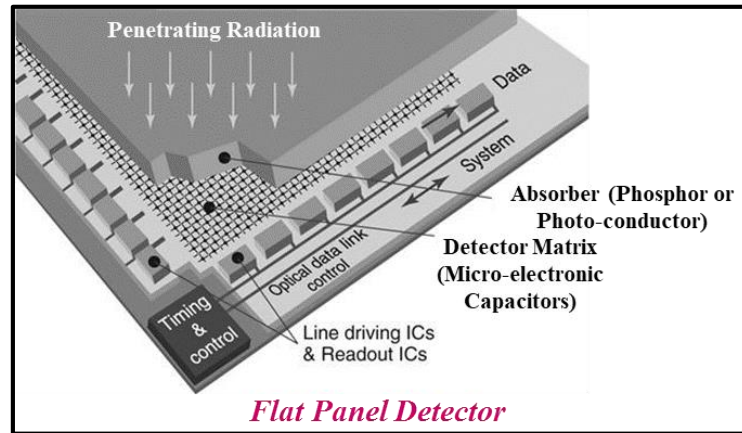
Working Procedure:

- ✓ As a laser scans the imaging plate, light is emitted where X-rays or gamma rays stimulated the phosphor during exposure.
- ✓ The emitted light is then converted to a digital value using analog-to-digital converter.



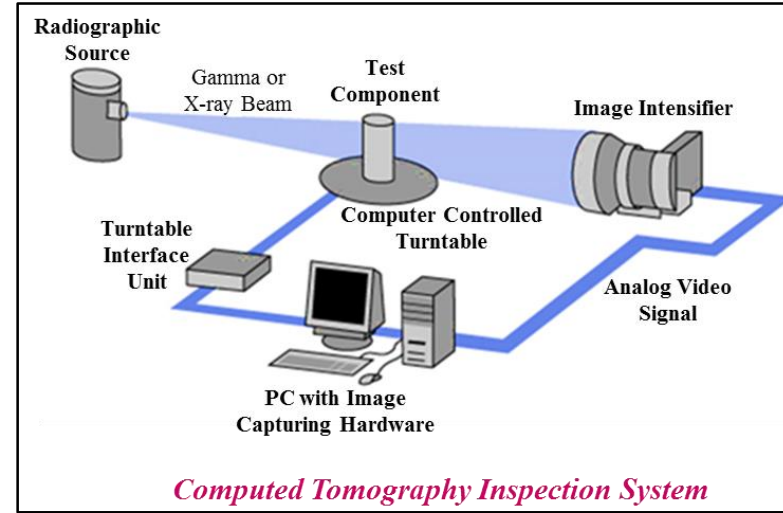
iii. Direct Radiography:

- Direct radiography (DR) is a form of real-time radiography that uses a special *flat panel detector*.
- The panel works by converting **penetrating radiation** passing through the test specimen into minute electrical charges.
- The panel contains many **micro-electronic capacitors**. The capacitors form an electrical charge pattern image of the specimen.
- Each capacitor's charge is converted into a pixel which forms the digital image.



iv. Computed Tomography:

- Classic digital radiography techniques cannot deliver any depth information of defects in their radiographic images as they are purely two dimensional.
- Computed tomography is a powerful technique for producing 2-D and 3-D cross-sectional images of an object.
- It uses a real-time inspection system employing a sample positioning system and special software.

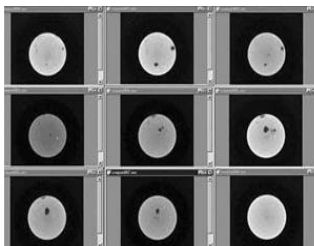


Working Principle:

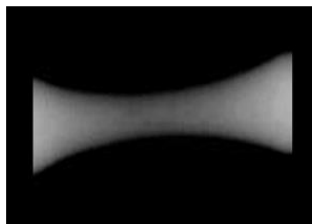
- “Tomography” means imaging an object by taking measurements from “slices” of its cross-section.

Example: Radiographic Inspection of Tensile Specimen:

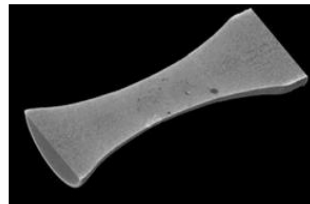
- Step-1:** CT slices through several locations of a tensile specimen are captured using CT inspection system.
- Step-2:** A number of slices through the object can be reconstructed to provide a 3-D view of internal and external structural details.
- Step-3:** The resultant 3-D image can then be manipulated and sliced in various ways to provide thorough understanding of the structure.



(i) CT Slices at Different Cross Sections



(ii) Compiled/Reconstructed Radiographic Image



(iii) Sliced 3-D Image for Inspection

Interpretation of Radiographs:

- *To identify the discontinuity on the radiograph and correlate them with their appearance and location in the actual object, the essential steps in interpretation are as follows:*
- Determine the accuracy of the identification of the radiograph.
 - Determine the work piece material and the manufacturing processing setup.
 - Verify the radiographic setup and procedure.
 - Review the film under good viewing conditions.
 - Determine if any false or irregular indications are present on the film.
 - Identify any surface irregularities and verify their type.
 - Evaluate relevance of discontinuities with code or specification requirement and Prepare radiographic report.

Interpretation of Radiographs in Weldments:

Defects	Appearance on radiographs
Porosity	Round or elongated smooth dark spots
Slag inclusion	Dark irregular shapes
Incomplete penetration	Continuous or intermitted dark lines in the middle of the weld.
Lack of fusion	Thick dark line
Tungsten inclusion	White areas of round or irregular shapes.

Advantages and Limitations of Radiography Testing:

Advantages:

- Information is presented pictorially.
- Permanent record is provided which may be viewed at a time and place distant from the test.
- Useful for thin sections.
- Access into small cavities.
- Technique is not limited by material type or density.
- Can inspect assembled components.
- Minimum surface preparation required.
- Sensitive to changes in thickness, corrosion, voids, cracks, and material density changes.
- Detects both surface and subsurface defects.

Limitations:

- Possible health hazard.
- Need to direct the beam accurately for two-dimensional defects.
- Film processing and viewing facilities are necessary.
- Not suitable for automation.
- High initial cost.
- Many hours of technician training prior to use.
- Access to both sides of sample required.
- Orientation of equipment and flaw can be critical.



Comparison between X-ray and Gamma Ray Radiography:

Advantages of Gamma Ray Radiography Over X-ray Radiography:

- No electrical or water supplies needed.
- Equipment smaller and lighter.
- More portable.
- Equipment simpler and more robust.
- More easily accessed.
- Less scatter & Greater penetrating power.
- Equipment initially less costly.

Disadvantages of Gamma Ray Radiography Over X-ray Radiography:

- Poorer quality radiographs.
- Exposure times can be longer.
- Sources need replacing.
- Radiation cannot be switched off.
- Poorer geometric unsharpness.
- Remote handling necessary.

Radiation Safety:

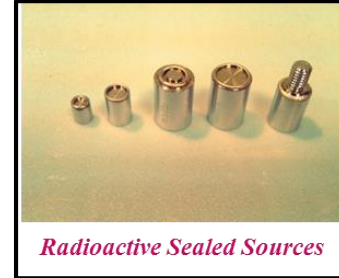
- Ionizing radiation (X-rays or gamma rays) is an extremely important NDT tool but it can pose a hazard to human health.
- For this reason, special precautions must be observed when using and working around ionizing radiation.
- Complicating matters further is the fact that Gamma and X-ray radiation are not detectable by the human body.
- However, the risks can be minimized when the radiation is handled and managed properly.

There are three basic methods of providing protection:

1. Introducing absorbing material around the source.
2. Increasing the distance between the source and personnel (the radiation dose-rate at any point depends inversely on the square of the distance from the source).
3. Reducing the time that it is necessary for personnel to be near the source.

Radioactive Source-Handling Equipment:

- Pellet of radioactive material cannot be safely handled except by special methods.
- Apart from hazards of radiation from source there would be contamination hazards from particles of radioactive matter wiped off by anything touching the pellet.
- Artificial radioactive sources for gamma-radiography are always supplied as “**sealed sources**” in a capsule by the atomic energy authority of the supplying country.
- There should be no need for the industrial radiographer ever to encounter the problems of handling unsealed sources.
- For transportation and handling the radioactive capsule must either be supported by
 - ✓ A mass of material which absorbs sufficient radiation for the dose-rate on the outside of the container to be reduced to a safe level.
 - ✓ Using long **tongs**, a long rod or by other remote-control handling equipment, so that the distance between source and handler reduces the dose-rate to a safe value.



Summary:

- Radiography testing involves using penetrating gamma or X-radiation on materials and products to look for defects or examine internal or hidden features.
- An X-ray generator or radioactive isotope is used as the source of radiation and radiation is directed through a part, onto a film or other detector.
- The resulting shadowgraph shows the internal features and soundness of the part.
- Material thickness and density changes are indicated as lighter or darker areas on the film or detector.
- Radiographic examination finds many application in inspecting casting, welding, structures etc. for internal soundness.

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INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 13: Leak Testing



Dr. Kaushik Pal

Associate Professor

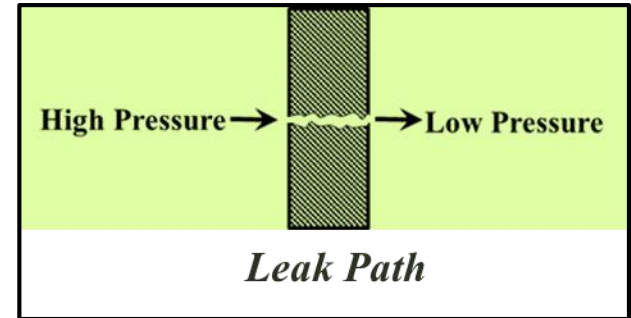
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What is a Leak?

- Leakage implies the escape of liquid or gas from a pressurised or evacuated enclosure or system (via an imperfection such as a hole, crack or bad seal).
- Leaks require a pressure difference to generate the flow; they always flow from higher pressure to lower pressure.
- Leaks are usually pictured as going from positive pressure (inside an object) to outside (at atmospheric pressure).
- This is not always the case (a leak could be from atmosphere to inside an evacuated object), but it helps to think about it this way because the units and terminology are based on this model.



What is Leak Testing?

- Leak testing is a process used to detect manufacturing defects which helps verify the integrity of products and improve consumer safety.
- Manufacturers that produce parts that contain gas or liquid, need to know if their products include any defects that could allow leakage.
- The objective of the leak test is locate and/or measure the amount of leak-liquid or gas flowing through a discontinuity.

Reasons for Leak Testing:

Economic:

- *To prevent material loss that interferes with system operation.*

Safety:

- *Prevent fire, explosion, and environmental contamination.*

Reliability:

- *Detect unreliable components, and those with leakage rates that exceed standards.*

Steps in Leak Testing:

1) *Locating the leak.*

2) *Measuring the rate of leakage.*

3) *Monitoring the leakage for maintenance of the system.*

Units of Leakage:

- Leak rates are generally measured in terms of quantity of a gas leaking in one second.
- Most commonly used units of leakage rates are:
 - Standard cubic centimetre per second (**std.cm³/s**).
 - Standard atmosphere cubic centimetre per second (**atm.cm³/s**).
 - For vacuum leak test torr litre per sec. (**torr l/s**) is used.
 - SI unit is Pascal cubic meter per second (**Pa m³/s**).

Acceptable Leakage:

<i>Substance</i>	<i>Acceptable leakage (std.cm³/s)</i>
Water	1×10^{-3}
Gasoline from storage tanks	1×10^{-4}
Gas from pipelines	1×10^{-5}
Leakage in a tanker	1×10^{-6}

Factors Affecting Leakage:

- i. Type of fluid.
- ii. Geometry of discontinuity.
- iii. Sensitivity of the instruments.

Use of Leak Testing Techniques:

- Used extensively in industry, construction, and municipal infrastructure to ensure the safety of gas lines, boilers, oil pipelines, and many other high-pressure and hazardous material storage applications.
- Testing for hydrogen gas lines is much more complex due to the small size of a hydrogen molecule, so electronic sniffing and sampling devices are often used for this application.

Leak Testing Systems:

- The four general classes of systems commonly leak tested are:

a) Hermetic (Airtight) Enclosures and Components:

- They are tested to prevent the entrance of contamination or preserve internally contained fluids.
- **Examples:** Electronic devices, integrated circuits, sealed relays and motors, pull-tab can ends, and connector multipin feedthroughs.



Hermetically Sealed Battery

b) Hermetic Systems:

- They are leak tested to prevent the loss of contained fluids or gases.
- **Examples:** Hydraulic and refrigeration systems; Plant valves, piping, and vessel systems in chemical and petrochemical industries.



Pressure Vessel System

c) Evacuated Enclosures and Components:

- They are leak tested to assure that there is not too rapid a deterioration of the vacuum system with time.
- **Examples:** Electronic tubes, including TV picture tubes, sensing bellows, and vacuum-packaged items.



Cathode Ray Tube

d) Vacuum Systems:

- These are tested to assure that leakage has been minimized so that optimum gas removal can be achieved at any given vacuum (absolute pressure) rating.

Methods of Leak Detection:

- Different methods can be used for leak testing:
 1. Ultrasonic Leak Testing
 2. Bubble Leak Testing
 3. Dye Penetrant Leak Testing
 4. Ammonia Colorimetric Leak Testing
 5. Pressure Change Leak Testing
 6. Differential Pressure Leak Testing
 7. Mass Flow Leak Testing
 8. Helium Mass Spectrometer Leak Testing
 9. Radioisotope Tracer Leak Testing



1. Ultrasonic Leak Testing:

- Ultrasonic leak testing has been specifically developed for detecting gas leaks in high-pressure lines.
- Depending on the nature of the leak, escaping gas produces ultrasonic sound that can be detected with an approximate sensitivity of 10^{-3} atm cc/s .

What produces ultrasound in a leak:

- ✓ Gas passing through a restricted orifice (leak) moves from pressurized laminar flow to low pressure turbulent flow
- ✓ Turbulence creates broad spectrum of sound called “white noise”
- ✓ Some components of “white noise” are ultrasonic
- ✓ The larger the leak, the greater the ultrasound level.



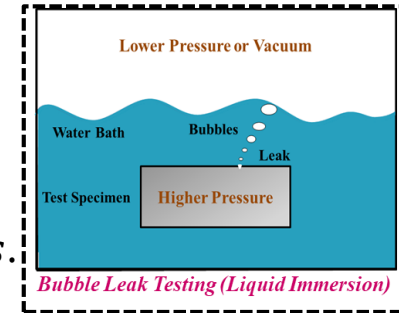
Ultrasonic Leak Detection

Applications:

- ✓ Ultrasonic leak detectors are used by a number of industries for detecting gas leaks in:
 - Internal combustion engine valving and piston blow-by, gaseous piping, and ducting;
 - Air brake systems;
 - Bearings;
 - Seals in refrigerated van bodies, clean rooms, and air ducts;
 - Various hydraulic components, and other items.
- ✓ Leaks can also be detected in overhead piping systems and at other locations from a considerable distance.
- ✓ The ultrasonic leak detector has the advantage that it is not sensitive to audible background noise.

2. Bubble Leak Testing:

- It also known as water immersion or air bubble observation test.
- The uppermost surface of the specimen shall be covered by not less than 1 in. (25 mm) of fluid.
- Bubble leak testing is more qualitative than quantitative.
- Small leaks produce numerous small bubbles, but it is difficult to determine the actual leak rate.
- The size of the bubbles and the emission frequency depend on:
 - ✓ *the type of gas flow,*
 - ✓ *the size of the leak,*
 - ✓ *the surface tension of the liquid.*
- Sensitivity of bubble leak tests has been estimated at 10^{-3} to 10^{-4} atm cc/s.



Types of Bubble Leak Testing:

- ❖ It is classified into three parts on the basis of how the liquid used for detection is applied:



Advantages:

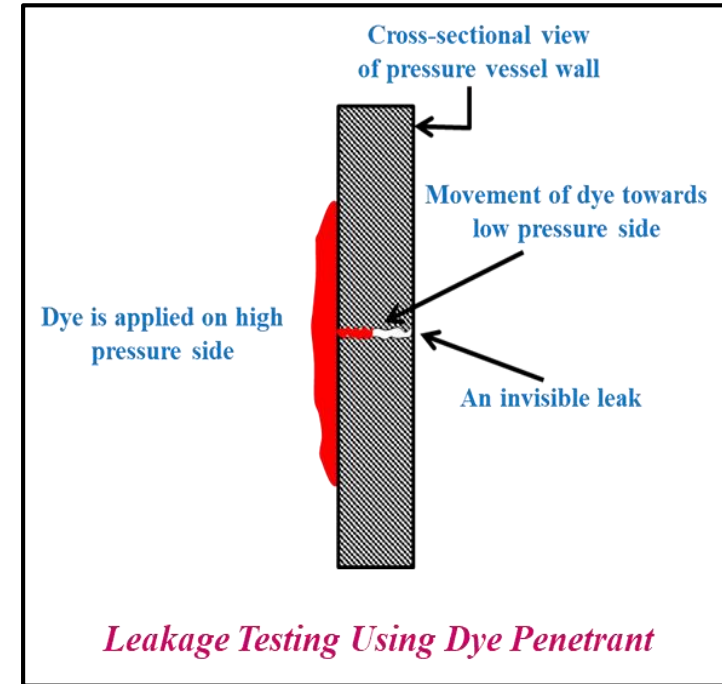
- Simple to use, rapid application, and inexpensive.
- Enables the observer to locate the exit point of leaks very accurately (compared to Pressure Change Test).
- Very large leaks and small leaks can be detected.
- Safe to apply BLT with proper inert gases, and testing liquids, in combustible areas.

Disadvantages:

- This method is not reliable due to following reasons:
 - The leak size cannot be easily quantified.
 - Component requires drying after test.
 - Extensive floor space required, low throughputs.
 - High dependency on the reliability of the operator.
 - Problems with bubbles:
 - ✓ *Get trapped in the component structure*
 - ✓ *Not produced because the leak is too small*
 - ✓ *False bubbles can be produced by air trapped in the component structure during its immersion in water*
 - Unpleasant working conditions (water can wet floors, operators, etc.)
 - Operational and maintenance costs (cleaning the water, lighting, etc..)

3. Dye Penetrant Leak Testing:

- Dye penetrant also provides an economical leak testing method.
- Special dyes can be sprayed on the high-pressure side of suspected leak areas.
- If a leak is present, the differential pressure of the system will cause the dye to seep through the leak and appear on the low-pressure side of the object.
- This method can take an hour or more for a leak test sensitivity of 10^{-4} atm cc/s .
- Because of the long time involved, this test method is infrequently used.



4. Ammonia Colorimetric Leak Testing:

- It is used to detect a leak in double wall tanks, pressure and vacuum vessels.
- Colorimetric leak testing generally employs two chemical agents:
 - ✓ *Ammonia as tracer gas*
 - ✓ *Developer*
- The tracer gas (e.g. Ammonia) is introduced into the vessel at a predetermined pressure and a thin coat of indicator developer powder is applied on the outer surface of object around suspected areas like seams and welds.
- Over a period of time, the tracer gas diffuses into the system.
- The gas escaping from the leak react with developer powder and changes its colour, indicating the location of the leak.

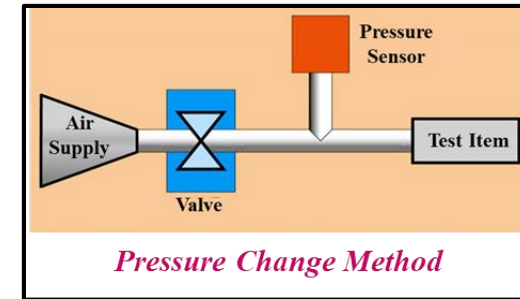


5. Pressure Change Leak Testing:

- Pressure change leak tests are also called pressure hold tests, pressure decay tests, or pressure loss tests.
- It is the most widely used method of leak testing in manufacturing production lines.

Working Procedure:

- ✓ The part under test is pressurized by filling it with air or other gas until it reaches a set pressure.
- ✓ An isolation valve is then used to disconnect the part from the supply pressure.
- ✓ The pressure within the part is then monitored using a pressure sensor, and as the air (or gas) leaks out, the pressure drops.
- ✓ The leak rate can then be calculated based on the change in pressure over a certain period of time.



$$\text{Leak rate} = Q_L = \frac{(P_1 - P_2) \times V}{t}$$

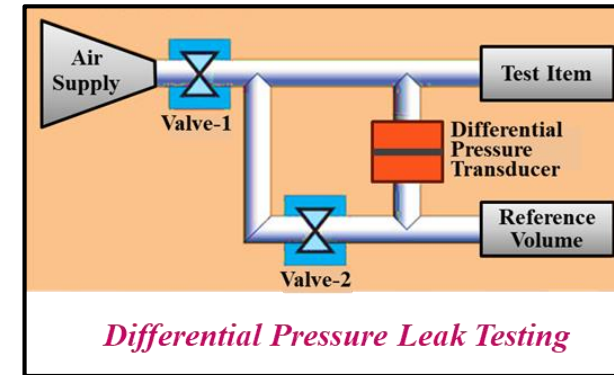
Where, P_1 = initial pressure,
 P_2 = final pressure,
 V = volume of test part,
 t = measurement time period.

6. Differential Pressure Leak Testing:

- It is a more accurate variant of the pressure-decay method.
- This method requires measuring pressure at two points in time to obtain a pressure change reading.
- It is an indirect method of measuring leakage rate because the time and pressure data must be converted into leakage rate.

Working Procedure:

- ✓ With valves 1 and 2 open, the test item and reference volume are pressurized and then isolated by closing valve 1.
- ✓ The reference volume is then isolated from the test item by closing valve 2.
- ✓ The pressure differential between the non-leaking reference volume and the test item is then measured by a transducer over time.

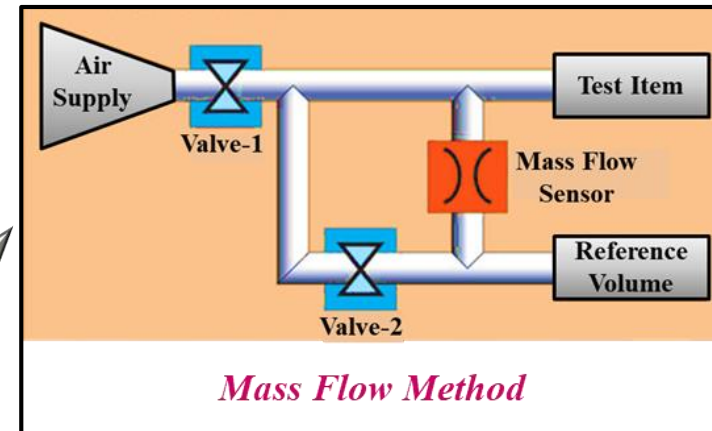


7. Mass Flow Leak Testing:

- Mass flow leak-testing system uses mass-flow sensors, which can provide fast and accurate testing over a much wider range of leak/volume ratios and testing.

Working Procedure:

- ✓ In this method, a part is pressurized along with a reference volume.
- ✓ Then the amount of air that flows into the part to replace a leakage flow is measured (in standard $\text{cm}^3/\text{minute}$) using mass-flow sensor.
- ✓ A number of error proofing techniques are also used to guarantee test system reliability.

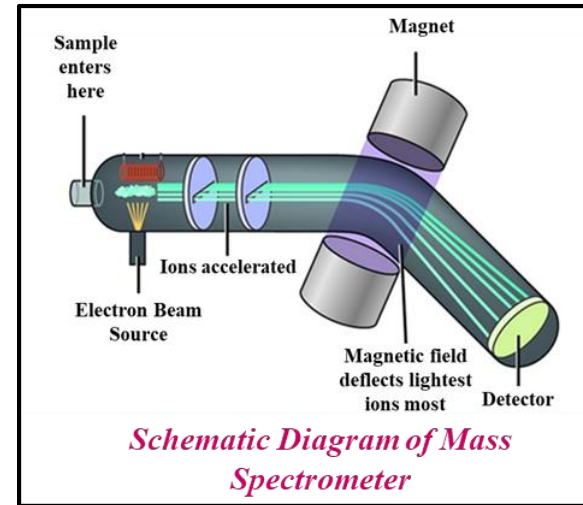


8. Helium Mass Spectrometer Leak Testing:

- Helium mass spectrometer leak detector (MSLD) is the most versatile of the industrial and laboratory leak detector methods.
- This method was developed in 1940s to meet the strictest requirements in the development of nuclear devices.
- The main part of the device is mass spectrometer, a sensor for different gas masses.

Operating Principle of Mass Spectrometer:

- In very low pressure (or vacuum) the molecules of rest gasses are transformed in ions by electron impact.
- These ions are accelerated by passing them into a powerful electric field.
- Ions of different atoms have different amounts of electric charge, and the more highly charged ones are accelerated most, so the ions separate out according to the amount of charge they have.
- Then, this ion beam is made to enter into magnetic field.
- When moving particles with an electric charge enter a magnetic field, they bend into an arc, with lighter particles (and more positively charged ones) bending more than heavier ones (and more negatively charged ones).
- Now, separating the ionized particles of different charge to mass ratios (q/m) it is possible to state the masses of present gases.



Reasons of Using Helium as Tracer Gas:

- Helium is an inert, nontoxic, non-condensable gas that is plentiful and relatively inexpensive.
- It is also a very small molecule and light, and therefore easily slips through very small leaks.
- There is only a low concentration of helium naturally present in the atmosphere (~ 5 ppm), so normally occurring background levels are manageable.

Mode of Operation:

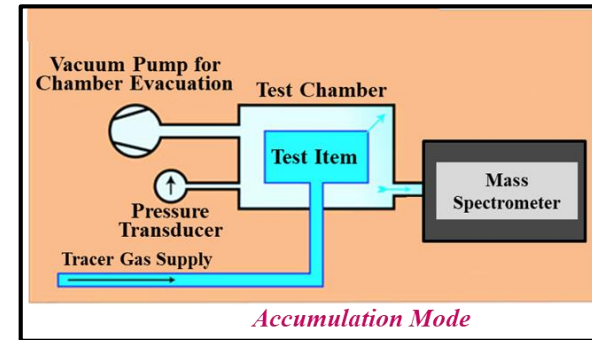
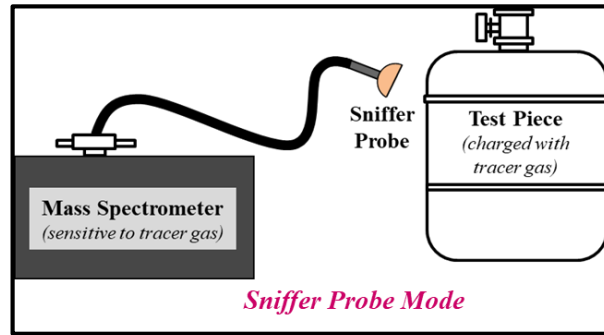
- This test can be carried out in two ways:

❖ Sniffer Probe Mode:

- ✓ The test item is pressurized with helium gas and the exterior is scanned with a sniffer probe connected to the mass spectrometer to localize the leak.
- ✓ This method is slow, non-quantitative but has the advantage of localizing the leak.

❖ Accumulation Mode:

- ✓ The part is pressurized with helium and the chamber is evacuated down to less than 0.1 mbar absolute to eliminate background effects.
- ✓ The presence of helium leaking into the chamber is then detected by the mass spectrometer.



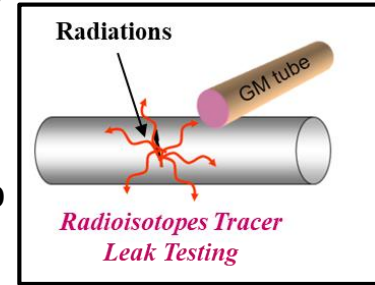
Applications:

- Helium mass spectrometer leak detectors are used in production line industries of:
 - Refrigeration and air conditioning systems
 - Automotive parts
 - Carbonated beverage containers
 - Food packages
 - Aerosol packaging
 - Steam products
 - Gas bottles
 - Fire extinguishers
 - Tire valves
 - All vacuum systems



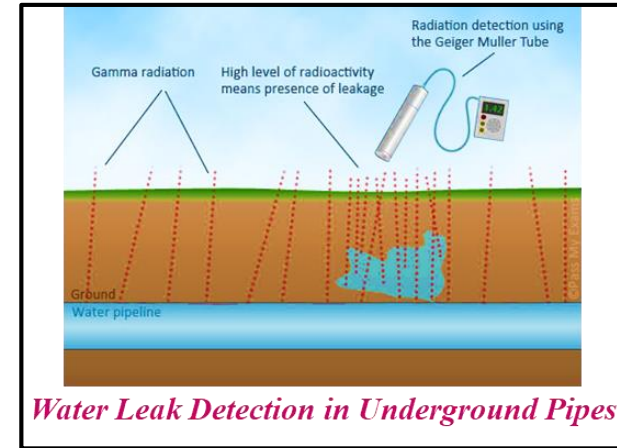
9. Radioisotope Tracer Leak Testing:

- In this method, short-life radioisotopes are used to leak test hermetically sealed cavities and closed piping systems.
- A radioactive isotope is injected into the pipe.
- Then the outside of the pipe is checked with a Geiger-Muller detector to find areas of high radioactivity.
- These are the points where the pipe is leaking.
- This is useful for underground pipes that are hard to get near.



Properties of Radioisotope Used:

- ✓ It must have a short half-life so the material does not become a long term problem.
- ✓ It must be gamma emitter so that it can be detected through the metal and the earth where the pipe leaks.



How to Choose the Test Method:

- The correct method for a given application is selected on the basis of following information:
 - How many points must be tested?
 - What is the pass/fail leak rate? (or how much time must the product last?)
 - What are the dimensions of the product to test?
 - What is the required test cycle time?
 - Does it have to be an automated system or manual?
 - What is the budget?
 - What is the test pressure?



Summary:

- Leak testing is a non-destructive technique used to ensure quality control which helps verify the strengths of the product and guarantee customer safety.
- Over the years, many methods have been developed for detecting and measuring leaks.
- Some of the most commonly used leak testing methods have been discussed along with their operating principle.

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CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 14: Thermographic Nondestructive Testing



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



Introduction:

- Thermographic non-destructive testing is also known as **thermal inspection, thermography, thermal imaging, thermal wave imaging** and **infrared thermography testing**.
- It was first developed for military purposes in the late 1950s and 1960s by Texas Instruments, Hughes Aircraft, and Honeywell.
- It involves the measurement or mapping of surface temperatures as heat flows to, from and/or through an object.
- The simplest thermal measurements involve making point measurements with a thermocouple.

Usefulness of Thermographic Inspection:

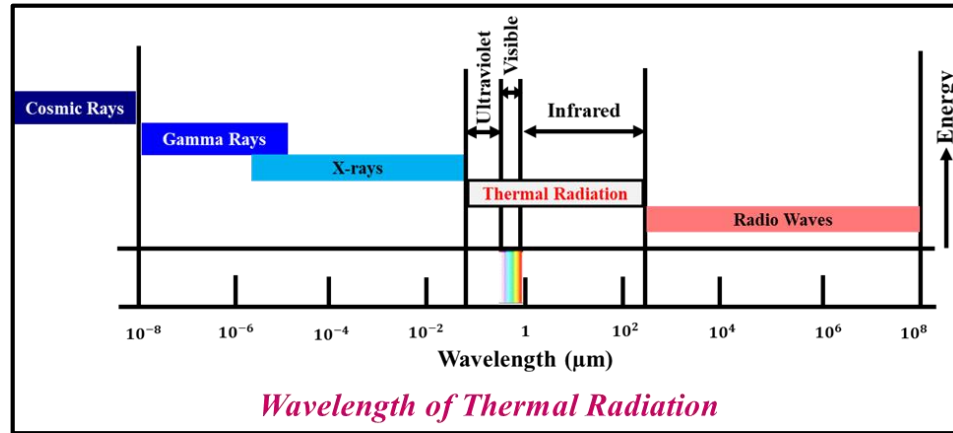
- ❖ This NDT method is useful in locating hot spots, such as a bearing that is wearing out and starting to heat up due to an increase in friction.

Application of Infrared thermography for space shuttle maintenance.



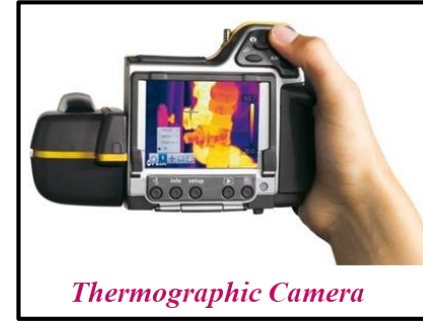
Principle of Thermography:

- Principle of thermography is based on the physical phenomenon that any body of a temperature above absolute zero ($-273.15\text{ }^{\circ}\text{C}$) emits electromagnetic radiation.
- The emitted infrared energy is a function of the object's temperature and its relative efficiency of thermal radiation, known as emissivity.
- Two dissimilar materials, possessing different thermophysical properties, would produce two distinctive thermal signatures that can be revealed by an infrared sensor (Thermographic Camera).



Thermographic Camera:

- It is also known as *infrared camera* or *thermal imaging camera*.
- It is a device that forms a heat zone image using infrared radiation, similar to a common camera that forms an image using visible light.
- Instead of the 400–700 nm range of the visible light camera, infrared cameras operate in wavelengths as long as 14,000 nm.



Thermographic Camera Construction:

- ✓ The focusing lenses of IR cameras are not made of glass, as glass blocks long-wave infrared light.
- ✓ Special materials such as Germanium or Sapphire crystals are used for this purpose.
- ✓ Germanium lenses are also quite fragile, so often have a hard coating to protect against accidental contact.
- ✓ The higher cost of these special lenses is one reason why thermographic cameras are more costly.

Types of Thermographic Camera:

- Thermographic cameras can be broadly divided into two types:
 - ❖ Cooled infrared detectors
 - ❖ Uncooled infrared detectors

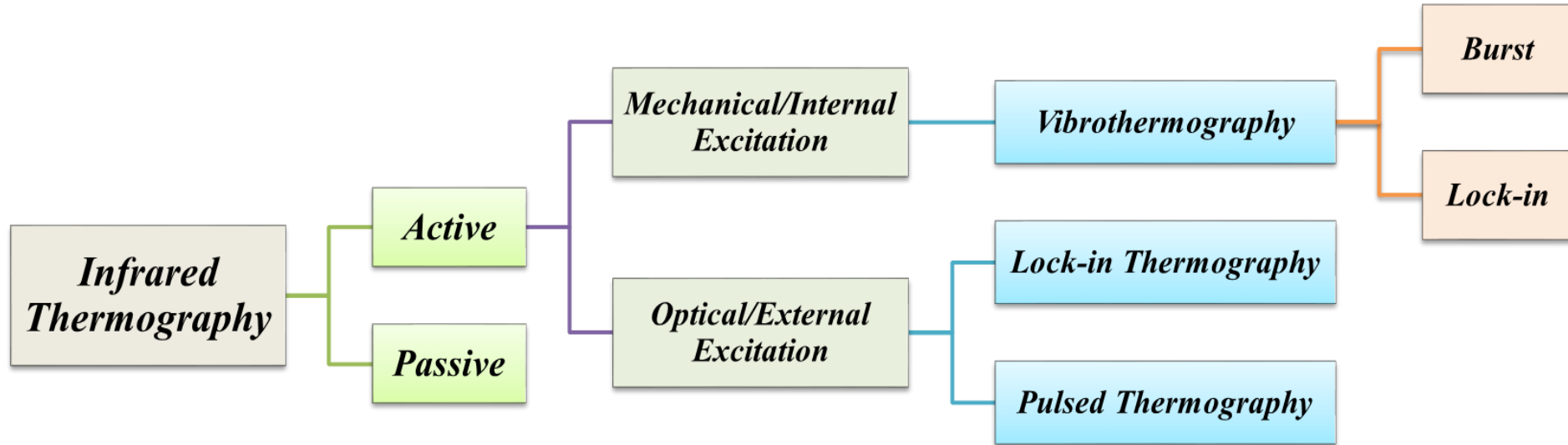
Cooled Infrared Detectors

- They are typically contained in a vacuum-sealed case and cryogenically cooled.
- The cooling is necessary for the operation of the semiconductor materials used.
- Typical operating temperatures range from 4 K to just below room temperature.

Uncooled Infrared Detectors

- Uncooled thermal cameras use a sensor stabilized at a temperature close to ambient using small temperature control elements.
- Modern uncooled detectors use sensors that work by the change of resistance, voltage or current when heated by infrared radiation.
- They have lower sensitivity than the cooled IR detectors.

Types of Thermographic Inspection:



ACTIVE THERMOGRAPHY:

- In active thermography, an energy source is required to produce a thermal contrast between the feature of interest and the background.
- The active approach is adopted in many cases given that the inspected parts are usually in equilibrium with the surroundings.
- **Example:** a specimen with internal flaws.

Energy Sources in Active Thermography:

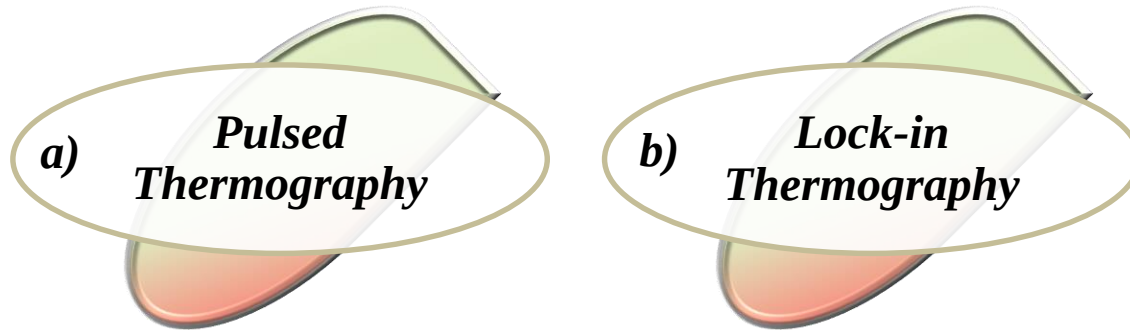
- A wide variety of energy sources can be used to induce a thermal contrast between defective and non-defective zones.
- These energy sources can be categorized as:
 - **External Energy Sources**
 - **Internal Energy Sources**

External Excitation:

- Energy is delivered to the surface and then propagated through the material until it encounters a flaw.
- **Examples:**
 - Photographic flashes (for heat pulsed stimulation)
 - Halogen lamps (for periodic heating)

Externally Excited Thermographic Methods:

- ✓ Externally applied active thermographic methods are further classified as:

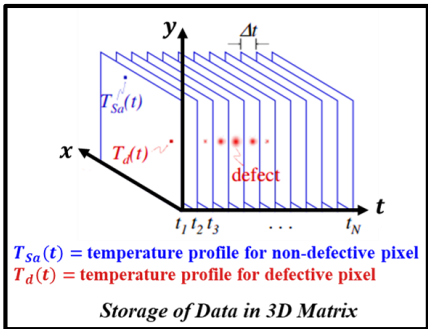
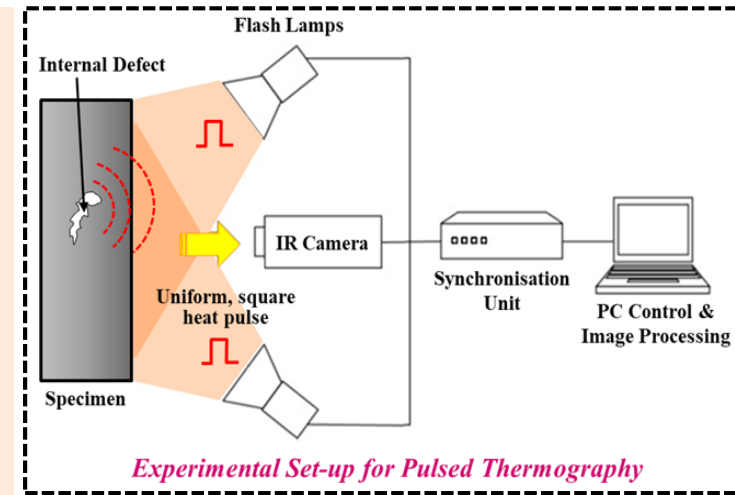


a) Pulsed Thermography:

- In pulsed thermography (PT), the specimen surface is submitted to a heat pulse using a high power source such as photographic flashes.
- A heat pulse can be thought as the combination several periodic waves at different frequencies and amplitudes.

Working Procedure:

- ✓ Two photographic flashes are used to heat up the specimen's surface, after what, the thermal changes are recorded with an infrared camera.
- ✓ A synchronization unit is needed to control the time between the launch of the thermal pulse and the recording with the IR camera.
- ✓ Data is stored as a 3D matrix, where x and y are the spatial coordinates, and t is the time.



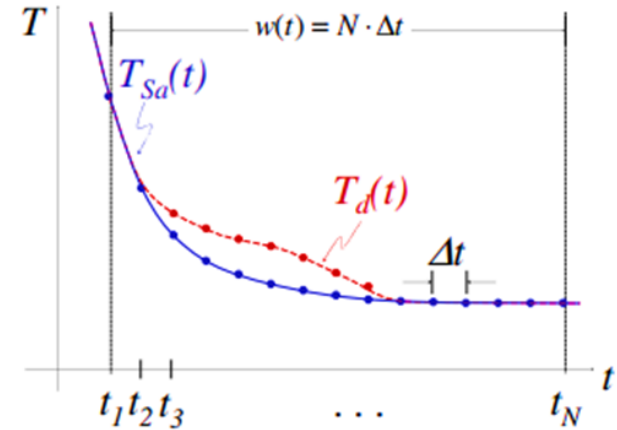
Processing of Pulsed Thermography Data:

- The data is analysed on the basis of assumption that:

“Temperature profiles for non-defective pixels should follow the decay curve given by the one-dimensional solution of the Fourier equation”.

- ❖ Temperature decreases approximately as $\sqrt{t}$ (as per Fourier equation), except for the defective areas, where the cooling rate is different.

$T_{Sa}(t)$ = temperature profile for non-defective pixel
 $T_d(t)$ = temperature profile for defective pixel



Temperature profile for a defective (dotted line) and non-defective (continuous line) pixels

Advantages:

- ✓ Pulsed thermography is fast and easy to deploy.
- ✓ It's experimentation time varies from a few seconds for high conductivity materials to a few minutes for low conductivity materials.
- ✓ Since a heat pulse can be seen as a set of several periodic thermal waves launched at once, several data points (amplitude or phase) can be extracted from a single experiment.
- ✓ Pulsed thermography is sensitive to voids and inclusions in the material which are difficult to detect.

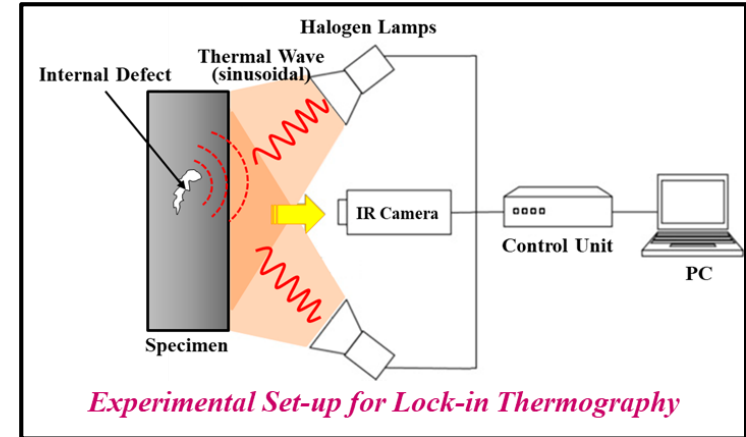
Disadvantages:

- ✓ The data processing of pulsed thermography technique is complex as compared to lock-in.
- ✓ The results are affected by non-uniform heating, emissivity variations, environmental reflections and surface geometry.



b) Lock-in Thermography:

- In lock-in thermography (LT) is also known as modulated thermography.
- In this method, a small surface spot is periodically illuminated by an intensity modulated laser beam to inject thermal waves into the specimen.
- Sinusoidal thermal waves are typically used in LT.
- The periodic wave propagates by radiation through the air until it touches the specimen surface where heat is produced and propagates through the material.
- Internal defects act as barrier for heat propagation, which produces changes in amplitude and phase of the response signal at the surface.
- The thermal response is recorded using an infrared detector and decomposed by a lock-in amplifier to extract the amplitude and phase of the modulation.



Selection of Working Frequency for Inspection of Different Materials:

- The rate of decay of the thermal wave as it penetrates through the material depends upon the thermal diffusion length (μ).
- Thermal diffusion length is defined as:

$$\mu \equiv \sqrt{\frac{2\alpha}{\omega}} = \sqrt{\frac{\alpha}{\pi \cdot f}}$$

*Where, α = thermal diffusivity of the material being inspected.
 f = frequency of the thermal wave.*

- From above relation, it is established that:
 - ❖ Thermal waves propagate deeper in more diffusive materials.
 - ❖ Information about deeper features is available when lower frequencies are used.
- These two aspects are important to correctly select the working frequency and to determine the depth of internal defects.

Processing of Lock-in Thermography Data:

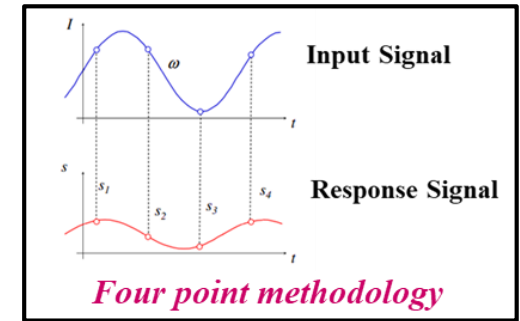
❖ Four Point Methodology (for sinusoidal waveform):

- For sinusoidal input signal, four point methodology is used for amplitude and phase delay estimation by lock-in thermography.
- Input and output have the same shape when sinusoids are used, there is only a change in amplitude and phase that can be calculated as follows:
- If S_1 , S_2 , S_3 and S_4 are four equidistant data points in a complete period then, the phase (ϕ) and amplitude (A) is given by:

$$A = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2}$$
$$\phi = \tan^{-1} \left(\frac{S_1 - S_3}{S_2 - S_4} \right)$$

❖ Discrete Fourier Transform (DFT) Method (for any waveform):

- The discrete Fourier transform (DFT) can also be used to extract amplitude and phase information from LT data.



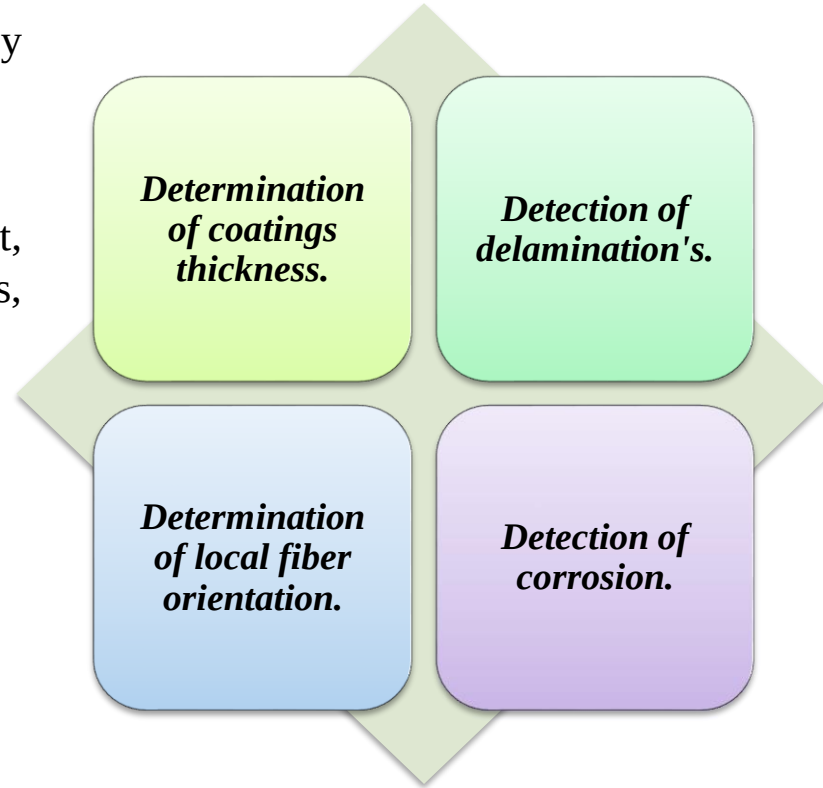
Advantages:

- ✓ Energy required to perform an LT experiment is generally less than in other active techniques, which is helpful:
 - If a low power source is to be used,
 - If special care has to be given to the inspected part, e.g. cultural heritage pieces, works of art, frescoes, etc.

Disadvantages:

- ✓ It is in general slower than other approaches such as pulsed thermography.
- ✓ Extra hardware, i.e. lock-in amplifier, is needed in order to retrieve the amplitude and phase of the response.

Applications:

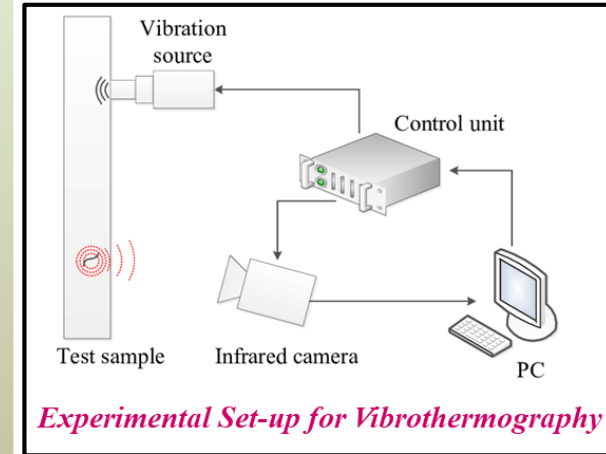


Internal Excitation:

- Energy is injected into the specimen in order to stimulate exclusively the defects.
- Vibrothermography technique uses internal excitation to perform the inspection.

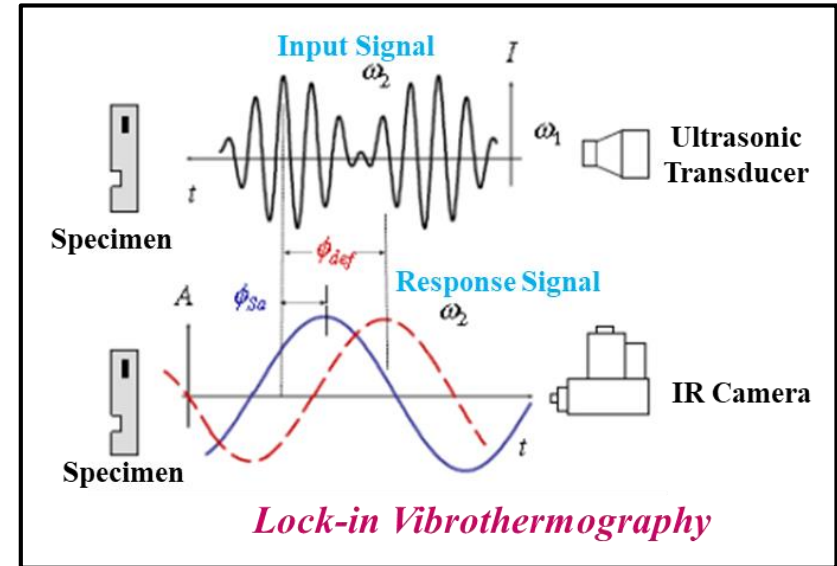
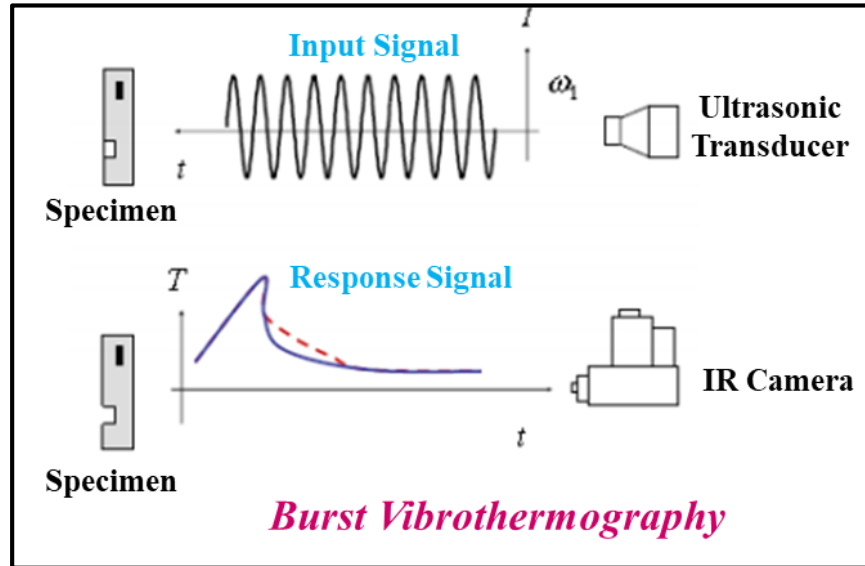
Vibrothermography (VT):

- ✓ It is also known as ***ultrasound thermography*** or ***thermosonics***.
- ✓ The ultrasound wave is produced within specimen by a transducer made of a stack of piezo elements and concentrated in a titanium horn that acts like a hammer.
- ✓ After the elastic waves are injected to the specimen, they travel through the material and dissipate their energy mostly at the defects so heat is locally released.
- ✓ The thermal waves then travel by conduction to the surface, where they can be detected with an IR camera.



Configurations of Vibrothermography Testing:

- There are basically two configurations for VT (similar to the optical methods discussed earlier):
 - Burst Vibrothermography** (analogous to Pulse Thermography)
 - Lock-in Vibrothermography** (analogous to Lock-in Thermography)



Advantages:

- ✓ In either lock-in or burst configuration, VT is extremely fast.
- ✓ Defect detection is independent from of its orientation inside the specimen, and both internal and open surface defects can be detected.
- ✓ It is the most appropriate technique to inspect some types of defects, *e.g.* micro cracks, delamination's.
- ✓ There is only minimal heating of the inspected specimen since energy is usually dissipated mostly at the defective areas.

Disadvantages:

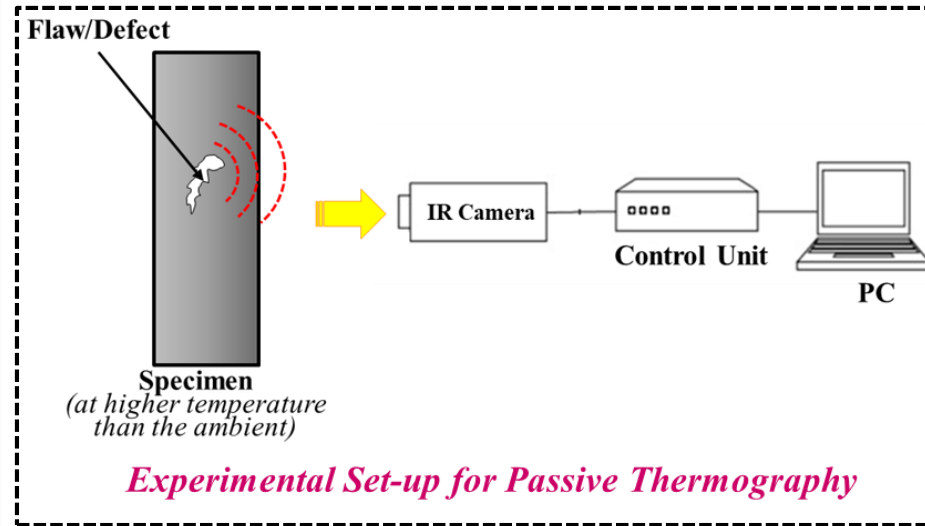
- ✓ It is necessary to relocate the transducer to cover a large area for inspection. Hence, VT is only suitable for relatively small objects.
- ✓ The most inconvenient aspect of VT is the need of a coupling media between the sample and the transducer, and the need of holding the specimen.
- ✓ A bad coupling implies a poor ultrasound transmission but more seriously it creates unwanted heat in the vicinity of the ultrasound injection point.

PASSIVE THERMOGRAPHY:

- In passive thermography, the features of interest are naturally at a higher or lower temperature than the background.

Example: surveillance of people on a scene.

- All objects above absolute zero emit thermal infrared energy, so thermal cameras can passively see all objects, regardless of ambient light.



Important Applications of Passive Approach:

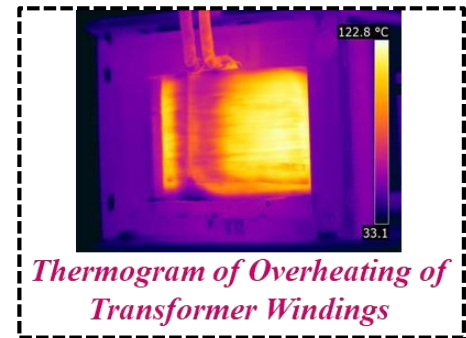
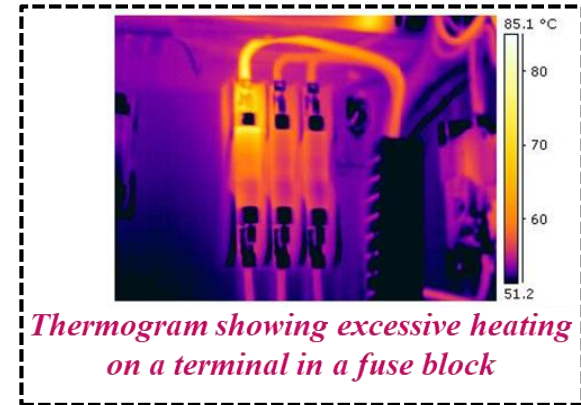
- Passive thermographic inspection has several applications in different sectors:

Production:

- ✓ Inspection of printed circuit boards (PCBs) to detect solder bridges and overheating components.
- ✓ Seam tracking in arc welding.
- ✓ In the production of metals, recording of temperature profiles enables monitoring of steel quality in continuous casting.
- ✓ In the paper industry, infrared thermography monitors quality in the production of high-gloss paper.

Maintenance:

- ✓ Inspection of turbine blades in jet engines.
- ✓ Thermal insulation of building envelopes, heated floors, furnace walls.
- ✓ Estimation of liquid level in tanks.
- ✓ Early detection of transformer overheating.
- ✓ Visualisation of gas leaks.



Medicine:

- ✓ Evaluation of patients with disorders of the musculoskeletal system.

Monitoring of Road Traffic:

- ✓ In the case of monitoring of road traffic, infrared thermography enables moving road vehicles, which will be hotter than their surroundings.

Detection of Forest Fires:

- ✓ Safety of forest areas through early detection of smouldering fires

Astronomy:

- ✓ Satellites with infrared imaging capabilities are also used to monitor the Earth's weather,
 - To study vegetation patterns, and geology
 - To measure surface, ocean and cloud temperatures

Military:

- ✓ Revealing the presence of potential targets in poor visibility conditions (e.g. at night or in fog).
- ✓ Air-to-air detection of incoming enemy missiles or aircraft from their hot exhaust gases.
- ✓ Surveillance in security, law enforcement and defence.



Advantages & Disadvantages of Thermographic Inspection:

Advantages:

- It is capable of catching moving targets in real time.
- It is able to find deterioration, i.e., higher temperature components prior to their failure
- It can be used to measure or observe in areas inaccessible or hazardous for other methods
- It can be used to find defects in shafts, pipes, and other metal or plastic parts.
- It can be used to detect objects in dark areas.

Disadvantages:

- Quality cameras often have a high price range due to the expense of the larger pixel array.
- Fewer pixels reduce the image quality making it more difficult to distinguish proximate targets within the same field of view.
- Accurate temperature measurements are hindered by differing emissivities and reflections from other surfaces.
- Most cameras have $\pm 2\%$ accuracy or worse in measurement of temperature and are not as accurate as contact methods.
- Methods and instruments are limited to directly detecting surface temperatures.

Summary:

- Thermographic Non-destructive Testing is a modern method for inspecting surface layers and thin parts made of various materials.
- Defects or foreign particles in an inspected part can be detected if their thermal properties are different from the inspected material.
- Two approaches are being followed in thermography:
 - i. Active Thermography
 - ii. Passive Thermography
- Several methods have been developed for active thermography for non-destructive evaluation.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 15: Advanced Nondestructive Testing Techniques, NDT Standards, Safety in NDT



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



Introduction:

- In response to increasing demands for speed, accuracy, and reliability of NDT inspections, advanced techniques are being developed.
- These techniques have extended the range of components that can be inspected.
- Some of the advanced NDT methods (Acoustic Emission, Thermography, etc.) already have been discussed in previous lectures.
- Other advanced NDT methods used in different industries are:

☐ ***Neutron Radiography and Neutron Radioscopy***

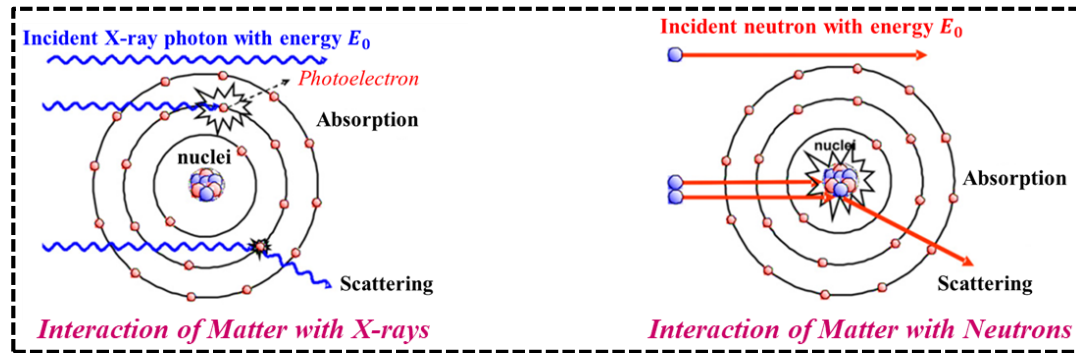
☐ ***RFT (Remote Field Testing)***

☐ ***IRIS (Internal Rotational Inspection System) Testing***

☐ ***Terahertz Non-destructive Evaluation***

Neutron Radiography (NR):

- It is an advance technique for Non-destructive testing of materials, which provides images similar to X-ray radiography.
- Neutron is a subatomic particle without a net charge, consequently electrostatic forces have no effect on it, when it travels through matter.
- The difference between neutron and X-ray interaction mechanisms produce significantly different and often complementary information.
- Unlike gamma ray and X-ray, neutron only interacts with atomic nuclei. Therefore, the attenuation pattern of thermal neutron is different from X-ray.

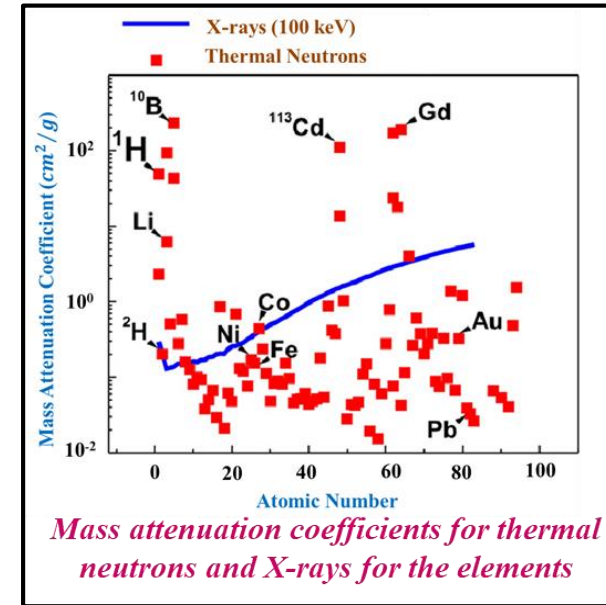


History:

- The history of neutron radiography with thermal neutrons can be traced shortly after the discovery of neutron by Chadwick, in 1932.
- Thewlis and Derbyshire produced the first reactor based neutron radiographs in 1956, using a reactor beam of the 8 MW BEPO reactor at Harwell.
- Commercial interest in neutron radiography began in mid 1960's and today this technique, finds extensive applications in nuclear, aerospace and other industries.

Neutron Beam vs X-ray Beam:

- The mass absorption coefficients for neutrons abruptly change and present a random picture when plotted against regularly increasing atomic number of absorber.
- On the other hand, the X-ray mass absorption coefficients increase with atomic number in a regular fashion.
- The differences in absorption coefficients between the neutrons and X-rays suggest a number of possible applications for NR, such as:
 1. Examination of dense materials like uranium, lead etc.
 2. Detection of light materials enveloped in denser materials.
 3. Differentiating between isotopes of same elements.
 4. Examination of radioactive material due to availability of image detection methods, which are not sensitive to the associated gamma rays.

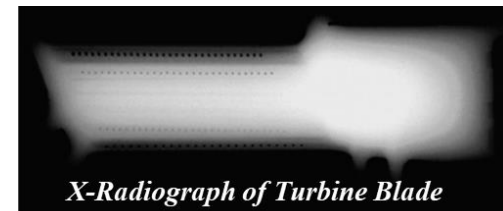
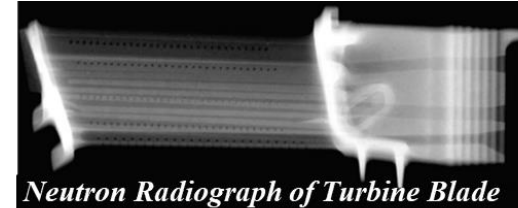


Neutron Radiography vs X-ray Radiography:

- X-rays are absorbed by dense materials, such as metals, whereas neutrons readily penetrate metals but are absorbed by materials containing hydrogen.
- X-rays interact with orbital electrons and are strongly tied to the physical density of the examined object.
- Neutrons interact with an object's nucleus rather than its orbital electrons, so there is usually no tie to the object's electron density, but rather its elemental composition.

Comparison between Neutron Radiograph and X-Radiograph of Turbine Blade:

- The internal structure, air pathways and blockages or inclusion in metal alloy turbine blades can be imaged very clearly using neutron radiography.
- Even areas surrounded by several centimeter thickness material, such as turbine blade root holes can be imaged very effectively.
- X-radiography is more suited to imaging metals inside of other materials.



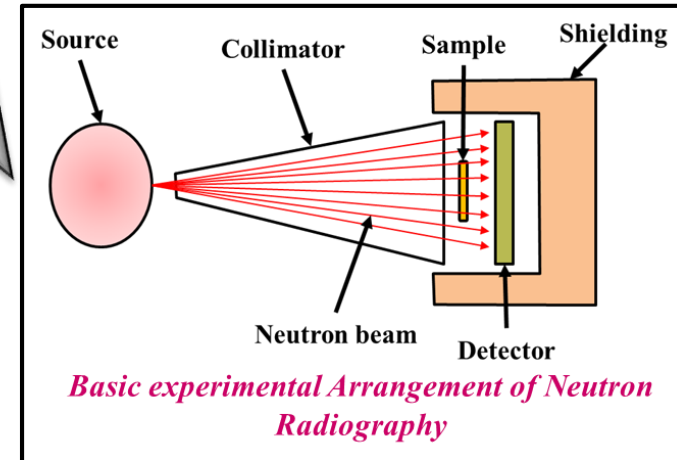
Principle of Neutron Radiography:

- All radiographic methods (X-rays, gamma rays, or neutron radiography) are based on the same general principle:

“Radiation is attenuated on passing through matter”.

Experimental Set-up:

- The NR arrangement consists of:
 - i. a neutron source,
 - ii. a pin-hole type collimator which forms the beam,
 - iii. a detecting system.
- The object under examination is placed in the incident neutron beam.
- After passing through, the beam that remains enters a detector.
- Any inhomogeneity in the object or an internal defect will show up as a change in neutron beam intensity reaching detector.



Neutron Sources:

- The neutron sources available for radiography fall conventionally into three classes namely:
 - i. Accelerator
 - ii. Radioactive Sources
 - iii. Nuclear Reactor

Intensity of Thermal Neutrons from Different Sources:

<i>Neutron Source</i>	<i>Neutron Flux or Intensity</i>
Accelerator	10^7 to 10^{10} n/cm ² /s
Radioactive Sources	10^5 – 10^9 n/cm ² /s
Nuclear Reactor	10^{10} to 10^{15} n/cm ² /s

i. Accelerator:

- Small neutron generators using the deuterium-tritium fusion reactions are the most common accelerator based neutron sources.
- They offer the benefit of intermittent operation and portability.
- In these systems, deuterium and tritium ions are accelerated towards a target also containing the same isotopes.
- Fusion of deuterium atoms ($D + D$) results in the formation of a He-3 ion and a neutron with a kinetic energy of approximately 2.5 MeV.



- Fusion of a deuterium and a tritium atom ($D + T$) results in the formation of a He-4 ion and a neutron with a kinetic energy of approximately 14 MeV.

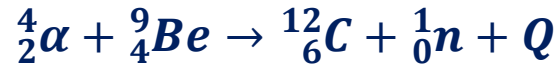


- The DT reaction is used more than the DD reaction because the yield of the DT reaction is 50–100 times higher than that of the DD reaction.

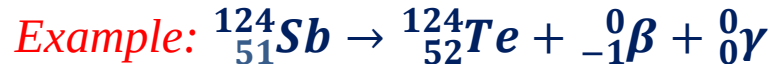
ii. Radioactive Sources:

- Radioisotope based neutron sources are attractive due to their portability and ease of operation.
- However, they have a lower strength than accelerator based neutron sources and consequently produce poor quality radiographs during same exposure time.
- The two important reactions in radioactive neutron sources are:

□ (α, n) Reaction



□ (γ, n) Reaction



Where,

Am = Americium, Np = Neptunium, Be = Beryllium,

Sb = Antimony, Te = Tellurium, C = carbon

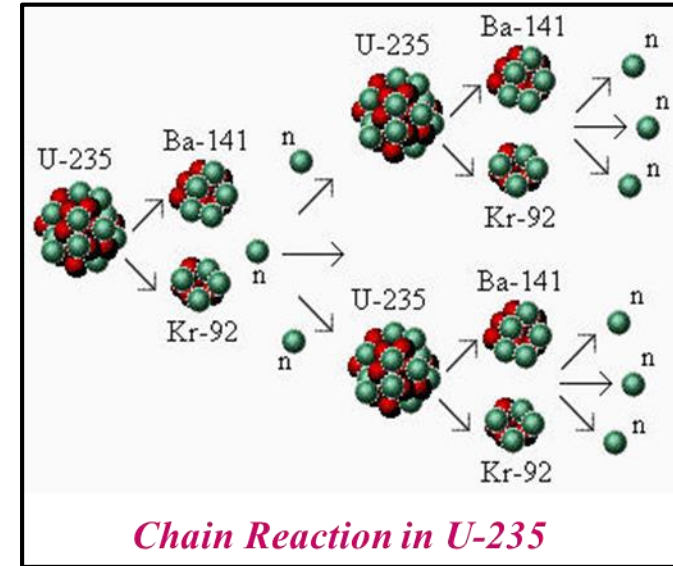
Q = energy released by that reaction

Characteristics of Radio-isotopic Neutron Sources:

Source	Half-life	Reaction	Neutron Yield (n/s.g)	Neutron Energy (MeV)
$^{124}\text{Sb-Be}$	60 d	Gamma/neutron	2.7×10^9	0.024
$^{210}\text{Po-Be}$	138 d	Alpha/neutron	1.28×10^{10}	4.3
$^{241}\text{Am-Be}$	458 y	Alpha/neutron	1×10^7	approx. 4
$^{226}\text{Ra-Be}$	1620 y	Alpha/neutron	1.3×10^7	approx. 4
$^{227}\text{Ac-Be}$	21.8 y	Alpha/neutron	1.1×10^9	approx. 4
$^{228}\text{Th-Be}$	1.91 y	Alpha/neutron	1.7×10^{10}	approx. 4
^{252}Cf	2.65 y	Fission	2.34×10^{12}	2.3

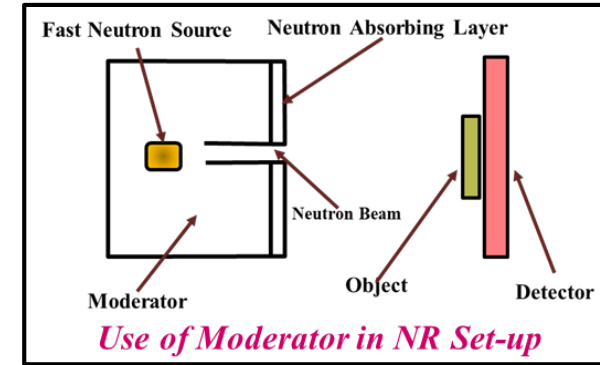
iii. Nuclear Reactor:

- Control of a nuclear reactor is achieved by simply removing neutrons from the process and thereby stopping the chain reaction.
- The neutrons are removed by inserting a neutron absorbing material into the reactor core and regulating the extent of the insertion in order to maintain the reactor at a steady operating power.
- It is a very intense neutron source (10^{10} to 10^{15} n cm⁻² s⁻¹) for neutron radiography.
- Their neutron yields can usually be changed by several orders of magnitude.
- In general, the neutrons are produced as a result of the fission of U-235.



Moderator:

- The neutrons born in the sources possess high energies with a continuous spectrum of energies peaking from 0.85 MeV from fission (in reactors) up to 14 MeV (in accelerators).
- Conventional neutron radiography, however, requires neutrons in the thermal/epithermal energy range of 0.025 eV–10 keV.
- Thus, some form of moderator with low neutron absorption cross section (to maximize flux) and high scattering cross section (to maximize energy loss) is required to slow down the neutrons to this energy range.
- The often-used moderator materials of water, heavy water, graphite, beryllium, and polyethylene meet these criteria.
- The nuclear reactor has an inherent advantage:
 - ✓ *the moderation of its core already produces a low-energy spectrum resulting in fewer neutrons lost in the moderation process.*



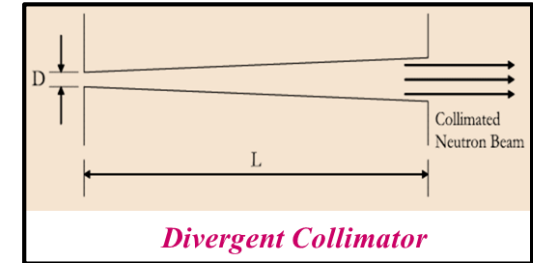
Collimator:

- In the moderator, neutrons travel in many different directions, whereas they should be collimated to produce a good image.
- To accomplish this, an aperture (an opening that will allow neutrons to pass through it surrounded by neutron absorbing materials), limits the neutrons entering the collimator.
- The most common collimator design is a divergent collimator with a small entrance aperture and a larger exit.
- This maximizes the neutron flux and permits a larger field at the imaging plane.

Collimation Ratio:

- ❖ The most important parameter of an NR facility is the collimation ratio.
- ❖ It is defined as: ***Collimation Ratio = L/D***
- ❖ A shorter collimation system or larger aperture will produce a more intense neutron beam but the neutrons will be traveling at a wider variety of angles.
- ❖ A longer collimator or a smaller aperture will produce more uniformity in the direction of travel of the neutrons, but significantly fewer neutrons will be present.
- ❖ A trade off exists between image quality and exposure time.

Where,
L = distance between the incident aperture of the collimator and the imaging plane,
D = diameter of the entrance aperture.



Neutron Detection and Imaging:

- Neutrons are not directly ionizing radiation and hence have no effect on the conventional films used in industrial radiography.
- Neutron detector consists of two mediums:
 - a. **Converter** (which emits an alpha, beta, gamma, or light when neutrons are absorbed)
 - b. **Sensor** (to detect the emitted radiation)

Working Mechanism:

- ❖ The converter screens are often metallic foils.
- ❖ The emissions from these foils can be either charged particles or electromagnetic radiation, which produce the image on the film/screen.
- ❖ When the image recorder is film, one possible converter material is a gadolinium foil which emits an electron with every absorbed neutron.
- ❖ The converter foil is placed in direct contact with the film's emulsion and the emitted electrons expose the emulsion, producing an image.

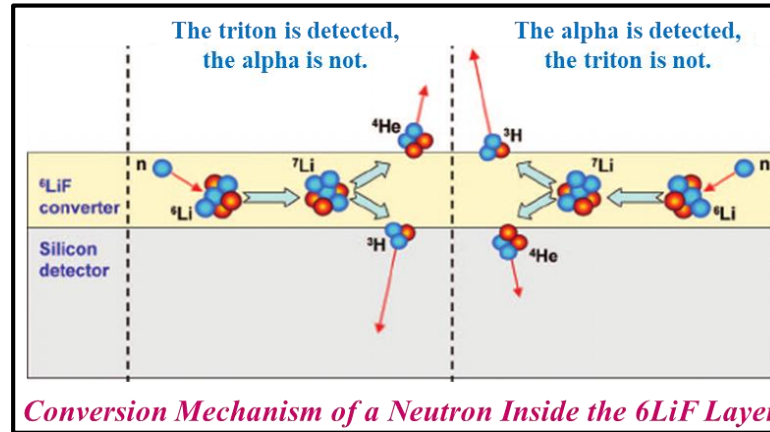
□ Example of Neutron Detection and Imaging:

➤ Thermal neutron detector consisting of a silicon detector coupled with a ${}^6\text{LiF}$ neutron converter layer:

- The neutron capture on ${}^6\text{Li}$ produces an alpha particle and a triton:



- As the two reaction products are emitted in opposite directions, only one of them may enter the sensitive layer and be detected.



Applications of Neutron Radiography:

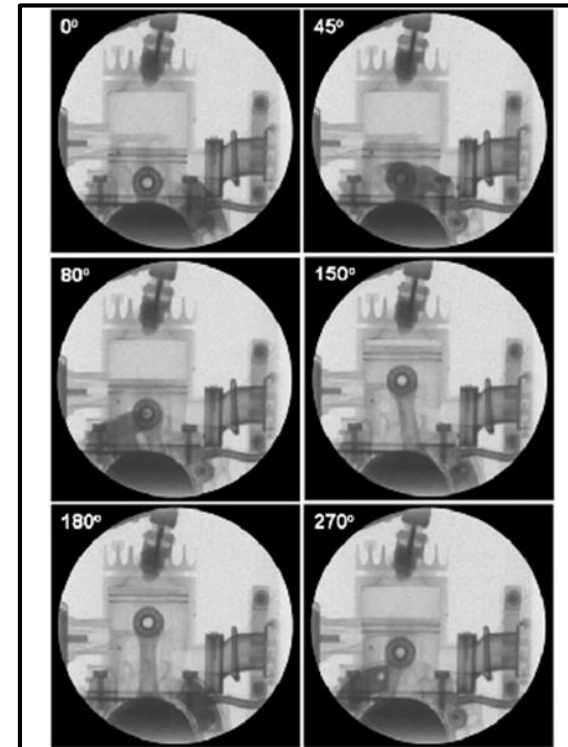
- ❑ Neutron radiography is a commercially available service, widely used in the aerospace industry for testing of :
 - ✓ *turbine blades in airplane engines,*
 - ✓ *components for space programs,*
 - ✓ *high-reliability explosive devices used in space programmes.*
- ❑ The ability to detect compounds containing hydrogen atoms is also used to inspect oil levels and insulating organic materials.
- ❑ Neutron radiography also facilitates the checking of adhesive layers in composite materials, surface layers (polymers, varnishes etc.).
- ❑ All types of O-rings and joints containing hydrogen can be observed even through a few centimetres thickness of steel.
- ❑ It is also used in other industries to identify problems during product development cycles.

Neutron Radioscopy:

- It is also known as Dynamic Neutron Radiography (dNR).
- It consists of the continuous visualisation of the attenuation of a neutron beam using a " real time " detector.
- It enables engineers and scientists to acquire real-time data and observe the inner workings of a system whose components often cannot be seen using other radiation modalities.

Applications of Neutron Radioscopy:

- ❖ Most of the applications known so far, consist in visualisation of fluids moving through metallic containers.
- ❖ The main fields where dynamic neutron imaging has been used are:
 - ✓ Oil lubrication (engines, gear boxes...)
 - ✓ Fuel behaviours (carburettors, injectors...)
 - ✓ Two-phase flow (heat exchangers, condensers, steam generator tubes...)
 - ✓ Transfer and migration of fluids into porous media (wetting of soils, pollution migration, plants growing...)



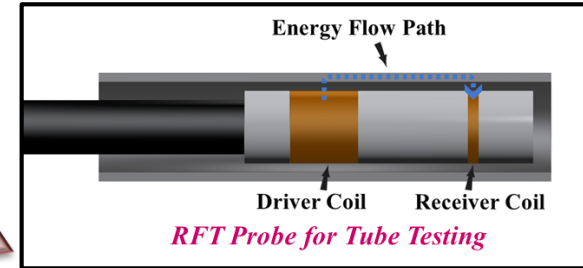
*dNR of Running Combustion Engine
(at 6 different crankshaft positions)*

Remote Field Testing (RFT):

- It is an advanced eddy current testing method, whose main application is finding defects in the external walls of carbon steel or ferritic stainless steel tubing when the outside wall is not accessible.
- This technology offers good sensitivity when detecting and measuring volumetric defects resulting from erosion, corrosion, wear, and baffle cut.

Working Procedure:

- ✓ The RFT probe has widely spaced coils to pick up the through-transmission field.
- ✓ The magnetic field must travel through the tube wall to reach the receiver. This is called through-transmission.
- ✓ Through-transmission allows external and internal defects to be detected with equal sensitivity.



Applications:

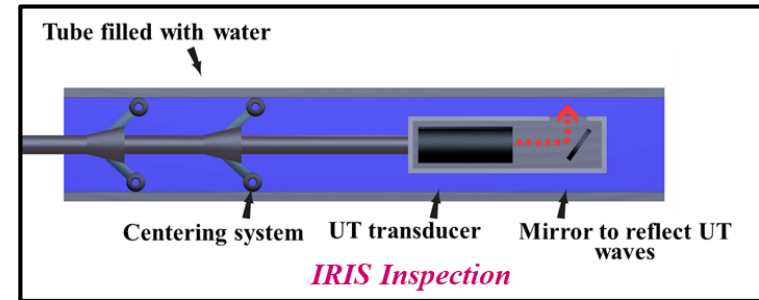
- Boilers,
- Heat exchangers,
- Cast iron pipes
- Other pipelines

Internal Rotary Inspection System:

- Internal rotary inspection system (IRIS) is an ultrasonic method for the non-destructive testing of pipes and tubes.
- The IRIS probe is inserted into a tube that is flooded with water, and the probe is pulled out slowly as the data is displayed and recorded.

Working Procedure:

- The IRIS probe consists of a rotating mirror that directs the ultrasonic beam into the tube wall.
- The mirror is driven by a small turbine that is rotated by the pressure of water being pumped into.
- As the probe is pulled the spinning motion of the mirror results in a helical scan path.
- The transducer utilized for the inspection has to be high frequency (10-25 MHz), enough to bounce back at both inner wall and outer wall.



Terahertz Non-destructive Evaluation:

- It is an advanced and emerging non-destructive evaluation (NDE) technique used for non-conducting materials such as ceramics and plastics.
- THz imaging has higher resolution but lower penetration than ultrasound imaging.

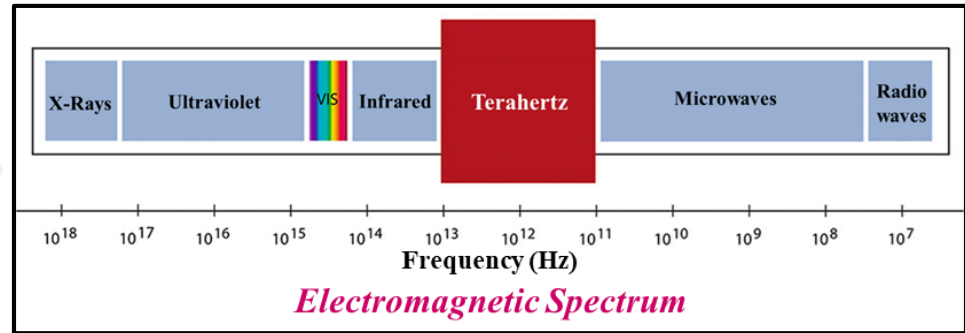
Terahertz (THz) Waves:

- ✓ Terahertz (THz) waves are electromagnetic waves, whose frequencies range between microwave and infrared.
- ✓ Investigating THz waves is difficult due to their weak characteristics and the lack of suitable THz sources and detectors.

Terahertz Waves:

Frequency range- 300 GHz to 3 THz

Wavelength range- 1 mm to 100 μm



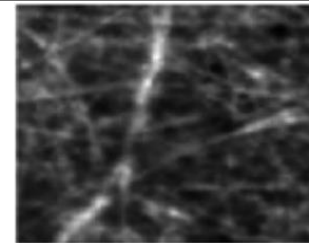
Applications of Terahertz Imaging:

- This technology is powerful for materials analysis and quality control in the pharmaceutical, biomedical, security, materials characterization, and aerospace industries.
- Some of the engineering applications of THz NDT techniques recently developed are in:
 - ✓ Composite materials,
 - ✓ Thermal barrier coatings, } *will be discussed in detail*
 - ✓ Car paint films,
 - ✓ Marine protective coatings, and
 - ✓ Pharmaceutical tablet coatings.

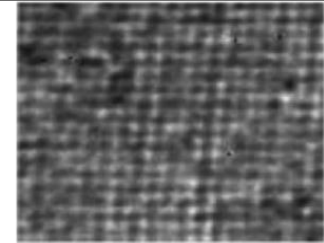
Composite Materials:

- ❖ THz technology with high resolution and good penetration has recently become a promising NDT technique for defect detection in composite materials.

THz NDT measurements of glass fiber composite material:



Irregular fiber orientation



Regular fiber orientation

Thermal Barrier Coating (TBC):

- A TBC is an advanced material system that is applied on high-temperature metallic surfaces, such as gas turbines and aero engines.
- Normally, a TBC system includes a ceramic topcoat and a metallic bond coat on metal substrates.

Thickness measurement of TBC topcoat using THz waves:

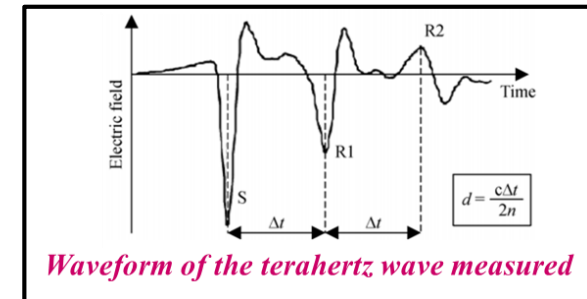
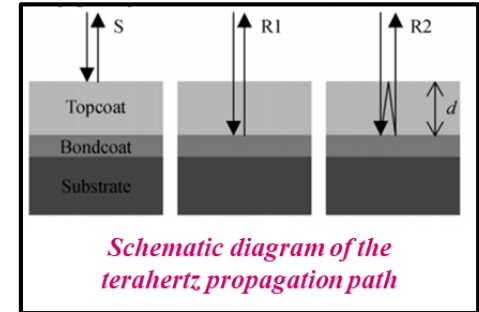
- ✓ The topcoat thickness is obtained from the time difference Δt between adjacent reflections (such as S and R1, or R1 and R2).
- ✓ The time Δt is the time required for the THz wave to travel round-trip through the topcoat (the distance is $2d$ when the thickness is d).
- ✓ The propagation speed of THz waves in the topcoat is:

$$V = c/n$$

where 'n' is the refractive index of the topcoat material in the THz region.

- ✓ Now, the thickness d is given by:

$$d = \frac{c\Delta t}{2n}$$



NDT Standards:

Standard:

- A set of technical definitions, instructions, rules, guidelines, or characteristics set forth to provide consistent and comparable results, including:
 - ✓ Items manufactured uniformly, providing for interchangeability.
 - ✓ Tests and analyses conducted reliably, minimizing the uncertainty of the results.
 - ✓ Facilities designed and constructed for safe operation.
- The procedures for testing and evaluation must be standardized in detail so that the test results will be least affected by the differences in the personnel skill.

NDT Standards: ASTM International

- ASTM International is one of the largest voluntary standards development organizations in the world, providing technical standards for materials, products, systems and services.
- Over 180 ASTM NDT standards are published in the ASTM Annual Book of Standards, Volume 03.03, Non-destructive Testing.
- ASTM NDT standards are divided in three categories:
 - ❑ **Guide:**
 - A guide increases the awareness of information and approaches in a given subject area.
 - ❑ **Practice:**
 - A practice is a definitive set of instructions for performing one or more specific operations or functions that does not produce a test result.
 - Examples: cleaning, collection, decontamination, installation, preparation, sampling, etc.
 - ❑ **Test Method:**
 - A test method is a definitive procedure that produces a test result.
 - Examples: identification, measurement and evaluation of one or more qualities, characteristics or properties, etc.



ASTM NDT Standards in Industries:

- Some of the more commonly used ASTM NDT standards are as follows:

ASTM E1444	Standard Practice for Magnetic Particle Testing
ASTM E1417	Standard Practice for Liquid Penetrant Testing
ASTM E164	Standard Practice for Contact Ultrasonic Testing of Weldments
ASTM E213	Standard Practice for Ultrasonic Testing of Metal Pipe and Tubing
ASTM E2375	Standard Practice for Ultrasonic Testing of Wrought Products
ASTM E94	Guide for Radiographic Examination
ASTM E1742	Practice for Radiographic Examination
ASTM E1030	Test Method for Radiographic Examination of Metallic Castings
ASTM E1032	Test Method for Radiographic Examination of Weldments
ASTM E999	Guide for Controlling the Quality of Industrial Radiographic Film Processing
ASTM E2007	Standard Guide for Computed Radiography

Safety in NDT:

- In all non-destructive testing methods, appropriate safety standards and plant practices should be followed.
- Aside from any hazards which might arise from the materials being used in the test, the technician must be constantly aware of the function of the object under test.
- For pressure related leak tests, the requirement to overpressure creates a hazard in itself.
- Investigating leaks in an operating system can be hazardous.
- Hazards are also associated with the working fluids/particles in the systems being tested or with the testing fluids (e.g. in dye penetrant tests, leak tests, etc.).
- Radiography techniques are high risk methods as exposure to ionising radiation above permissible limits can result in serious biological damage.
- For radiation safety proper protection measures should be considered.



Summary:

- Advanced non-destructive testing methods provide more accurate inspection data with an improved probability of detection (PoD).
- Neutron radiography is a well established NDT technique, majorly used in aerospace and nuclear industries.
- RFT and IRIS tests are used for inspection of pipes and tubes accurately.
- Terahertz non-destructive evaluation is an emerging technique, which can be used for non-conducting materials.
- NDT Standards are the set of instructions or guidelines developed to perform consistent and reliable inspections.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 16: Engineering Metrology- Linear Measurement



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



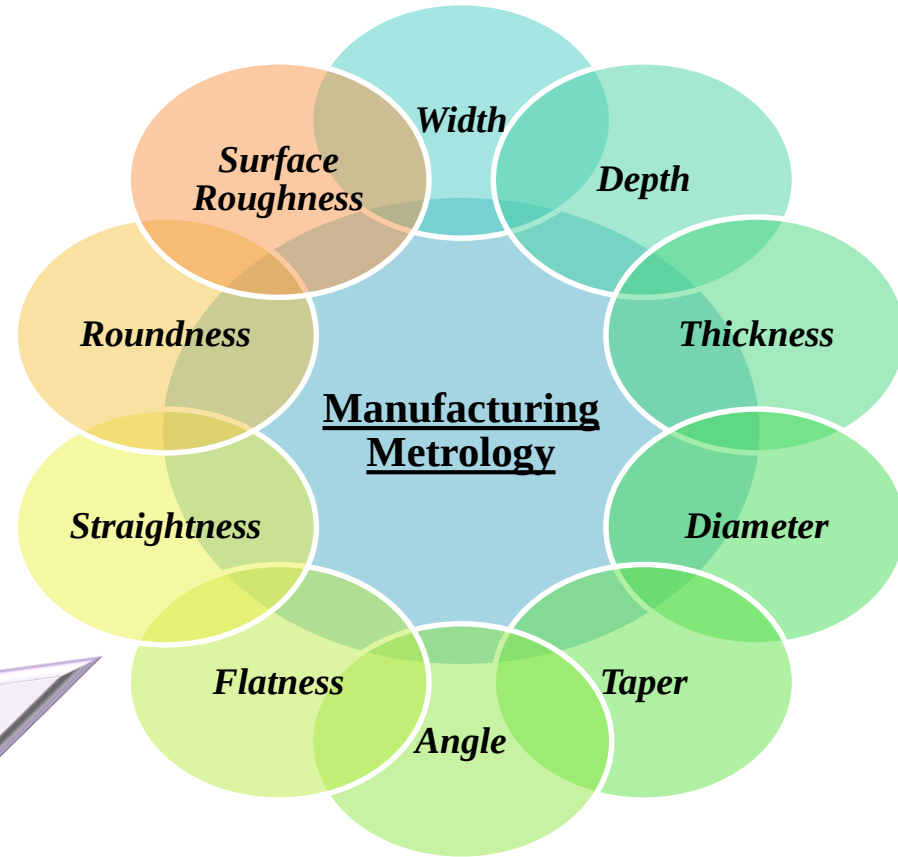
Metrology:

Definition:

Metrology is a science of measurement of six fundamental quantities: Length, Mass, Time, Temperature, Electric Current, and Light Radiation.

Manufacturing Metrology:

Mainly concerned with measurement of length quantity in many ways in which it manifests itself in a manufactured part or product such as:



Objective of Metrology:

“To provide the required accuracy in measurement at minimum cost”.

Basic objective
of metrology

Need of Metrology:

- ✓ Modern industrial mass production system is based on interchangeable manufacture, when articles are to be produced on a large scale.
- ✓ In mass production the production of complete article is broken up into various component parts and production of each component part becomes an independent process.
- ✓ Different component parts are made in large quantities in different shops.
- ✓ Some parts are purchased from other factories also and then assembled together at one place.
- ✓ Therefore, it becomes essential that any part chosen at random should fit properly with any other mating parts that too selected at random.
- ✓ This is possible only when dimensions of component parts are made with close dimensional tolerances.
- ✓ This is only achieved when parts are inspected at various stages during manufacturing.

Principles of Metrology:

- In design, design engineer should not only check his design from the point of view of the strength or economical production, but he should also keep in mind how the dimensions specified can be checked or measured.
- Higher productivity and accuracy can be achieved by properly understood, introduced the Metrology.
- We can improve the measuring accuracy and dimensional and geometrical accuracies of the product.
- Proper gauges should be designed and used for rapid and effective inspection.
- Also automation and automatic control, which are the modern trends for future developments, are based on measurement. Digital instruments also we can used for inspection.

Different Ways of Metrological Inspection:

- It is the examination of a part or product characteristic to determine whether or not it conforms to the design specifications.
- It can be done in two ways:

Inspection by Attributes	Inspection by Variables
• Using Gauges to determine whether the part or product characteristic of interest is within the tolerance limit.	• Part or product characteristic of interest is measured numerically by means of a calibrated instrument.
• Most commonly known as Gauging or Gaging.	• Measurement is generally accepted industrial term for inspection by variables.
• Results can be Yes or No; Acceptable or Not; Go or Not-go; Good or Bad.	• Gives the numerical value of the inspected characteristics.
• Quick, less expensive, and less informative.	• Slow, costly, and more informative.
• Simple and requires use of unskilled labour.	• Complex and requires use of skilled labour.

Characteristics of a Measuring Instrument:

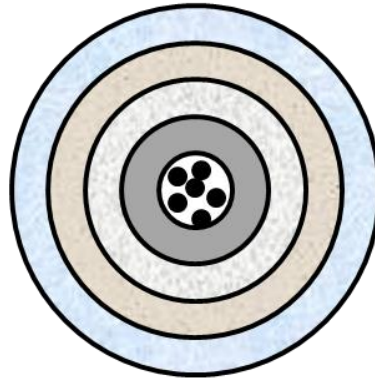
- Various specific terms which describe the characteristics and quality of measuring instruments are:
 - 1) Accuracy and Precision
 - 2) Resolution or Sensitivity (Least Count)
 - 3) Calibration
 - 4) Speed of Response
 - 5) Stability
 - 6) Operating Range
 - 7) Reliability



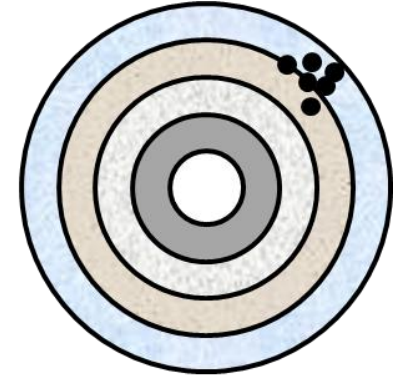
1) Accuracy vs. Precision:

Accuracy	Precision
Degree to which the measured value agrees with true value of the quantity	Degree of repeatability of the measurement process
A measurement procedure is accurate when Systematic Errors are absent	A measurement process is precise when Random Errors in the measurement are minimized.
	Random errors are usually associated with the human participation in the measurement process.
Systematic errors are positive or negative deviations from the true value that are consistent from one measurement to the next	Human contributor to random errors: • Variations in the setup • Imprecise reading of the scale • Round-off approximations Non-human contributors to random errors: • Changes in temperature • Gradual wear of working elements of the device • Misalignment of working elements of the device
	Random errors are assumed to obey normal distribution with zero mean
Accuracy of the instrument is maintained by proper and regular calibration.	Precision of an instrument is achieved by selecting the proper and regular calibration technology for the application

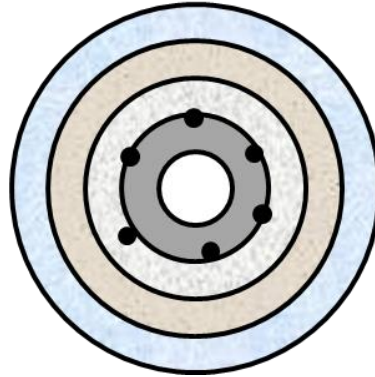
*High Accuracy
High Precision*



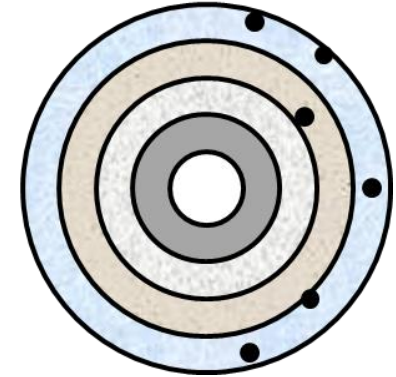
*Low Accuracy
High Precision*



*High Accuracy
Low Precision*



*Low Accuracy
Low Precision*



Determination of Right Level of Precision:

- Rule of 10 is often used to determine the right level of precision.

Rule of 10 or Gage Capability (Gage Maker's Rule):

- ✓ An instrument or gage should be 10 times more precise than the tolerance to be measured.
- ✓ This rule applies to all stages in the inspection sequence.

Example:

- A company manufactures ball point pens with a ball outer diameter of 0.35 mm and acceptable balls range from 0.34 to 0.36 mm.
- Process tolerance = $(0.36 - 0.34) \text{ mm} = 0.02 \text{ mm}$
- Using the Rule of Tens,
 $10\% \text{ of the process tolerance} = 0.10 \times 0.02 = 0.002 \text{ mm}$
- This means our gage must be able to detect a difference of at least **0.002 mm** between balls.

2) Resolution or Sensitivity (Least Count):

- The smallest unit of scale or smallest variation of the variable that can be detected.

3) Calibration:

- Procedure of checking a measuring instrument against a known standard.
- Adjusting or setting an instrument to give readings that are accurate within a reference standard.
- Calibration should be quick and uncomplicated.

4) Speed of Response:

- How long the instrument takes to measure the variable.

5) Stability:

- Capability of an instrument to retain its calibration over a period of time.
- As devices become more accurate, they often lose stability and become more sensitive to small changes in temperature and humidity.

6) Operating Range:

- Capability to measure the physical variable throughout the entire span of practical interest to the user.

7) Reliability:

- Absence of frequent failures of the device.



Linear Measurement:

- Linear measurement applies to measurement of lengths, diameters, heights, and thickness including external and internal measurements.

Linear Measuring Instruments:

- Linear measuring instruments consists of series of accurately spaced painted or marked lines on them.
- These instruments can be categorized as:

Non-precision Measuring Instruments

Precision Measuring Instruments

Electrical Measuring Devices

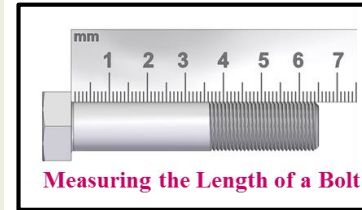
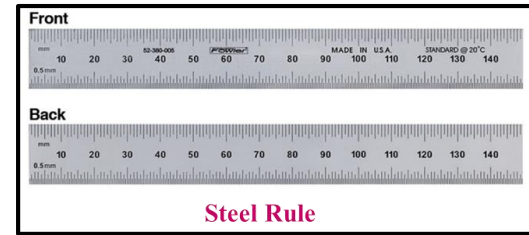
Non-precision Measuring Instruments:

- These instruments are limited to the measurements are parts to a visible line graduation on the instrument used.
- They are used where high measurement accuracy is not required.



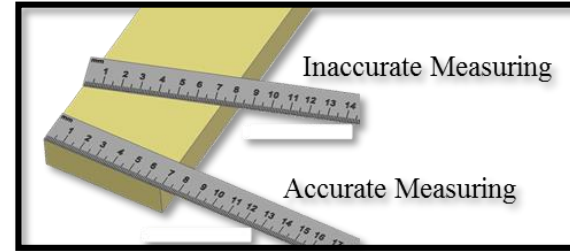
a) Rules:

- Simplest and most common measuring instrument in inspection.
- Rule must be graduated uniformly throughout its length.
- There are rules that have got some attachment and special features with them to make their use more versatile.
- They may be made in folded form so that they can be kept in pockets.
- Degree of accuracy when measurements are made by a rule depends upon quality of rule, and skill of the user in estimating part of a millimetre.

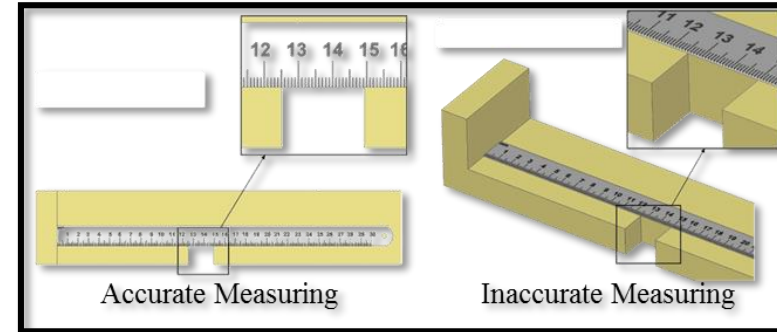


Precautions:

- Keep the rule at a right angle to the object.



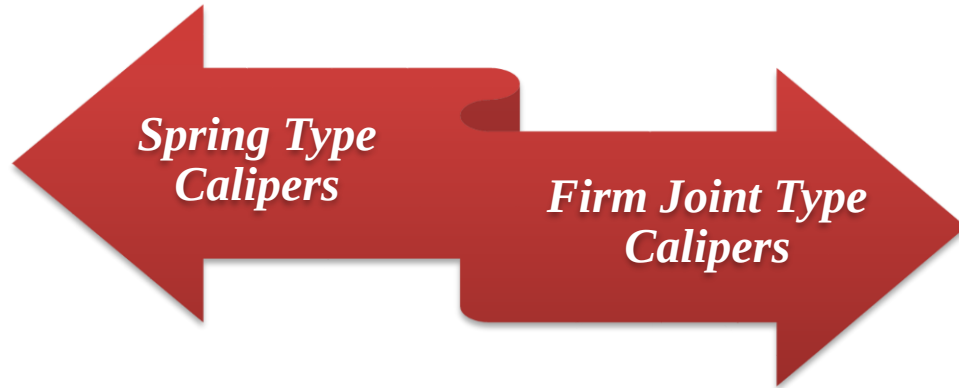
- Read the measurement from directly above the rule.



- Whenever there are several measurements to be made along a straight line, the rule should not be raised until all are made, for with each placing of the rule errors are likely to occur.

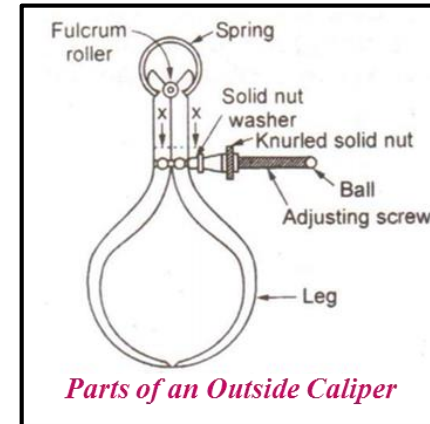
b) Calipers:

- They are used for measurement of parts, which cannot be measured directly with the scale.
- Generally used as accessories to scales and consist of two legs hinged at top, and the ends of legs span part to be inspected.
- This span is maintained and transferred to the scale.
- Calipers are of two types:



i. Spring Type Calipers:

- Two legs are attached with spring in this type of calipers.
- Working ends of each leg of a spring calipers should be identical in shape and have contact points equally distant from the fulcrum.
- Cross-section of the legs is either rectangular or circular in shape.
- Calipers are adjusted to set dimensions by mean of either knurled solid nut or a knurled quick action release nut operating in a finely threaded adjusting screw.
- Top portions of the legs are located in a flanged fulcrum roller and held in position by a spring in order to maintain the alignment of the working ends.
- Spring provides sufficient tension to hold the legs rigid at all points of the adjustment.
- Separate washer under the nut minimizes the friction between the adjusting nut and the leg.



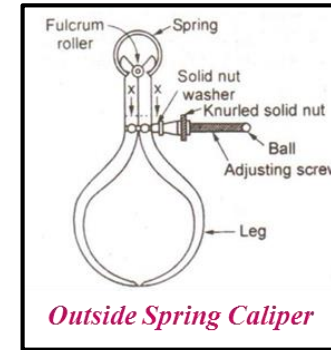
Types of Spring Type Calipers:

❖ Outside Spring Calipers:

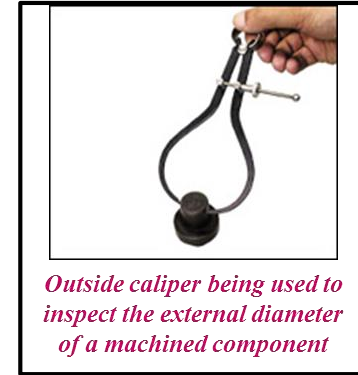
- ✓ It is designed to measure outside dimensions.
- ✓ For accurate settings, the distance between the outside calipers may be set by slip gauges or by micrometer anvils.

❖ Inside Spring Calipers:

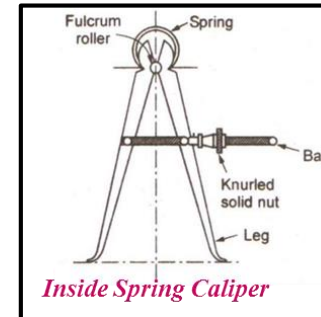
- ✓ They are designed to measure the inside dimensions.
- ✓ An inside spring caliper is exactly similar to an outside caliper with its legs bent outward.
- ✓ They are used for comparing or measuring hole diameters, distances between shoulders, or other parallel surfaces of any inside dimensions.



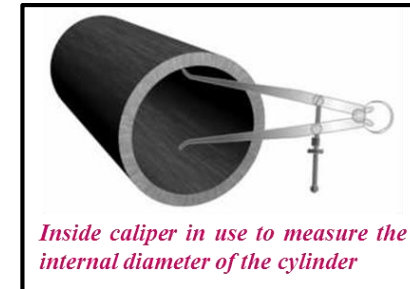
Outside Spring Caliper



Outside caliper being used to inspect the external diameter of a machined component



Inside Spring Caliper



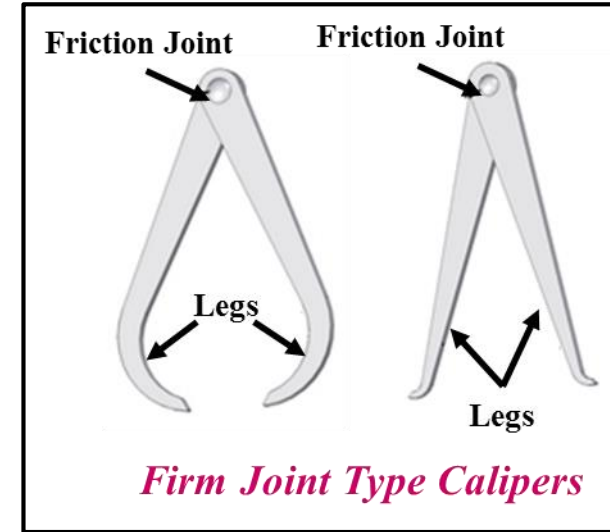
Inside caliper in use to measure the internal diameter of the cylinder

ii. Firm Joint Type Calipers:

- They work on the friction created at the junction of the legs.
- The two legs are identical in shape with the contact points equally distant from the fulcrum and are joined together by a rivet.
- The component parts of the calipers should be free from seams, cracks and must have smooth bright finish.

Firm joint calipers are of following types:

1. Outside Firm Joint Caliper
2. Inside Firm Joint Caliper
3. Transfer Caliper
4. Hermaphrodite Caliper

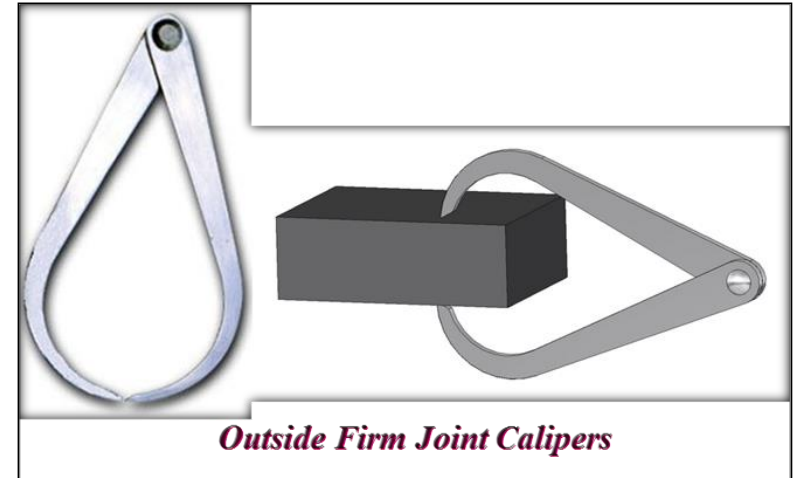
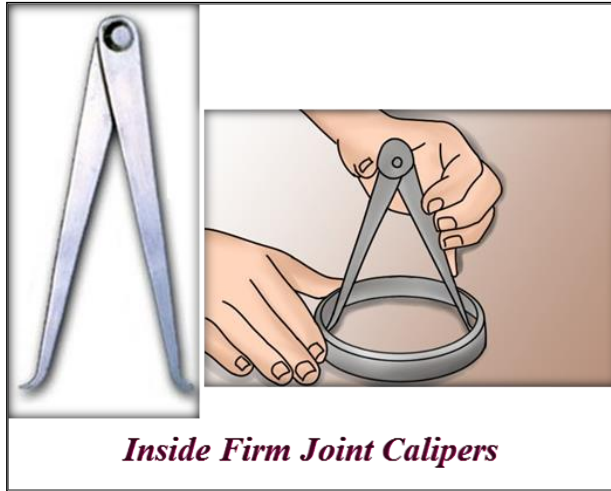


1. Outside Firm Joint Caliper:

- Unlike spring type outside calipers, it does not have any spring.
- The construction is quite simple with two identical legs held firmly by the fulcrum.

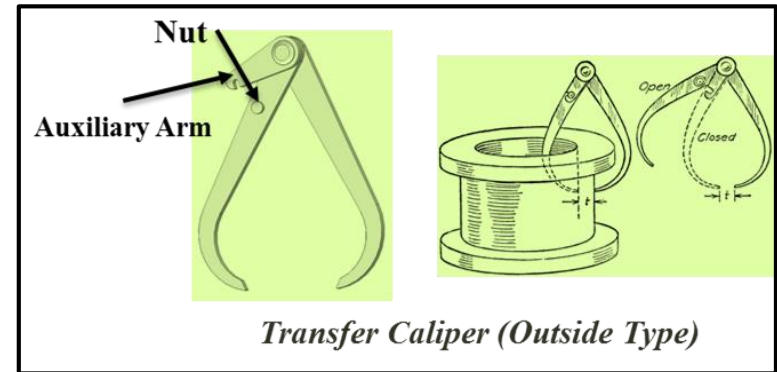
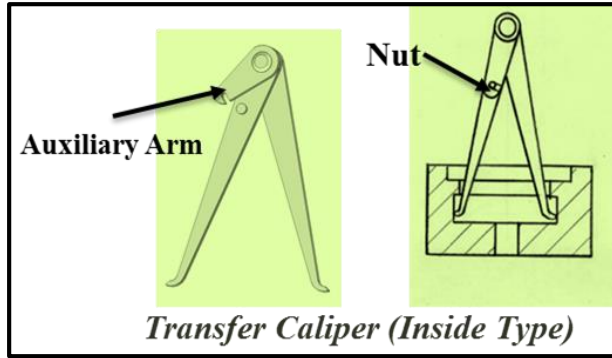
2. Inside Firm Joint Caliper:

- Inside firm joint calipers are almost similar to inside spring joint caliper with the exception that it does not have any spring to hold the legs.



3. Transfer Caliper:

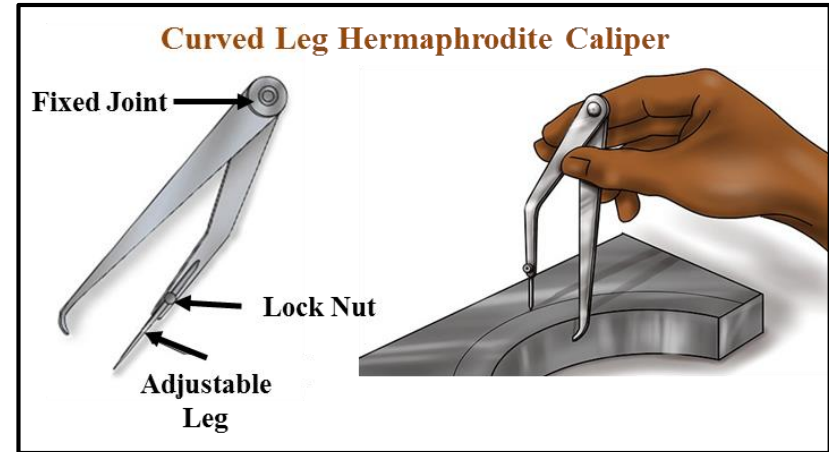
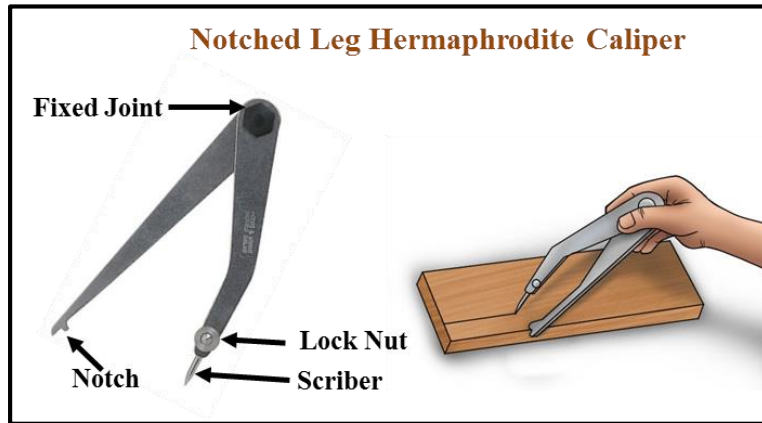
- These are used for measuring recessed areas from which the legs of calipers can not be removed directly but must be collapsed after the dimension has been measured.
- Therefore, an auxiliary arm is provided with two legs so that it can preserve the original setting after the legs are collapsed.
- Nut is first locked and the caliper opened or closed against the work.
- Nut is then loosened and the leg is swung to clear the obstruction leaving the auxiliary arm in position. Leg can be moved back to the auxiliary leg, where it will show the size previously measured.



4. Hermaphrodite Caliper:

- It is also known as odd leg caliper consisting of one divider and one caliper leg.
- It is used for layout work like scribing lines parallel to the edge of the work and for finding the centre of a cylindrical work.
- It can be with two types of legs, viz. notched leg or curved leg.

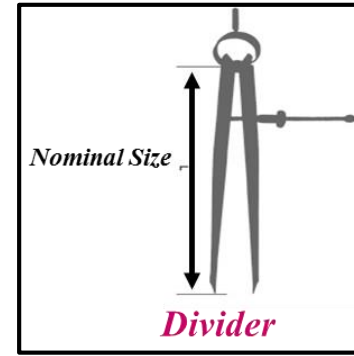
Examples:



Marking Out using Odd Leg Calipers

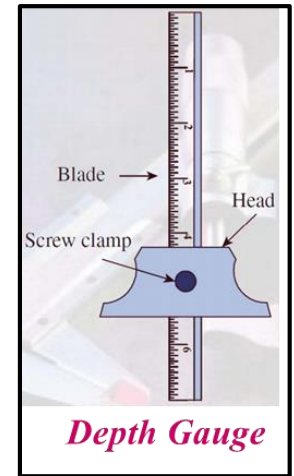
c) Divider:

- A divider is similar in construction to a caliper except that both legs are straight with sharp hardened points at the end.
- These are used for scribing arcs and circles and general layout works.
- The distance between the fulcrum roller centre and the extreme working end of one of legs is known as the *nominal size*.
- A steel scale must be used with this instrument.



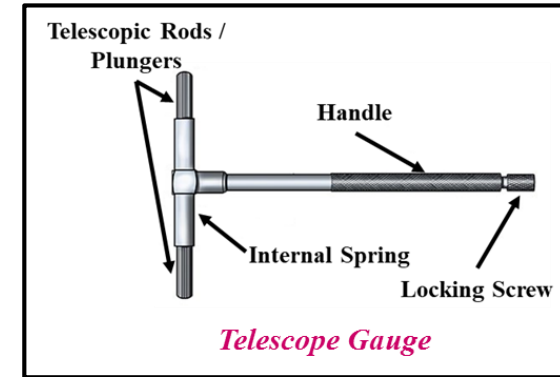
d) Depth Gauge:

- This tool is used to measure the depth of blind holes, grooves, slots, the heights of shoulders in holes and dimensions of similar character.
- This is essentially a narrow steel rule to which a sliding head is clamped at the right angles to the rule.
- The head forms a convenient marker in places where the rule must be held in a distance from the point being measured.



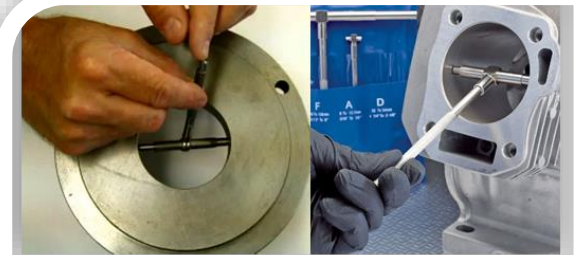
e) Telescopic Gauge:

- Telescopic gauge is used for the measurement of internal diameter of a hole during machining operation.
- It consists of a handle and two plungers, one telescopic into the other and both under spring tension.
- Ends of the plungers have spherical contacts.
- The plungers can be locked in position by turning a knurled screw at the end of the handle.



Measuring Procedure:

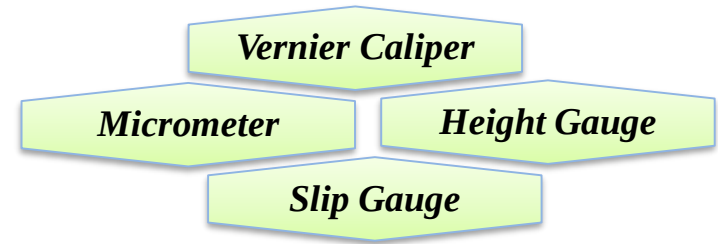
- **Step-1:** To measure the diameter of a hole, the plungers are first compressed and locked in position.
- **Step-2:** Next, the plunger end is inserted in the hole and allowed to expand the opposite edges.
- **Step-3:** Finally, they are locked in place, taken out of the hole and measured by an outside micrometer.



Using Telescope Gauge to measure Internal dia.

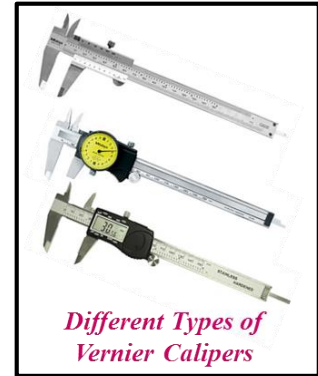
Precision Measuring Instruments:

- Since modern production processes is concerned with interchangeable products, precise dimensional control is required in industry.
- Precision measurement instruments are different techniques and phenomena to measure distance with accuracy.
- Some mostly used precision measuring instruments are:



i. Vernier Caliper:

- ✓ Vernier calipers are precision measuring instruments that generally give an accuracy of 0.1 mm to 0.01 mm.
- ✓ The main scale carries the fixed graduations, one of two measuring jaws, a vernier head having a vernier scale engraved on.
- ✓ Modern calipers are digital and have an LCD display on which the reading appears – there is no possibility of human error in reading the scale.



Vernier Caliper Parts and their Functions:

❖ Lower Jaws or External Jaws:

- They allow the vernier caliper to measure outer dimensions of objects such as the length, width or diameter.

❖ Upper Jaws or Internal Jaws:

- Used for measuring inside dimensions of hollow objects such as inside diameters of pipes, lengths and widths of boxes etc.

❖ Depth Rod:

- It is used to measure the depths of holes or steps.

❖ Locking Screw:

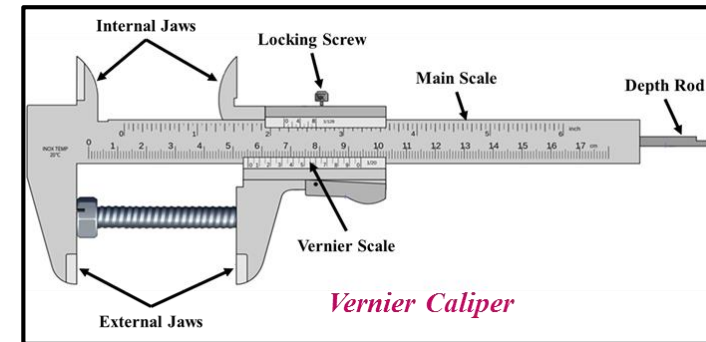
- Lock screw is used to fix the position of the jaws once the object is positioned properly so that readings can be taken without the fear of spoiling the position.

❖ Main Scale:

- It is the large scale which runs along the body of the vernier caliper. The main scale is stationary.

❖ Vernier Scale:

- It is a smaller scale attached to the main scale and can move along the main scale as the jaws are opened or closed.



Working Principle of Vernier Caliper:

Principle: When two scales or divisions slightly different in size are used, the difference between them can be utilized to enhance the accuracy of measurement.

Example to understand the working principle of a vernier caliper:

- Consider that the Vernier scale has got 20 divisions which equals to 19 divisions of the main scale.
 - ✓ *One smallest division of the vernier scale < smallest division of the main scale*
- This difference between 1 main scale division and 1 Vernier scale division is called **Vernier Constant (VC)** for that particular vernier caliper.
- When **VC** is multiplied with the smallest unit of the main scale, it gives the **Least Count (LC)** of that vernier.

Now as considered,

$\therefore 20 \text{ vernier scale divisions (VSD)} = 19 \text{ main scale divisions (MSD)}$

$\therefore 1 \text{ VSD} = \frac{19}{20} \text{ MSD}$

$\therefore \text{Vernier Constant (VC)} = 1 \text{ MSD} - 1 \text{ VSD} = 1 \text{ MSD} - \frac{19}{20} \text{ MSD} = \frac{1}{20} \text{ MSD}$

Now, if the smallest unit of the main scale be 1 mm, the least count of the vernier scale,

$$LC = VC \times \text{one smallest unit of the main scale} = \frac{1}{20} \times 1 \text{ mm} = 0.05 \text{ mm}$$

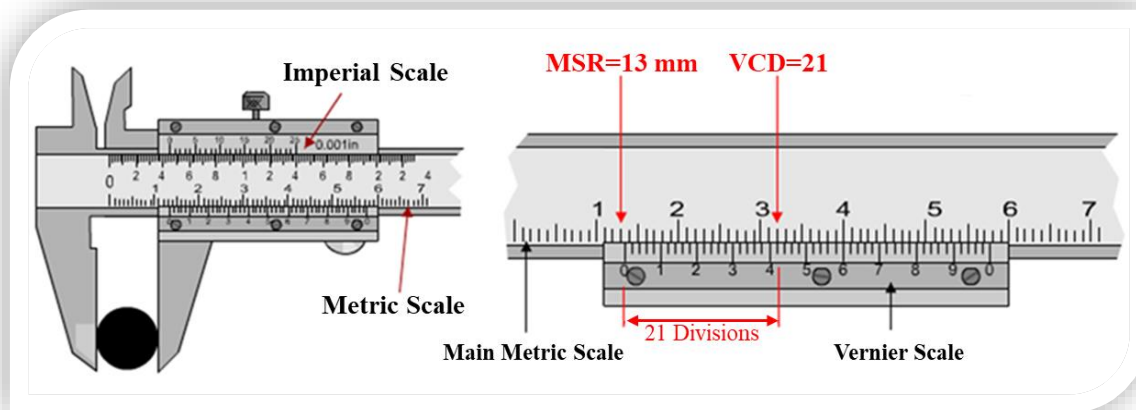


How to Read a Vernier Caliper?

- To read a measurement from a vernier caliper, first the main scale reading (MSR) up to the zero of the vernier scale is noted down. It will give accuracy up to the smallest division of the main scale.
- Next, read the graduation (or vernier coinciding division, VCD) where two graduation lines on main and vernier scale perfectly match.
- Now, the final reading is obtained as: ***Final Reading = MSR + (VCD × LC)***

Example:

Where,
MSR = main scale reading,
LC = least count, and
VC = vernier coinciding division.



- ❖ For the given Vernier caliper,
Least Count = 0.02 mm
- ❖ The final reading is:
$$= 13 + 21 \times 0.02$$
$$= 13.42 \text{ mm}$$

ii. Micrometers:

- Most widely used precision instruments.
- Primarily used to measure external dimensions like diameters of shafts, thickness of parts etc. to an accuracy of 0.01 mm.

Parts and their Functions:

Anvil:

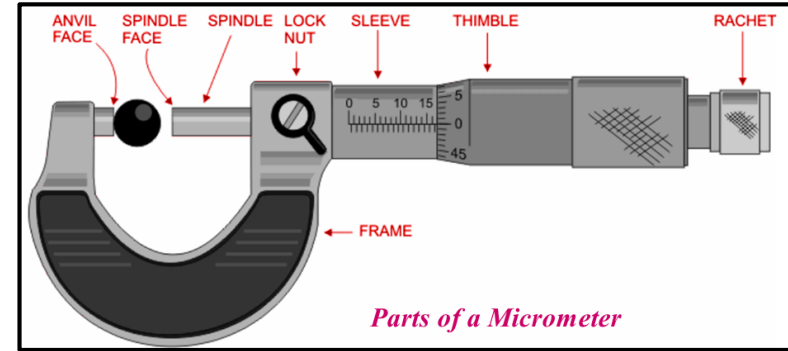
- Small stationary cylindrical part of micrometer located in far end of c-frame.
- Acts as one holding point for measuring objects.

Spindle:

- Cylindrical long part which is mounted through all other parts sleeve, lock nut and thimble.
- It is moveable part and has a connection with ratchet.
- As we rotate the ratchet clockwise/counter clockwise the spindle slides out/inward to adjust it with compare to measuring object size.

Anvil Face and Spindle Face:

- Faces of both anvil and spindle which are opposite to each other are the measuring points of micrometer.
- They hold the measuring object collectively.



Lock nut:

- The knurled component that one can tighten to hold the spindle stationary, such as when momentarily holding a measurement.

Sleeve:

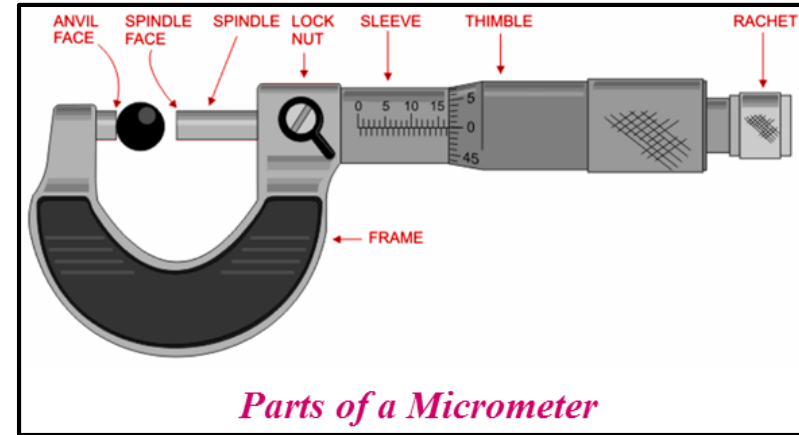
- The stationary barrel type cylindrical component with the linear scale (**main scale**) engraved on it, sometimes with vernier markings.
- Thimble rotates around that sleeve and spindle.

Thimble:

- Thimble is also mounted on spindle and a scale is engraved around its perimeter (**circular scale**).
- Scale of thimble is to show the measurement value in fraction.

Ratchet:

- It's a knurled thumb grip to rotate the spindle into desired direction for measuring process.
- It is provided with ratchet action to avoid over tightening of micrometer across the measuring object and also ensures equal pressure force of each measurement.



Working Principle of Micrometer:

- Micrometer works on the principle of screw and nut to amplify small distances.
- The amount of rotation of an accurately made screw can be directly and precisely correlated to a certain amount of axial movement (and vice versa), through the constant known as the screw's lead or pitch.
 - ✓ A screw's lead or pitch is the distance it moves forward axially with one complete turn (360°).
- With an appropriate lead and major diameter of the screw, a given amount of axial movement will be amplified in the resulting circumferential movement.

Least Count of a Micrometer:

- The linear distance moved by the screw is directly proportional to the rotation given to it.
- The linear distance moved by the screw when it is rotated by one division of the circular scale (thimble), is the least distance that can be measured accurately by the instrument.

$$\text{Least Count} = \frac{\text{Pitch}}{\text{No. of Divisions on Circular Scale}}$$

Example:

- For a micrometer with a pitch of 0.5 mm and 50 divisions on the circular scale.
$$\text{Least Count (LC)} = 0.5/50 = 0.01 \text{ mm}$$
- This is the smallest length one can measure with this micrometer.

How to Read a Micrometer?

Step-1: Taking the Linear Scale Reading

- The mark on the linear scale which lies close to the left edge of the circular scale is the linear scale reading.

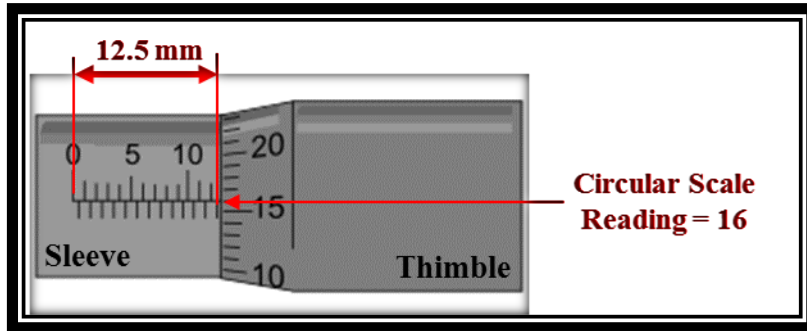
Step-2: Taking Circular Scale Reading

- The division of circular scale which coincides with the main scale line is the reading of circular scale.

Step-3: Final Reading

- $\text{Total Reading} = \text{Linear Scale Reading} + \text{Circular Scale Reading} \times \text{Least Count}$

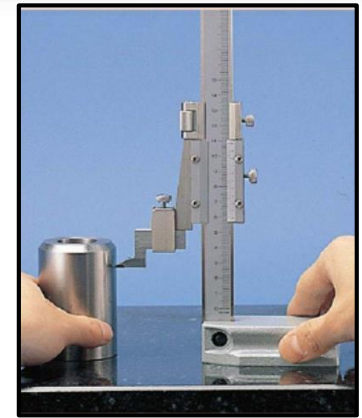
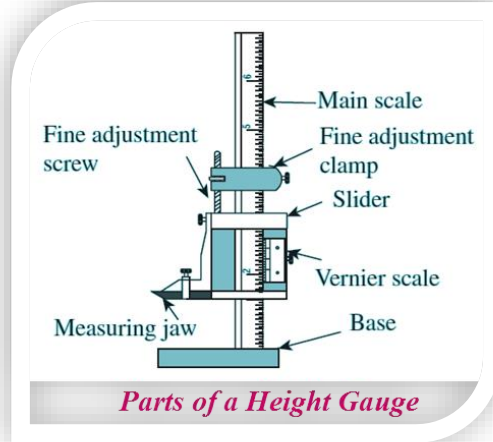
Example:



- ❖ For the given micrometer, Least Count = 0.01 mm
- ❖ Linear scale reading = 12.5 mm
- ❖ Circular scale reading = 16
- ❖ The final reading is:
$$= 12.5 + 16 \times 0.01$$
$$= 12.66 \text{ mm}$$

iii. Height Gauge:

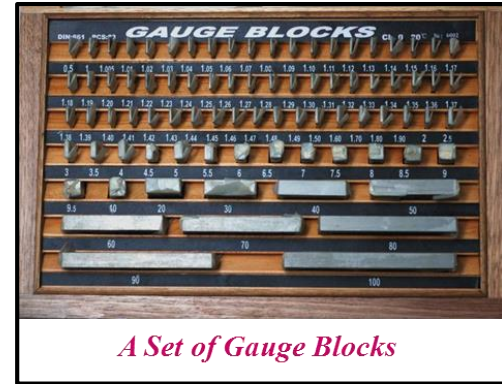
- ✓ This uses the same principle of vernier caliper and is used especially for the measurement of height.
- ✓ It is equipped with a special base block, sliding jaw assembly and a removable clamp.
- ✓ The upper and lower surfaces of the measuring jaws are parallel to the base, which make possible to measure both over and under surfaces.
- ✓ A scribing attachment in place of measuring jaw can be used for scribing lines at certain distance above the surface.
- ✓ Specification of a vernier height gauge is made by specifying the range of measurement, type of scale required and any particular requirement in regard to the type of vernier desired.



Measurement of height of a cylinder using height gauge

iv. Slip Gauges or Gauge Blocks:

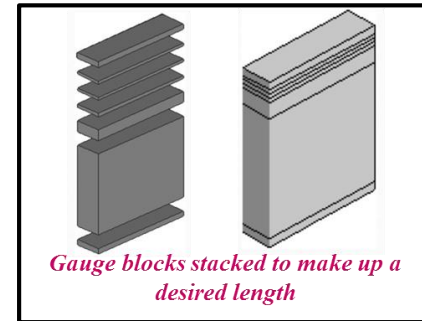
- ✓ Slip gauges (also known as gauge blocks, gage blocks, Johansson gauges, or Jo blocks) are a system for producing precision lengths.
- ✓ The individual gauge block is a metal or ceramic block that has been precision ground and lapped to a specific thickness.
- ✓ Gauge blocks come in sets of blocks with a range of standard lengths.
- ✓ In use, the blocks are stacked to make up a desired length.
- ✓ Also used for the verification and graduation of measuring apparatus and for direct measurement of linear dimensions of industrial components.



A Set of Gauge Blocks

Uses of Slip Gauge:

- Setting up a comparator to a specific dimension
- Direct Precise measuring purpose.
- To inspect the Vernier Calliper, Micrometers and some other linear measuring instruments.
- Conjunction with sine bar to measure the angle of the workpiece.
- Used to Check the distance between the parallel faces.



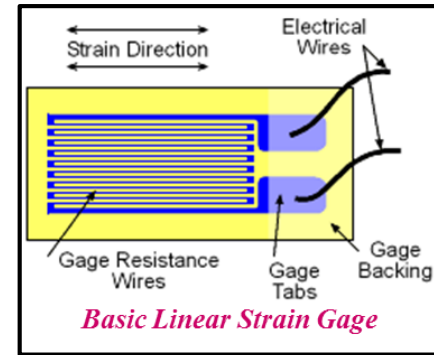
Gauge blocks stacked to make up a desired length

Electrical Measuring Devices:

- Electrical measuring devices give the most precise value of measurement among all the instruments discussed earlier.
- They use electrical transducers that transform a variety of physical quantities and phenomena into electrical signals.
- Some of the most commonly used electric devices in linear measurement are:
 - ❖ Strain Gauge
 - ❖ Linear Variable Differential Transformer (LVDT)

❖ Strain Gauge:

- ✓ It is based on the resistive properties of electrical conductors.
- ✓ They are constructed from a single wire that is wound back and forth.
- ✓ The gage is attached to the surface of an object with wires in the direction where strain is to be measured.
- ✓ Electrical resistance in the wires change when they are elongated. Thus, voltage change in the wires can be collaborated to the change in strain.

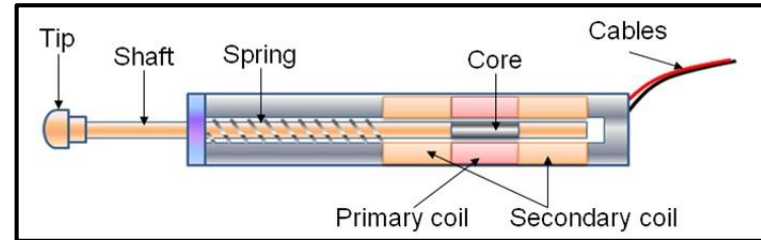


❖ Linear Variable Differential Transformer (LVDT):

- ✓ It is a type of electrical transformer used for measuring linear displacement (position).
- ✓ LVDT converts a position or linear displacement from a mechanical reference (zero, or null position) into a proportional electrical signal containing phase (for direction) and amplitude (for distance) information.

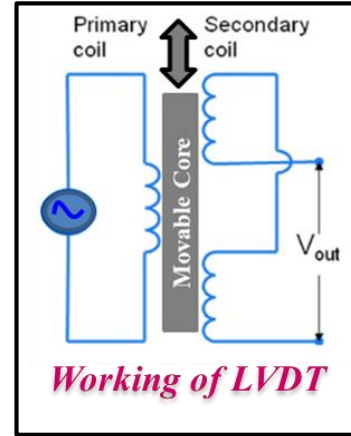
Construction of LVDT:

- LVDT consist of a single primary winding and two secondary windings.
- They are wound on a hollow cylindrical bobbin which is non-magnetic and insulating material.
- The secondary windings have equal number of turns and are identically placed on either side of the primary winding.
- The primary winding is connected to an alternating current source.
- A movable soft iron core is placed inside the bobbin.



Working of LVDT:

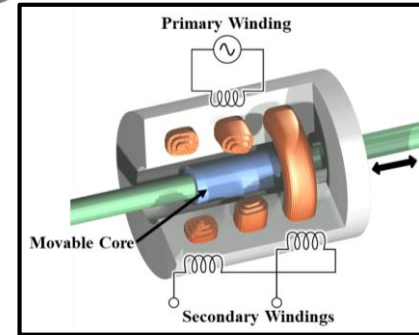
- The displacement to be measured is applied to the arm attached to the soft iron core.
- Since the primary winding is excited by an alternating current source, it produces an alternating magnetic field which in turn induces alternating current voltages in the two secondary windings.
- If the magnetic core is displaced, then the value of resultant voltage increases/decreases in proportion with the displacement.
- Resultant differential output across the secondary winding can be measured by voltmeter.



Interpretation of Result:

- Phase of the secondary voltage indicates the direction of displacement of core, and the magnitude indicates by how much.

Cutaway view of an LVDT



Summary:

- The study of measurement (metrology) is a basic requirement in engineering and manufacturing.
- It has a very crucial role in achieving modern industrial mass production system based on interchangeable manufacturing.
- In this lecture, different types of linear measuring instruments (Non-precision, precision and electrical measuring devices) have been discussed.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 17: Angular Measurement and Measurement of Surface Finish



Dr. Kaushik Pal

Associate Professor

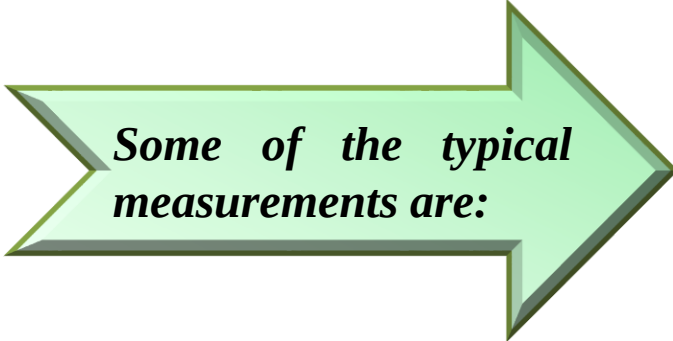
Dept. of Mech. & Indl. Engg.

Joint faculty: Centre of Nanotechnology



Angular Measurement:

- Precise measurement of angles is one of the important requirements in workshops and tool rooms.
- It is the measure of the opening between two lines which meet at a point.
- There are a wide variety of geometric features that are measured in angular units.



Some of the typical measurements are:



Tapers of bores

Flank angle and included angle of a gear

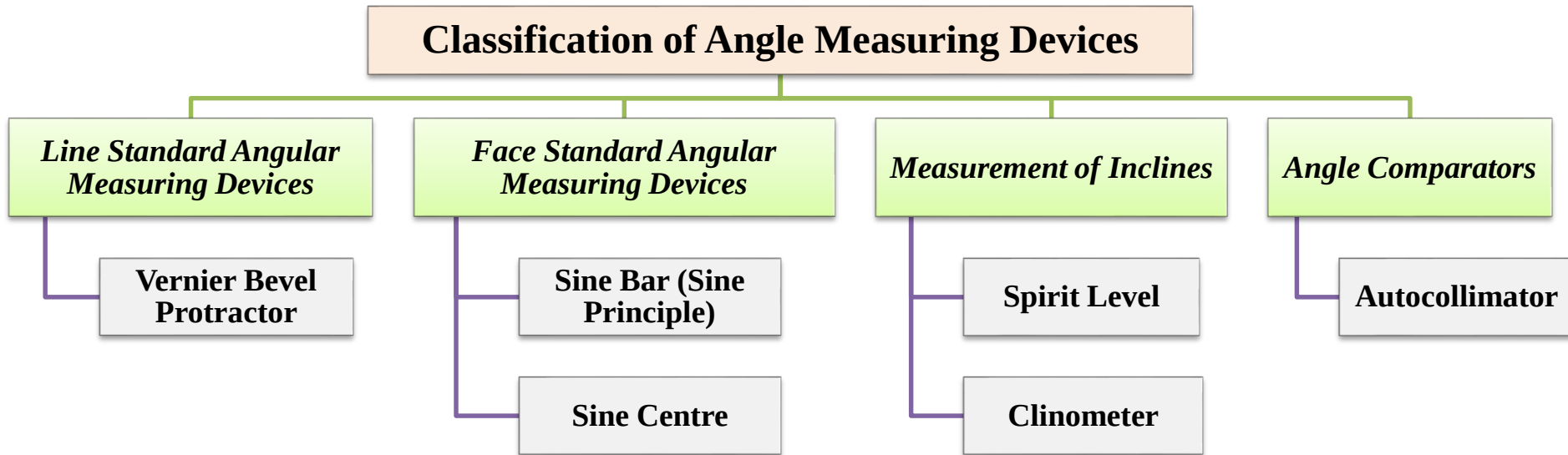
Angle made by a seating surface of a jig with respect to a reference surface

Taper angle of a jib and so on.

- The angle reading is also used as a measure of the error of alignment of machine parts.

Angular Measuring Instruments:

- Because of diverse geometrical forms of parts, different types of methods and equipment are available to measure angles in common angular units of degree, minute and second.
- Angle measuring devices are classified as:

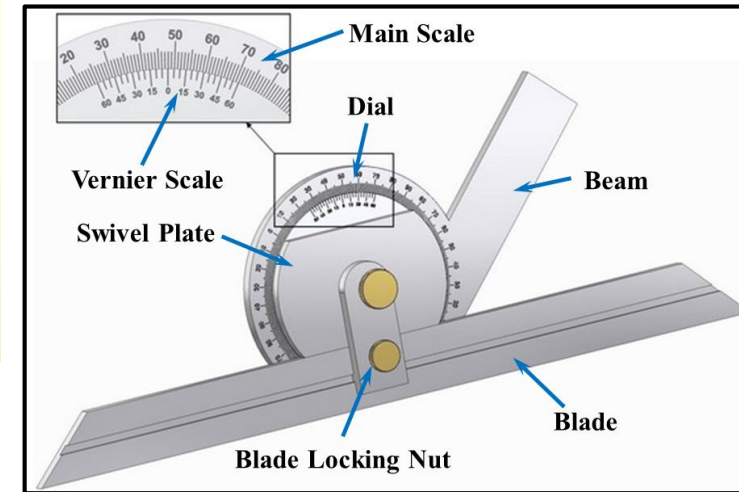
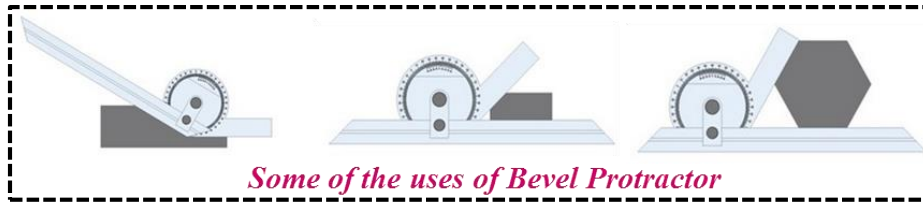


Line Standard Angular Measuring Devices:

- Line standard gives direct angular measurement from the engraved scales in the instruments.
- They are not very precise. Hence they are not used when high precision is required.
- Vernier bevel protractor is the most commonly used line standard angular measuring.

a) Vernier Bevel Protractor:

- It is the simplest instrument for measuring angles between two faces.
- It consists of two arms and an engraved circular scale.
- Two arms can be set along the faces between which the angle is to be measured.



Face Standard Angular Measuring Device:

a) Sine Bars:

- The sine principle uses the ratio of the length of two sides of a right triangle in deriving a given angle.
- The sine bar in itself is not a complete measuring instrument. Another datum such as a surface plate is needed, as well as other auxiliary equipment , notably slip gauges, and indicating device to make measurements.
- Sine bars used in conjunction with slip gauges constitute a very good device for the precise measurement of angles.
- Some holes are drilled in the body of the bar to reduce the weight and facilitate handling.
- Sine bars are made from high carbon, high chromium, corrosion resistant steel, hardened, ground and stabilized.



Measurement of Angle of Small Size Components:

- ✓ For measuring the angle of small size components, a sine bar is set up at an angle on a surface plate by suitable combination of slip gauges.

$$\sin \theta = \frac{\text{perpendicular}}{\text{hypotenuse}} = \frac{h}{L}$$

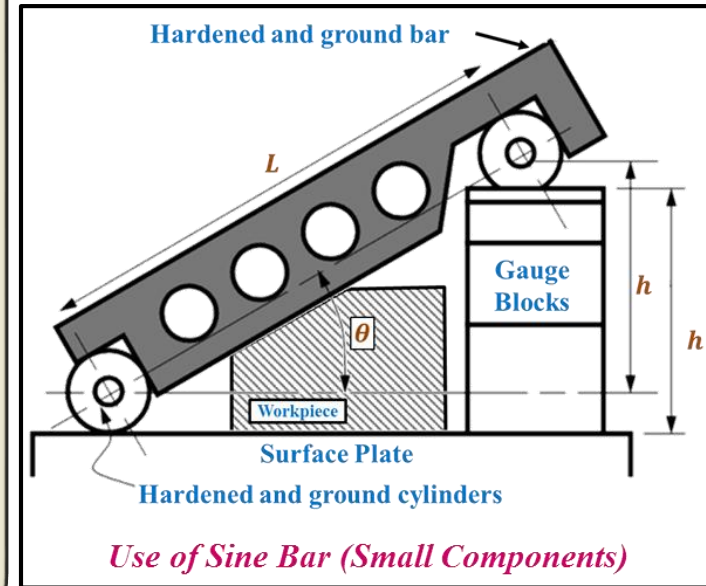
$$\theta = \sin^{-1} \left(\frac{h}{L} \right)$$

Here,

L = distance between centers of ground cylinders

h = height of the gauge blocks

θ = taper angle of the workpiece

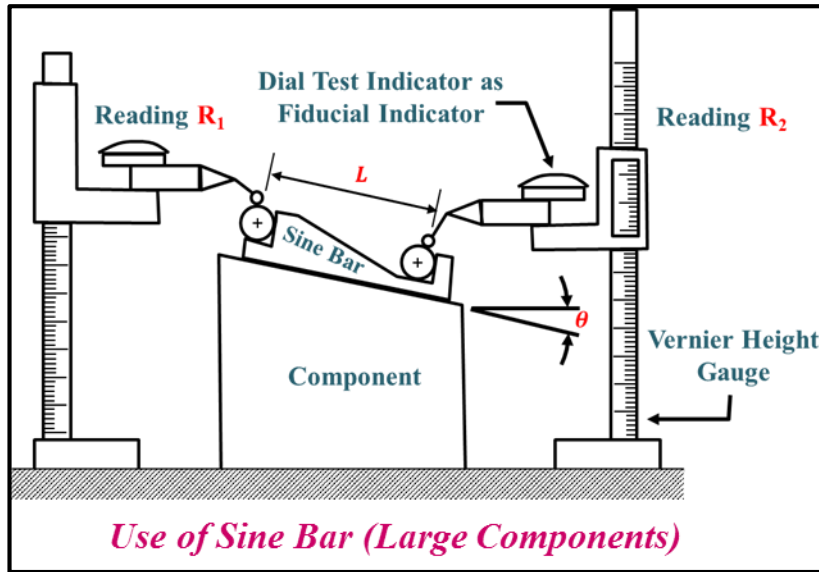


Measurement of Angle of Large Size Components:

- ✓ When component is too large to be mounted on the sin-bar, the sine bar can be mounted on the component.
- ✓ The height over the rollers is measured by means of a vernier height gauge.
- ✓ A dial gauge is also used to check the measuring pressure.
- ✓ Height gauge is adjusted until the dial gauge reads zero reading.
- ✓ Now, the angle of the component is given by:

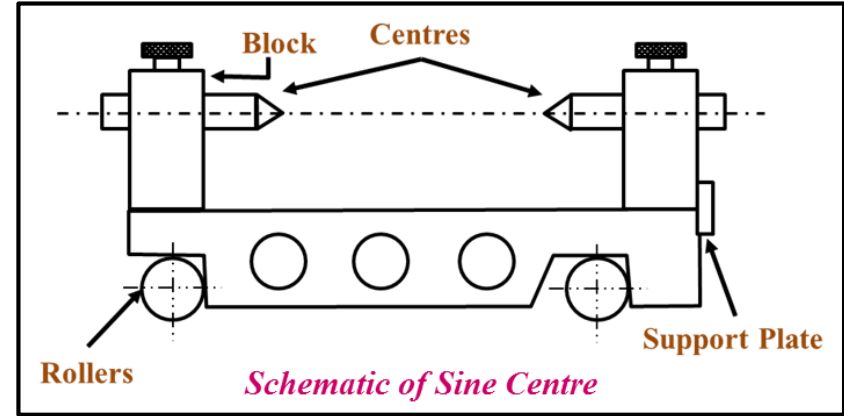
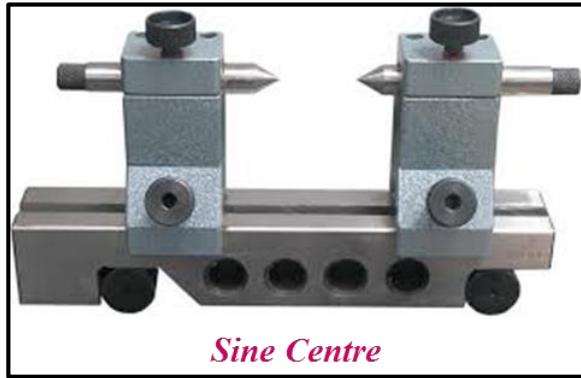
$$\sin \theta = \frac{R_1 - R_2}{L}$$

$$\theta = \sin^{-1} \left(\frac{R_1 - R_2}{L} \right)$$



b) Sine Centre:

- Special type of sine bar is sine centre which is used for conical objects having male and female parts.
- It cannot measure the angle more than 45 degrees.
- It has block holding centres which can be adjusted and rigidly clamped in any position depending on the length of the conical workpiece.
- Extremely useful since the alignment accuracy of the centres ensures that the correct line of measurement is made along the workpiece.

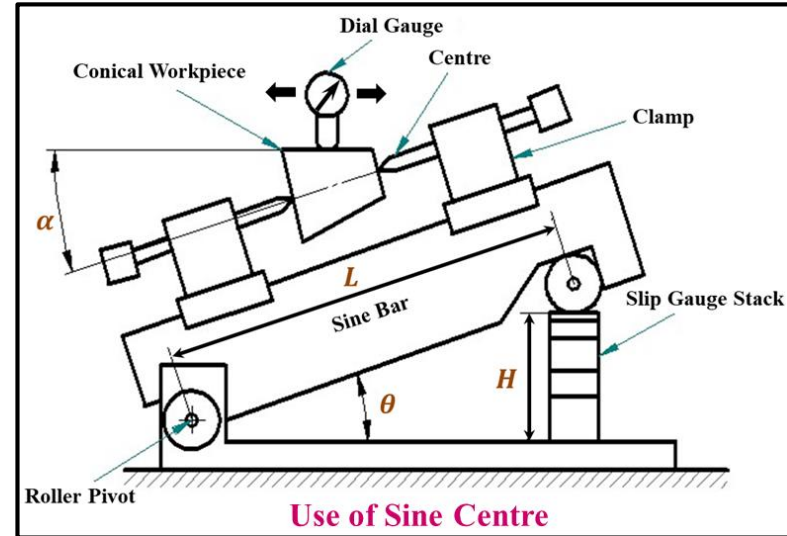


Measurement of Semi-conical Angle Using Sine Centre:

- ✓ The component being checked is placed over the surface of a sine bar.
- ✓ Dial gauge is moved over the component throughout its length.
- ✓ If there is a variation in parallelism of the upper surface of the component and the surface plate, it is indicated by the deflection of pointer.
- ✓ Now, the slip gauges height is adjusted so that the dial indicator reads zero position.

❖ For the dial gauge to read zero, the accurate semi cone angle is given as:

$$\alpha = \theta = \sin^{-1}(H/L)$$



Measurement of Inclines:

a) Spirit Level:

- A spirit level, bubble level or simply a level is an instrument designed to indicate whether a surface is horizontal or vertical.

❖ Construction of Spirit Level:

- ✓ It consists of a close glass tube of accurate form. It is called as the vial.
- ✓ It is filled almost entirely with a liquid, leaving a small space for the formation of an air or gas bubble.
- ✓ Generally, low viscosity fluids, such as ether, alcohol or benzol, are preferred for filling the vial.
- ✓ Proper liquid and material for the spirit level is required as temperature variations in the ambient condition cause both liquid and vial to expand or contract.
- ✓ To reduce the effect of heat transfer in handling spirit levels are made of a relatively stable casting and are equipped with thermally insulated handles.



❖ Working of Spirit Level:

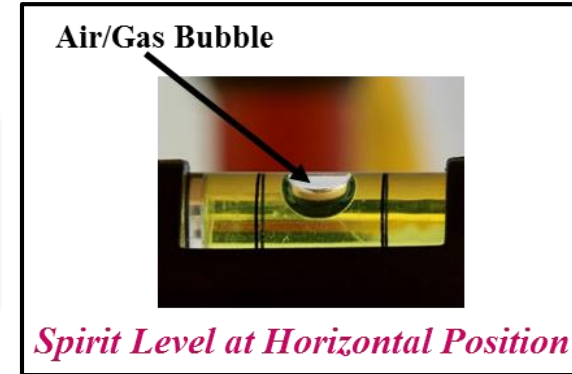
- ✓ The liquid due to its greater specific weight tends to fill the lower portion of the closed space. Upper side of the vial is graduated in linear units.
- ✓ When the base is horizontal, the bubble rests at the center of the graduated scale.
- ✓ Inclination of a surface can be known from the deviation of the bubble from its position when the spirit level is kept in a horizontal plane.



Precise Spirit Level

❖ Application:

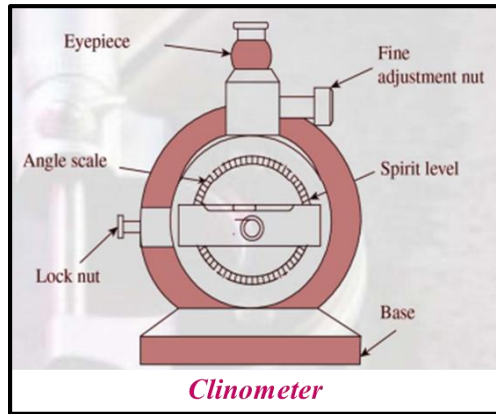
- ✓ A precision level is used to check and correct the twist in a machine (or workpiece).



Spirit Level at Horizontal Position

b) Clinometer:

- Special case of spirit level, while the spirit level is restricted to relatively small angles, clinometers can be used for much larger angles.
- It comprises a level mounted in a frame so that the frame may be turned to any desired angle to a horizontal reference.



❖ Working of Clinometer:

- ✓ To measure with clinometers, the base is kept on the surface of the work piece.
- ✓ Lock nut is loosened and the dial comprising the circular scale is gently rotated till the bubble in spirit level is approximately at centre.
- ✓ Now, lock nut is tightened and the fine adjustment nut is operated till the bubble is exactly at the centre of the vial scale.
- ✓ Rotation of the disc can be read on the scale. It represents the deviation of the surface over which the clinometer is placed from the horizontal plane.

Applications:

- ✓ Used to determine straightness and flatness of surfaces.
- ✓ Also used for setting inclinable table on jig boring machine and angular jobs on surface grinding machines.
- ✓ They provide superior accuracy compared to ordinary spirit levels.

Angle Comparators:

- Angle comparators are the metrological instruments used for finding the difference between two nearly equal angles.
- In practice, they are frequently used in calculating the difference between the angle of working standard gauges or instruments.
- It is also used in measuring angle of a number of angle gauges wrung together, or the angle between two faces of a standard polygon.
- The most widely used angle comparators are Autocollimators.

a) Autocollimators:

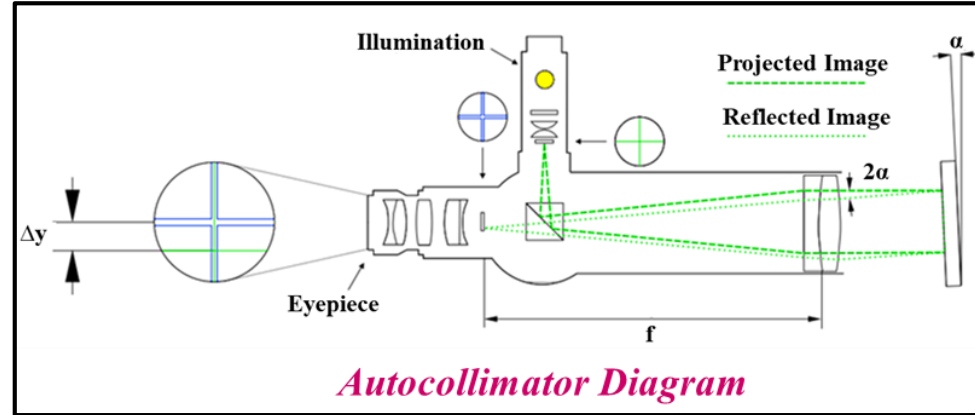
- The two main principles used in an autocollimator are:
 - ✓ Projection and the refraction of a parallel beam of light by a lens, and
 - ✓ Change in direction of a reflected angle on a plane reflecting surface with change in angle of incidence.

Working:

- ❑ The autocollimator measures the deviation between the emitted beam and the reflected beam to detect the angular movement.
- ❑ In this diagram of an autocollimator, the angle of mirror deviation (α) is calculated using the formula:

$$\alpha = \Delta y / 2f$$

where, f = focal length of the autocollimator,
 Δy = vertical deviation of the reflected beam
due to angular moment of the workpiece.

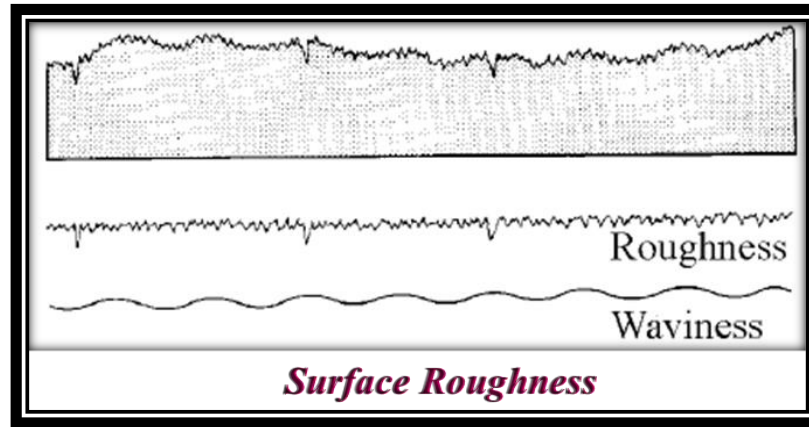


Applications:

- ✓ Checking of an internal right angle.
- ✓ Comparative measurement using master angles.
- ✓ Measuring straightness and flatness of the surfaces.
- ✓ For machine tool adjustment setting.

Surface Roughness:

- Surface roughness often shortened to roughness, is a component of surface texture.
- An engineering component processed by casting, forging, drawing, welding or stamping, etc. may not have equally finished surface.
- It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form.
- If these deviations are large, the surface is rough; if they are small, the surface is smooth.



Elements of Surface Roughness:

❑ Surface:

- Surface of the part is confined by the boundary which separates that part from another part, substance or space.

❑ Profile:

- Profile is defined as the contour of any section through a surface.

❑ Actual Surface:

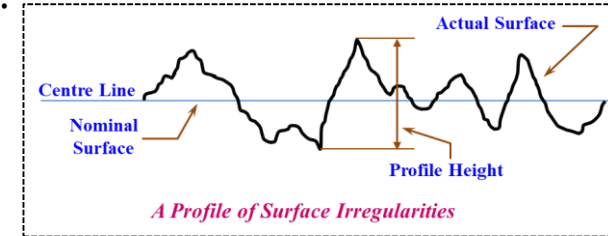
- This refers to the surface of a part which is actually obtained after a manufacturing process.

❑ Nominal Surface:

- A nominal surface is a theoretical, geometrically perfect surface which does not exist in practice, but is an average of the irregularities that are superimposed on it.

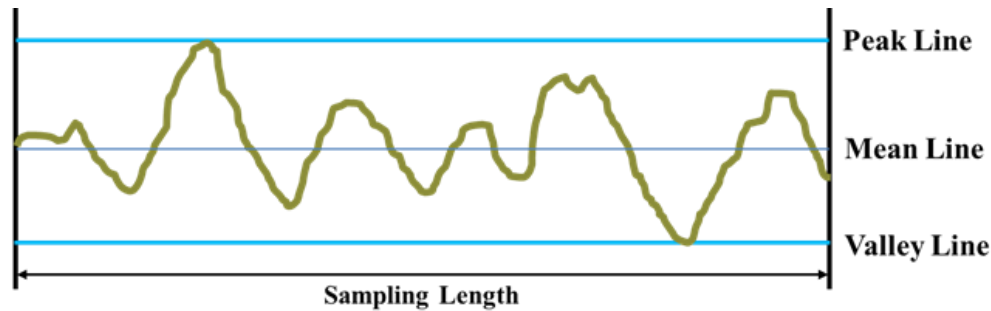
❑ Centre Line:

- Centre line of profile is the line parallel to the general direction of the profile for which the areas embraced by the profile above and below the line are equal.



□ Mean Line:

- Mean line of the profile is the line having the form of the geometrical profile and dividing the effective profile so that within the sampling length the sum of the squares of distances between effective points and the mean line is minimum.
- When the waveform is repetitive, the mean line and the centre line are equivalent.



Surface Roughness

❑ **Lay Direction:**

- Predominant direction or pattern of the surface texture.

❑ **Roughness:**

- Roughness refers to relatively finely spaced irregularities such as might be produced by the action of a cutting tool.

❑ **Roughness Height:**

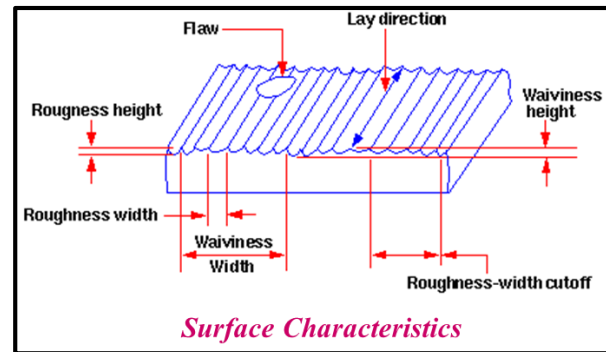
- This is rated as the arithmetical average deviation expressed in micro-inches or micro-metres normal to an imaginary centre line, running through the roughness profile.

❑ **Roughness Width:**

- Roughness width is the distance parallel to the normal surface between successive peaks or ridges that constitute the predominant pattern of the roughness.

❑ **Roughness Width Cut-off (Sampling Length):**

- This is the maximum width of surface irregularities that is included in the measurement of roughness height.
- This is always greater than roughness width and is rated in inches or centimetres.



❑ Waviness:

- Waviness consist of those surface irregularities which are of greater spacing than roughness and it occurs in form of waves.
- It may be caused by vibrations, machine or work deflections, warping, etc.

❑ Waviness Width:

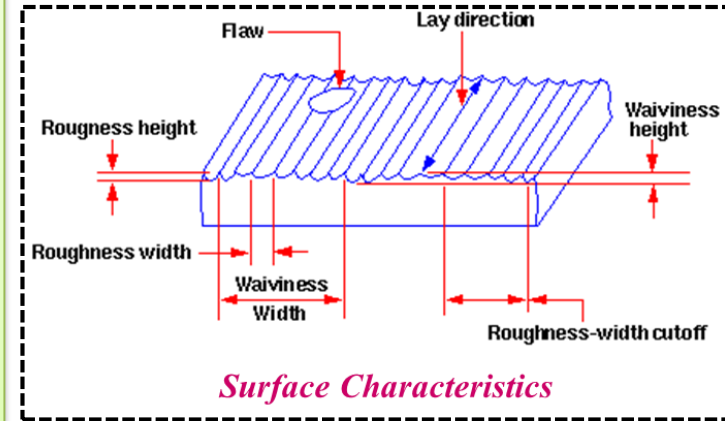
- It is the distance between successive wave peaks or successive wave valleys.

❑ Waviness Height:

- It is the distance from wave peak to valley.

❑ Flaws:

- Flaws are surface irregularities or imperfections which occur at infrequent intervals and at random intervals.
- Such imperfections are: scratches, holes, cracks, pits, checks, porosity, etc.



Evaluation of Surface Roughness:

- There can be many ways, through which the surface roughness plot can be evaluated.
- Few of the most popular methods of surface roughness plot interpretation are:

(i) Root mean square value: r. m. s. value.

(ii) Centre line average (CLA) or arithmetic mean deviation denoted as R_a .

(iii) Maximum peak to valley height, denoted as R_t or R_{max} .

(iv) Average of the five highest peaks and five deepest valleys in the sample, denoted as R_z .

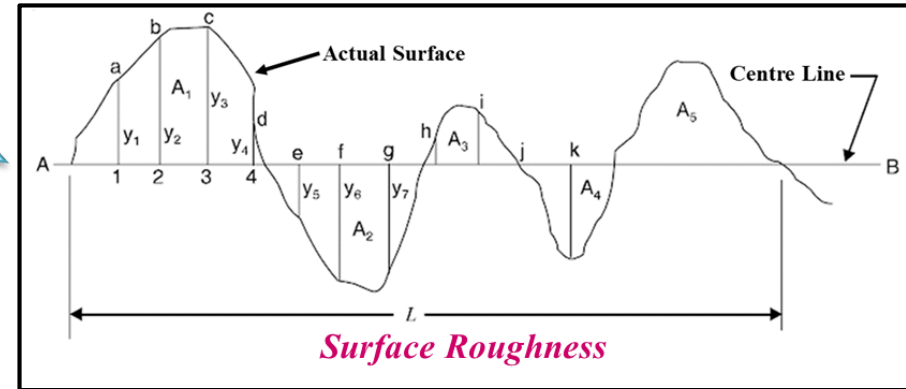
i. Root Mean Square Value (RMS):

- The centre line is first located such that the sum of the areas above the line is equal to the areas below the line.
- The distances above the centre line are taken as positive and below as negative.
- Then n measurements are made (plus or minus) from the centre line vertically to points on the profile and are called y_i .
- Root mean square value is the positive square root of the arithmetic mean of the value of the squares of the values in the set.

RMS Calculation:

$$\begin{aligned} \text{RMS Value} &= \sqrt{\frac{y_1^2 + y_2^2 + y_3^2 + \dots}{n}} \\ &= \left[\left(\sum y_i^2 \right) / n \right]^{1/2} \end{aligned}$$

Where, y_i is the profile deviation.



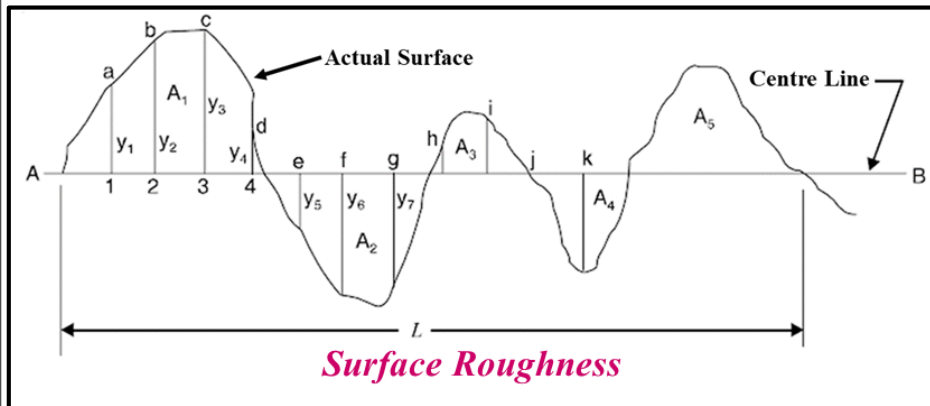
ii. Centre Line Average (CLA) or Arithmetic Mean Deviation (R_a):

- In this method, the surface roughness is measured as the average deviation from the nominal surface or centre line.
- Arithmetic average or centre line average is defined as the average value of the ordinates from the centre line, the algebraic sign of the ordinates are not considered.

Calculation:

Arithmetic Average, $AA = R_a = \frac{1}{L} \int_0^L |y(x)| dx$

or, approximately, $R_a = \frac{\sum_{i=1}^n |y_i|}{n}$

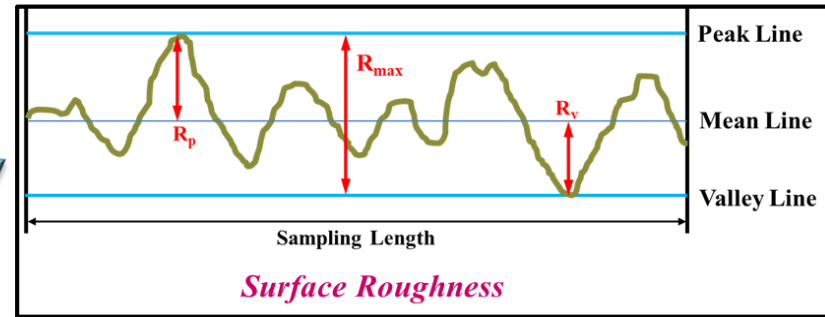


iii. Maximum Peak to Valley Height ($R_{\max}$ or R_t):

- This is the parameter which is simplest to be determined from the graph of the profile. However, this does not give complete characteristics of surface roughness.
- This parameter is, however, important when the roughness is to be removed, for example, by polishing, to increase the fatigue resistance of the work.

Calculation:

- ❖ R_p = Highest peak above the mean line
- ❖ R_v = Deepest valley below the mean line
- ❖ $R_{\max}$ = Distance from the highest peak to the deepest valley $R_{\max} = R_p + R_v$



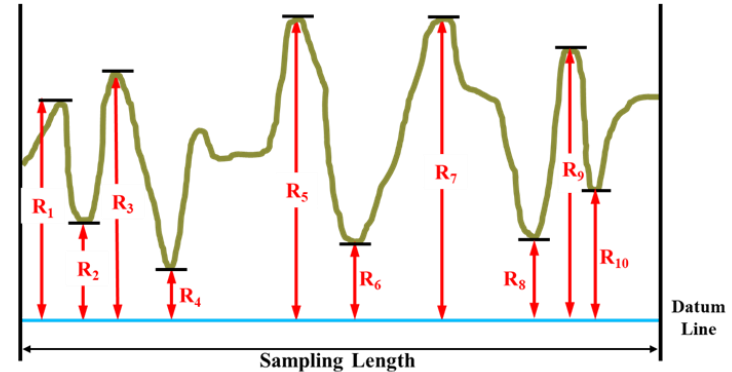
iv. Average Peak to Valley Height (R_z):

- This parameter is easier to obtain from a profile graph than R_a .
- This is the average difference between the five highest peaks and the five deepest valleys within sampling length measured from a line drawn parallel to the general direction of the profile.
- This line does not cross the profile.

This parameter is obtained as:

$$R_z = \frac{1}{5} [(R_1 + R_3 + R_5 + R_7 + R_9) - (R_2 + R_4 + R_6 + R_8 + R_{10})]$$

- ❖ R_1, R_3, R_5, R_7, R_9 : Tallest 5 peaks within sample length
- ❖ $R_2, R_4, R_6, R_8, R_{10}$: Lowest 5 peaks within sample length



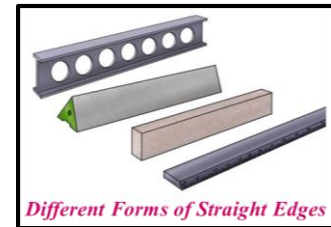
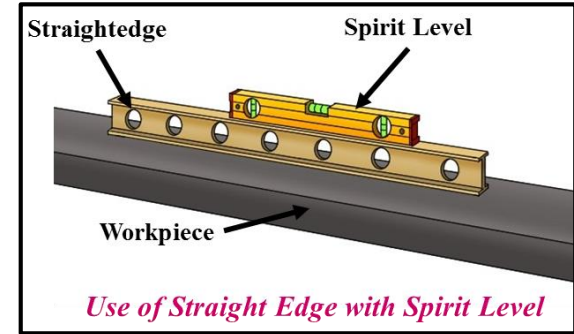
Surface Roughness Measurement:

- The surface roughness may be measured, using any of the following :



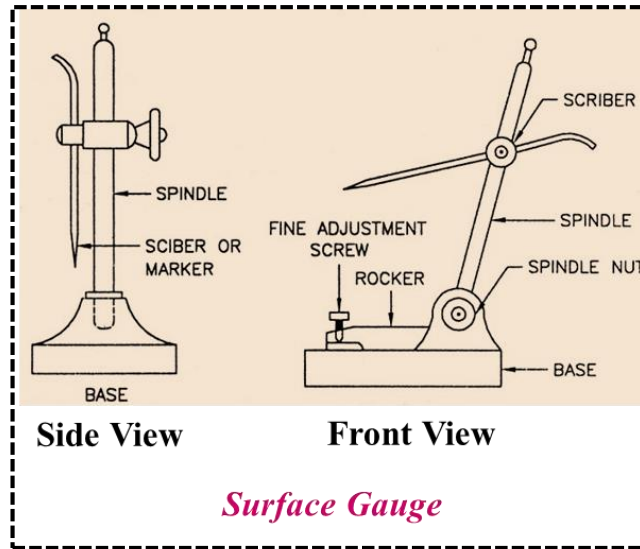
a) Straightedge:

- It is a tool with a straight edge, used for drawing straight lines, or checking their straightness.
- They are used in the automotive service and machining industry to check the flatness of machined mating surfaces.
- A pair of straightedges called winding sticks are used in woodworking to amplify twist in pieces of wood.



b) Surface Gauge:

- Surface gauges are used to measure the profile height of the surface.
- The attached scriber helps to mark out the surface profile with respect to a reference line.

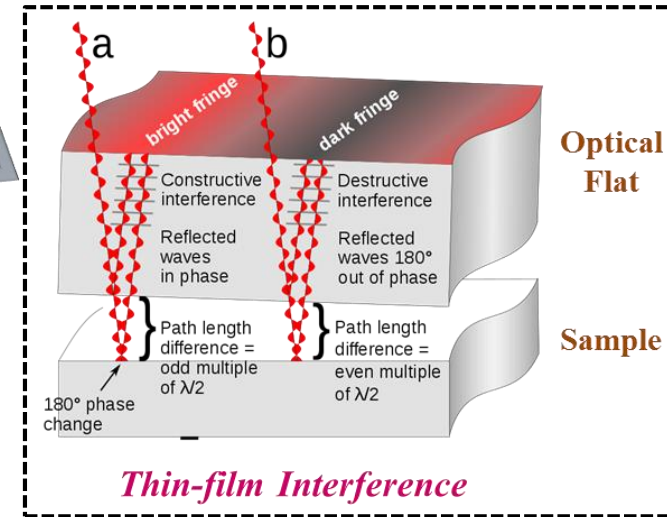


c) Optical Flat:

- It is an optical-grade piece of glass lapped and polished to be extremely flat on one or both sides, usually within a few tens of nanometres.
- They are used with a monochromatic light to determine the flatness (surface accuracy) of other surfaces.

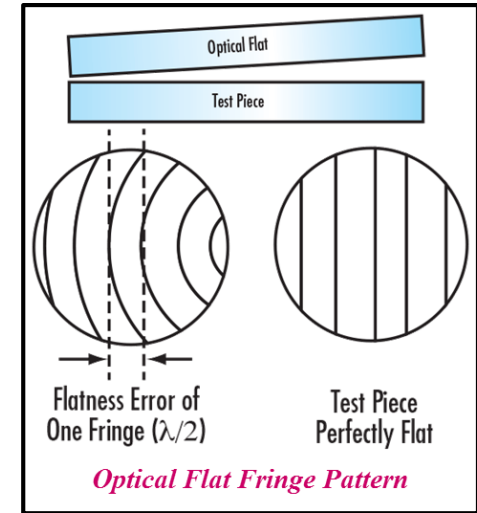
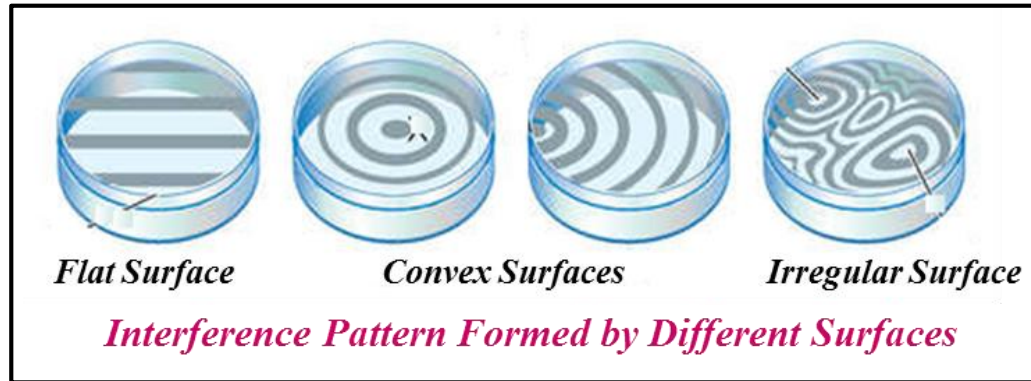
Working of Optical Flats:

- ✓ When an optical flat is placed on another surface and illuminated, the light waves reflect off both the bottom surface of the flat and the surface it is resting on.
- ✓ This causes a phenomenon similar to **thin-film interference**.
- ✓ The reflected waves interfere, creating a pattern of interference fringes visible as light and dark bands.
- ✓ The spacing between the fringes is smaller where the gap is changing more rapidly, indicating a departure from flatness in one of the two surfaces.



Interpretation of Results:

- ❑ Straight, parallel, and evenly spaced interference fringes indicate that the work surface flatness is equal to or higher than that of the reference surface.
- ❑ Two adjacent fringes indicate a difference in elevation of one-half wavelength of the light used, so by counting the fringes, differences in elevation of the surface can be measured to better than one micrometre.



d) Profilometer:

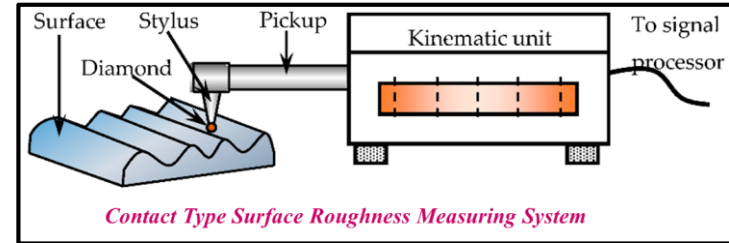
- A profilometer is a measuring instrument used to measure a surface's profile, in order to quantify its roughness.
- There are two types of profilometers as:

a. *Contact Profilometers*

b. *Non-contact Profilometers*

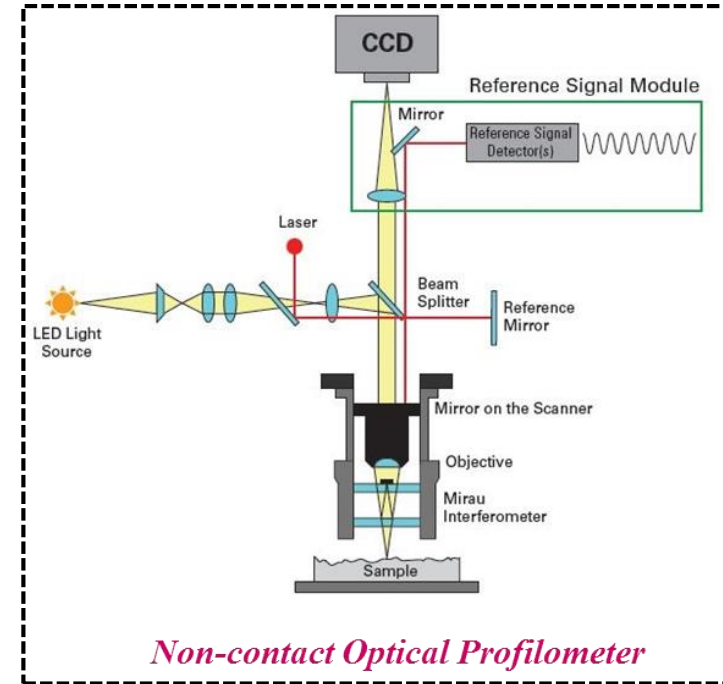
a. Contact Profilometers:

- ✓ A diamond stylus is moved vertically in contact with a sample and then moved laterally across the sample for a specified distance and specified contact force.
- ✓ The height position of the diamond stylus generates an analog signal which is converted into a digital signal, stored, analyzed, and displayed.
- ✓ It can measure small vertical features ranging in height from 10 nanometres to 1 millimetre.



b. Non-contact Profilometers:

- ✓ An optical profilometer is a non-contact method for providing much of the same information as a stylus based profilometer.
- ✓ It generally uses light instead of a physical probe.
- ✓ Surface texture is measured by optically scanning a surface with a light or laser.
- ✓ Optical or light-based instruments may also use triangulation or interferometry to measure or capture a surface profile.
- ✓ Although most surface profilometers provide only a two-dimensional (2D) or line file, some instruments can provide three-dimensional (3D) or areal topography measurements.



Summary:

- The quantification and measurement of angles is important in scientific as well as manufacturing applications.
- Different types of instruments are used to perform the angular measurement e.g. bevel protractor, sine bar, sine centre, spirit level, clinometer, etc.
- The shape and size of irregularities on a machined surface (surface roughness) also have a major impact on the quality and performance of that surface, and on the performance of the end product.
- Many parameters have been established regarding the measurement and assessment of surface roughness.

THANK YOU





IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 18: Screw Thread Metrology



Dr. Kaushik Pal

Associate Professor

Dept. of Mech. & Indl. Engg.

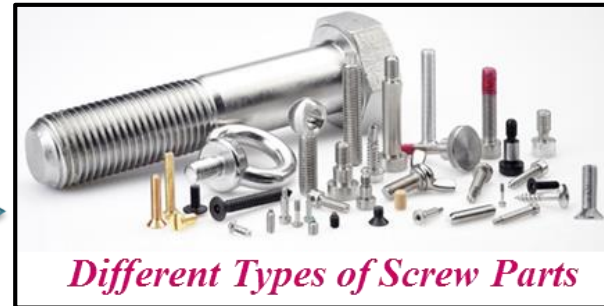
Joint faculty: Centre of Nanotechnology



Screw Thread:

- It is a helical structure used to convert between rotational and linear movement or force.
- Screw thread is formed by cutting a continuous helical groove on a cylindrical surface.
- Interchangeable screwed parts, e.g. bolts and nuts, are produced in bulk quantity for several applications.
- These parts are usually inspected to ensure that the accepted parts will assemble within the limits for quality of fit.
- Screw threads are employed basically for two purposes:
 - To fasten two components with the help of nuts, bolts and studs.*
 - To transmit power, as in case of lathe machine lead screw.*

There are a large number of different standard forms of screw threads in common use.



Elements of Screw Thread:

- A screw thread has several individual elements each of which may be measured separately.
- These elements are:

❖ Major Diameter:

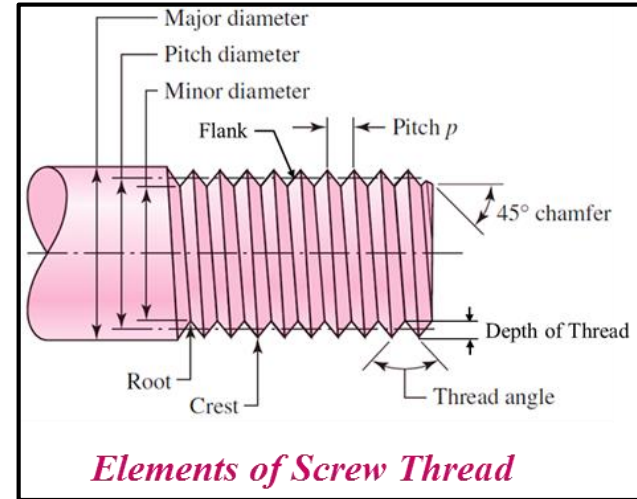
- It is the largest diameter of an external or internal screw thread.
- The screw is specified by this diameter.
- It is also known as *outside* or *nominal diameter*.

❖ Minor Diameter:

- It is the smallest diameter of an external or internal screw thread.
- It is also known as *core* or *root diameter*.

❖ Pitch Diameter/Effective Diameter:

- It is the diameter of an imaginary cylinder, on a cylindrical screw thread, the surface of which would pass through the thread at such points as to make equal the width of the thread and the width of the spaces between the threads.
- In a nut and bolt assembly, it is the diameter at which the ridges on the bolt are in complete touch with the ridges of the corresponding nut.

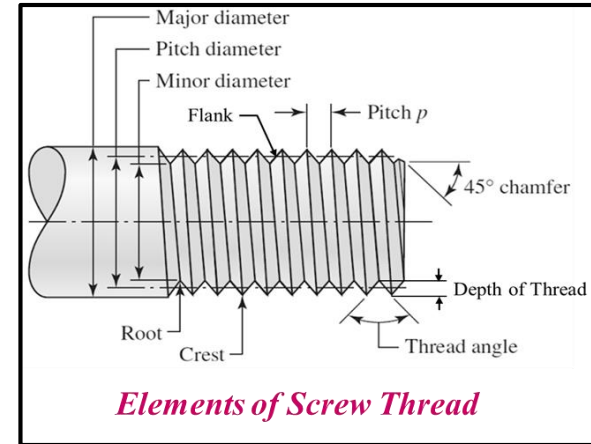


❖ Pitch:

- It is the distance from a point on one thread to the corresponding point on the next.
- This is measured in an axial direction between corresponding points in the same axial plane.
- Mathematically,
$$\text{Pitch} = \frac{1}{\text{No. of threads per unit length of screw}}$$

❖ Lead:

- It is the distance between two corresponding points on the same helix.
- It may also be defined as the distance which a screw thread advances axially in one rotation of the nut.
- Lead is equal to the pitch in case of single start threads, it is twice the pitch in double start, thrice the pitch in triple start and so on.



❖ Crest & Root:

- Crest is the top surface of thread while root is the bottom surface created by two adjacent flanks of the thread.

❖ Depth of Thread & Flank:

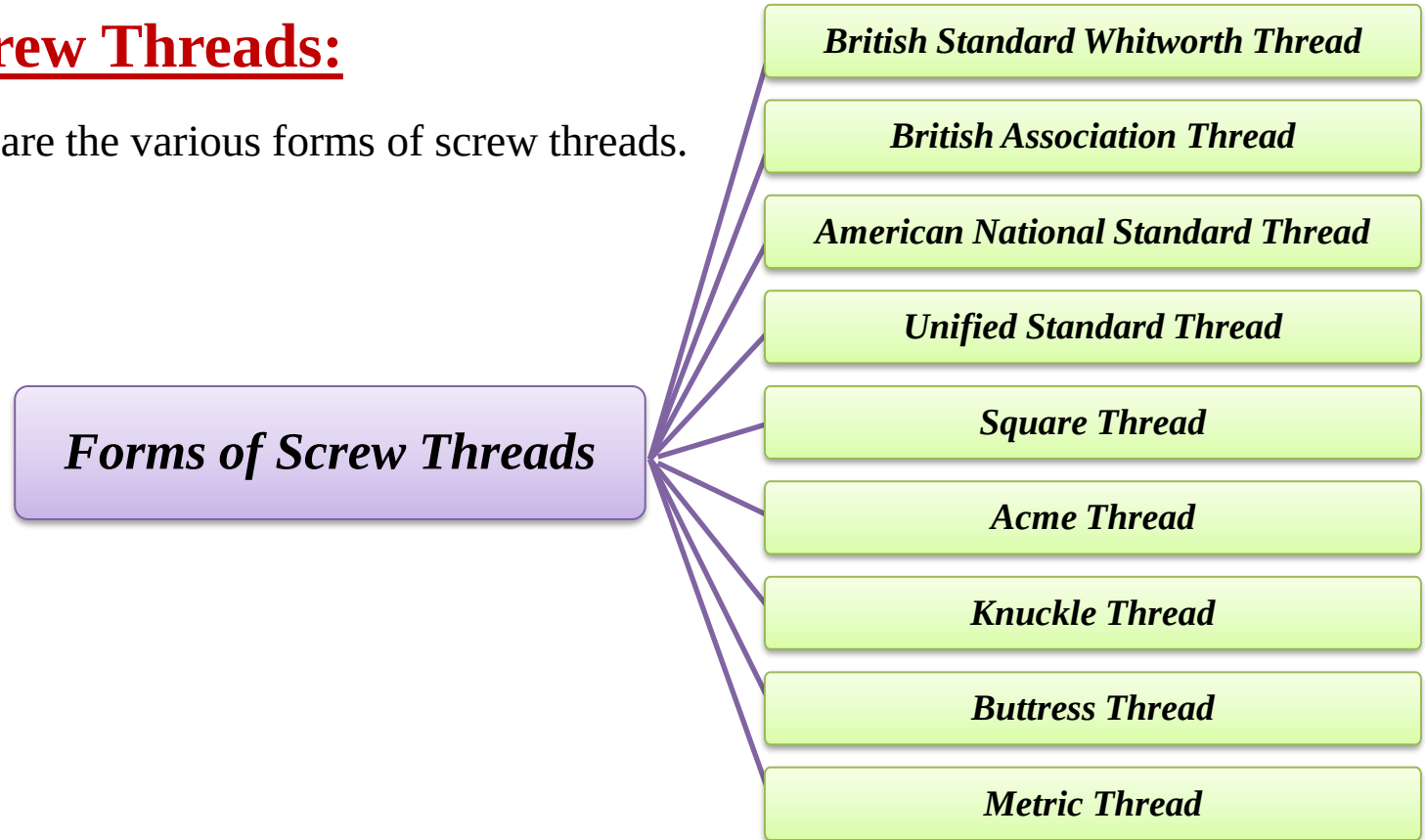
- Depth of thread is the perpendicular distance between the crest and root while flank is the surface joining the crest and root.

❖ Angle of Thread & Slope:

- Angle of thread is the angle included by the flanks of the thread while slope is half the pitch of the thread.

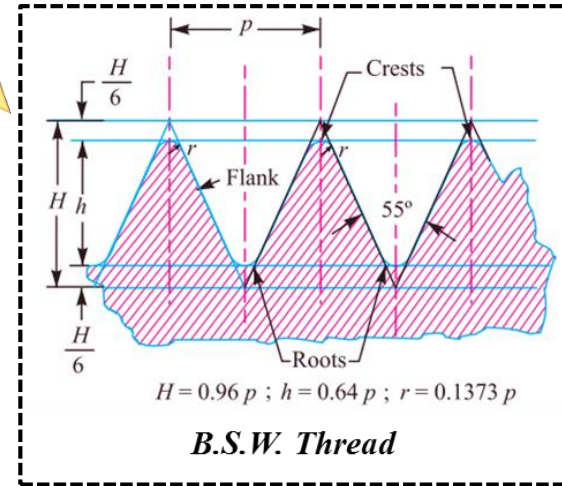
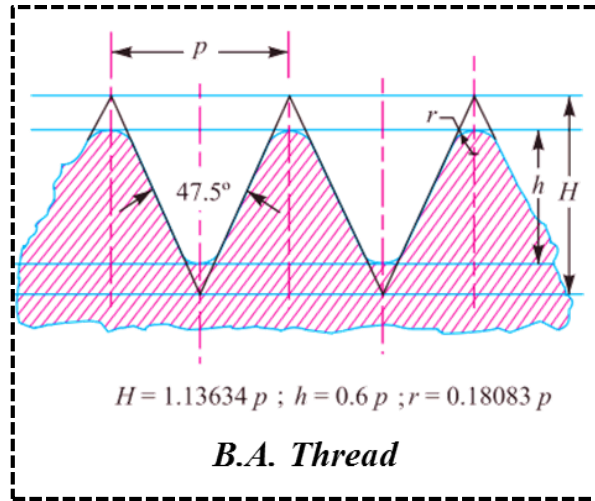
Forms of Screw Threads:

- The following are the various forms of screw threads.



1. British Standard Whitworth (B.S.W.) Thread:

- This is a British standard thread profile and has coarse pitches.
- It is a symmetrical V-thread in which the angle between the flanks, measured in an axial plane, is 55° .
- These threads are found on bolts and screwed fastenings for special purposes.

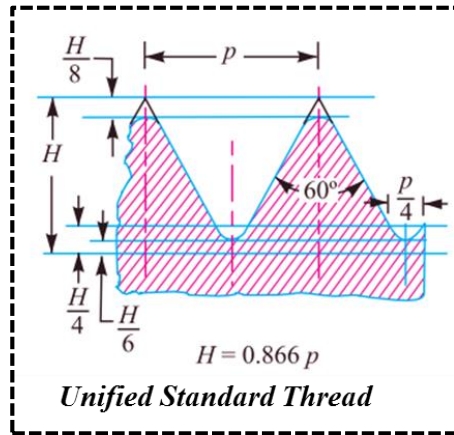
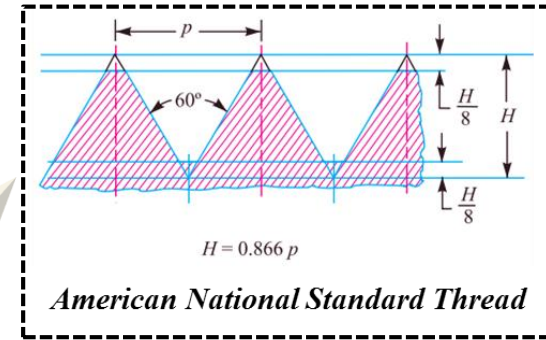


2. British Association (B.A.) Thread:

- This is a B.S.W. thread with fine pitches.
- These threads are used for instruments and other precision works.

3. American National Standard Thread:

- The American national standard or U.S. or Seller's thread has flat crests and roots.
- The flat crest can withstand more rough usage than sharp V-threads.
- These threads are used for general purposes e.g. on bolts, nuts, screws and tapped holes.

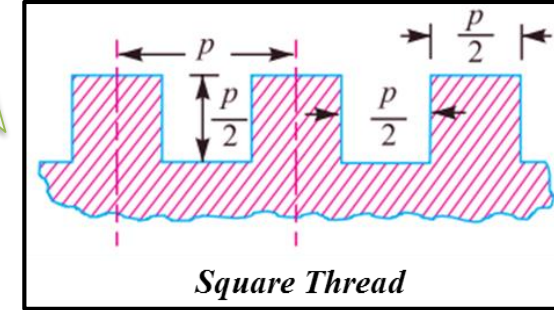


4. Unified Standard Thread:

- The three countries i.e., Great Britain, Canada and United States came to an agreement for a common screw thread system with the included angle of 60° , in order to facilitate the exchange of machinery.
- The thread has rounded crests and roots.

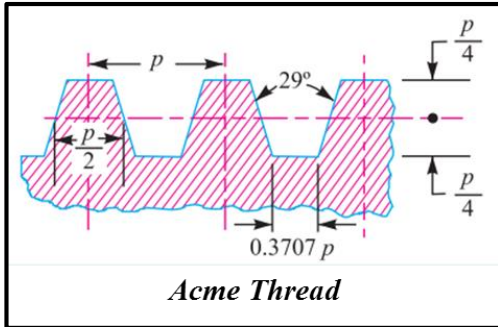
5. Square Thread:

- The square threads, because of their high efficiency, are widely used for transmission of power in either direction.
- Such type of threads are usually found on the feed mechanisms of machine tools, valves, spindles, screw jacks etc.
- The square threads are not so strong as V-threads but they offer less frictional resistance to motion than Whitworth threads.
- The pitch of the square thread is often taken twice that of a B.S.W. thread of the same diameter.



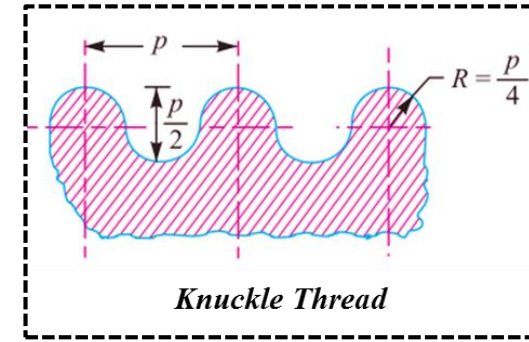
6. Acme Thread:

- It is a modification of square thread.
- It is much stronger than square thread and can be easily produced.
- These threads are frequently used on screw cutting lathes, brass valves, cocks and bench vices.
- When used in conjunction with a split nut, as on the lead screw of a lathe, the tapered sides of the thread facilitate ready engagement and disengagement of the halves of the nut when required.



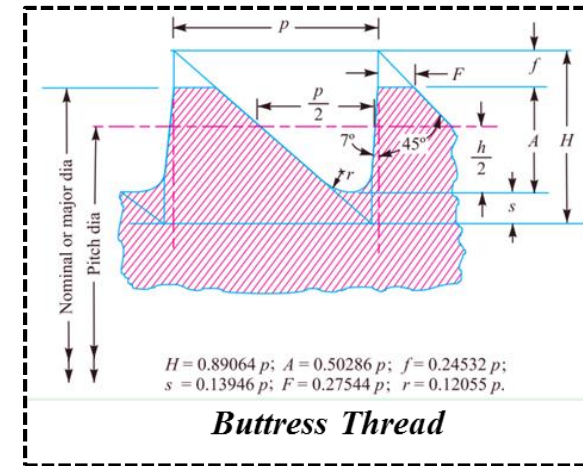
7. Knuckle Thread:

- It is also a modification of square thread.
- It has rounded top and bottom.
- It can be cast or rolled easily and can not economically be made on a machine. These threads are used for rough and ready work.
- They are usually found on railway carriage couplings, hydrants, necks of glass bottles and large moulded insulators used in electrical trade.



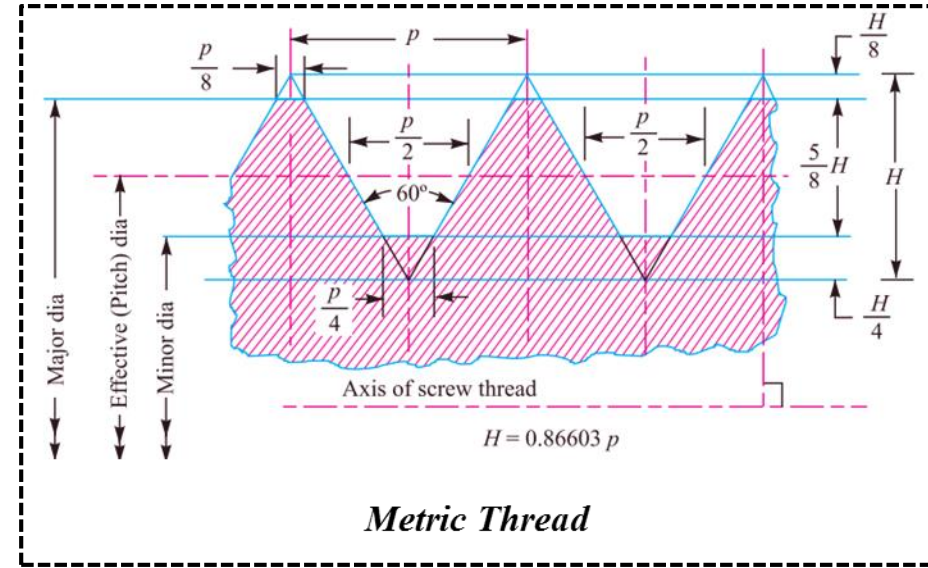
8. Buttress Thread:

- It is used for transmission of power in one direction only.
- The force is transmitted almost parallel to the axis.
- This thread units the advantage of both square and V-threads.
- It has a low frictional resistance characteristics of the square thread and have the same strength as that of V-thread.
- The spindles of bench vices are usually provided with buttress thread.



9. Metric Thread:

- It is an Indian standard thread and is similar to B.S.W. threads.
- It has an included angle of 60° instead of 55° .



Measurement of Screw Threads:

To find out the quality of a threaded element, the following elements of screw threads are measured:

Major Diameter

Minor Diameter

Effective or Pitch Diameter

Pitch

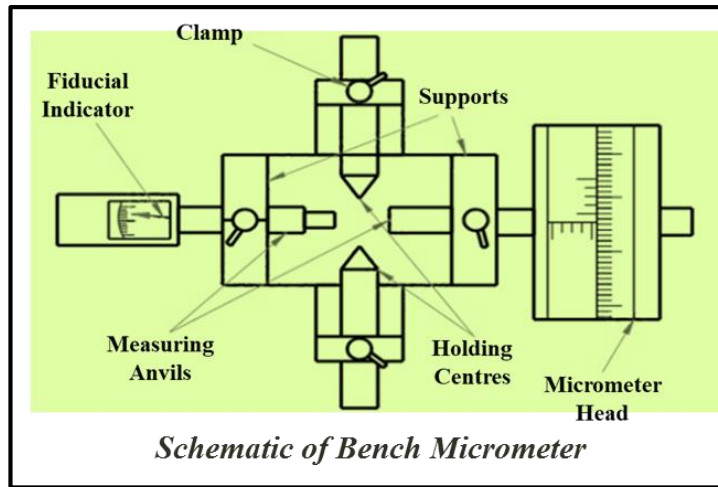
Thread Angle

I. Measurement of Major Diameter:

- It is most commonly measured by means of a **bench micrometer**.

Bench Micrometer:

- For getting the greater accuracy the bench micrometer is used for measuring the major diameter.
- The fiducial indicator is used to ensure all the measurements are made at same pressure.



❖ Measuring Major Diameter of External Threads:

1. A calibrated setting cylinder having approximately the same diameter as major diameter of the thread to be measured is used as setting standard.
2. The setting cylinder is held between the anvils and the readings of micrometer (R_1) are noted.
3. Then the cylinder is replaced by the threaded workpiece and the new reading (R_2) is noted for the same reading of fiducial indicator.

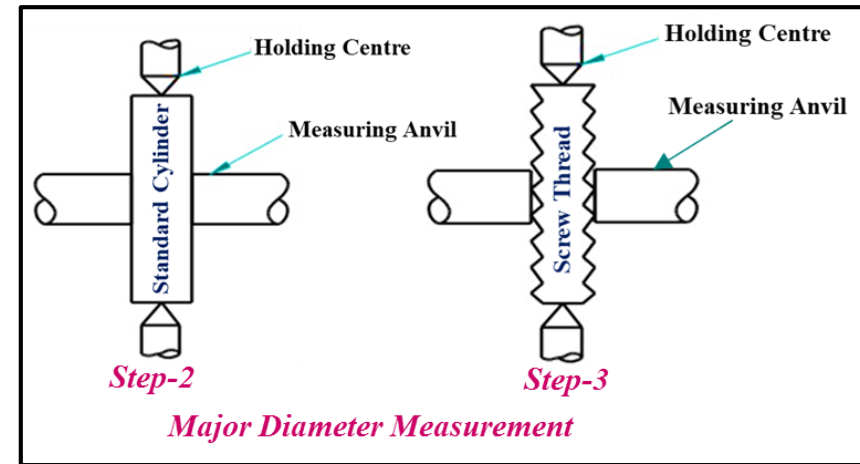
The major diameter of screw thread is given by:

$$D = S + (R_2 - R_1)$$

Where, S = diameter of setting cylinder

R_1 = micrometer reading on setting cylinder

R_2 = micrometer reading on screw thread



❖ Measuring Major Diameter of Internal Threads:

- An indirect approach of measuring internal threads is obtained by obtaining the cast of the thread.

II. Measurement of Minor Diameter:

❖ Measuring Minor Diameter of External Threads:

- Floating carriage micrometer is used to measure the minor diameter for externally threaded elements.

Floating Carriage Micrometer:

- ✓ The floating carriage diameter-measuring machine is a bench micrometer mounted on a carriage.
- ✓ It is suitable for almost all kinds of threads.
- ✓ The Vee-pieces available in various sizes having suitable radii at the edge are used along with the setting standard.



Floating Carriage Micrometer

Working Procedure:

- The threaded workpiece is mounted between the centers of the instrument and the V pieces are placed on each side of the workpiece with their bases against the anvil of the micrometer.
- After mounting the workpiece, the micrometer reading (R_2) is noted.
- Then the threaded workpiece is replaced by a standard reference, and the corresponding reading (R_1) is taken.

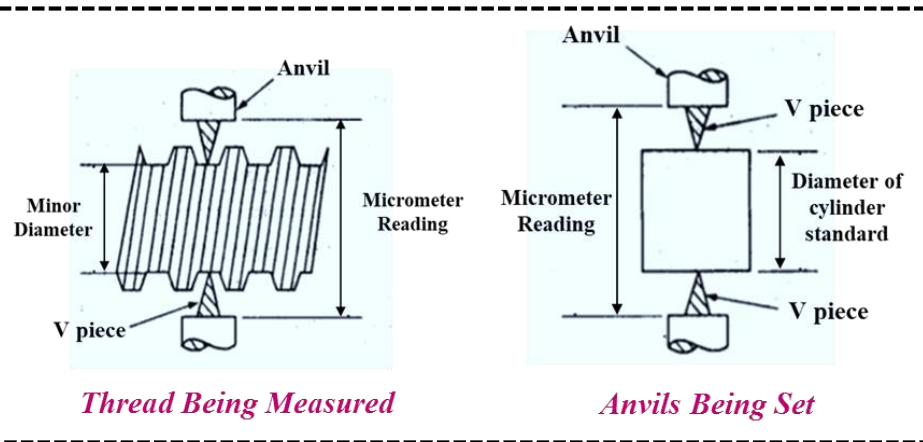
The minor diameter of screw thread is given by:

$$D = S + (R_2 - R_1)$$

Where, S = Diameter of cylinder gauge.

R_2 = Micrometer reading on threaded workpiece.

R_1 = Micrometer reading on cylindrical gauge.



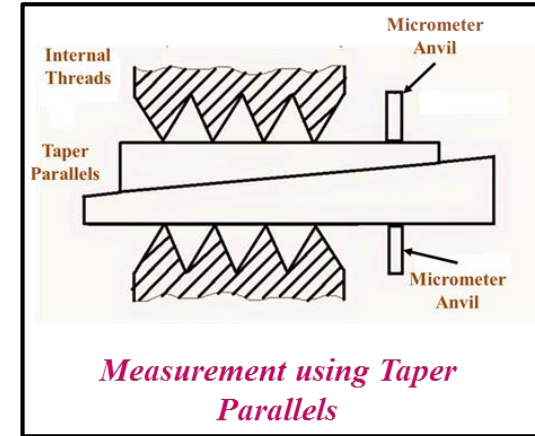
❖ Measuring Minor Diameter of Internal Threads:

➤ Minor diameter for internal threads are measured by using:

- ❑ Taper Parallels
- ❑ Rollers

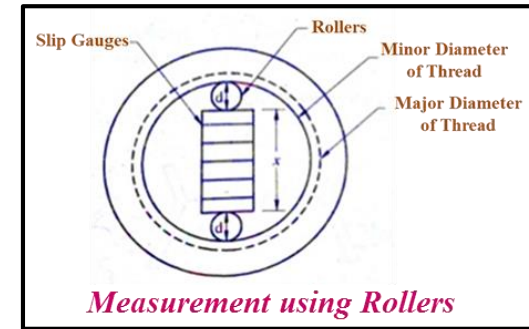
Taper Parallels :

- ✓ The taper parallels are pairs of wedges having reduced and parallel outer edges.
- ✓ The diameter across their outer edges can be changes by sliding them over each other.
- ✓ Inside the internal threads taper parallels are inserted and it is just stayed until form contact is established with minor diameter.



Rollers:

- ✓ In this method precision rollers are inserted inside the thread and proper slip gauges inserted between the rollers.
- ✓ The minor diameter is equal to the length of the slip gauges plus twice the diameter of the Roller.



III. Measurement of Pitch Diameter:

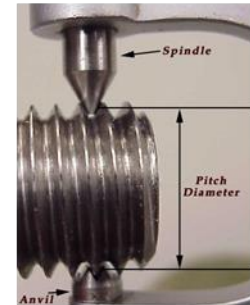
- Pitch diameter or effective diameter measurement is carried out by following methods:
 - a) Thread Micrometer Method
 - b) Two-wire Method
 - c) Three-wire Method

a) Thread Micrometer Method:

- The screw thread micrometer is designed to measure the pitch diameter of screw threads up to 0.01mm of accuracy.
- It is similar to an outside micrometer but has following the differences:
 - i. *The movable spindle is pointed, and*
 - ii. *The end of the anvil is the same as the screws thread to be measured.*
- The reading is read in similar way as in case of outside micrometer.
- Different pairs of interchangeable Vee- anvils and spindle points are provided with the micrometer.



Screw Thread Micrometer



Screw Thread Micrometer

b) Two-wire Method:

- The effective diameter of a screw thread may be ascertained by placing two wires or rods of identical diameter between the flanks of the thread and measuring the distance over the outside of these wires.
- Wires of exactly known diameters are chosen such that they contact the flanks at their straight portions.
- The wires used are made of hardened steel to sustain the wear and tear in use. These are given a high degree of accuracy and finish by lapping to suit different pitches.
- If the size of the wire is such it contacts the flanks at the pitch line, it is called **best size wire** which can be determined by geometry of screw thread.

Working Procedure:

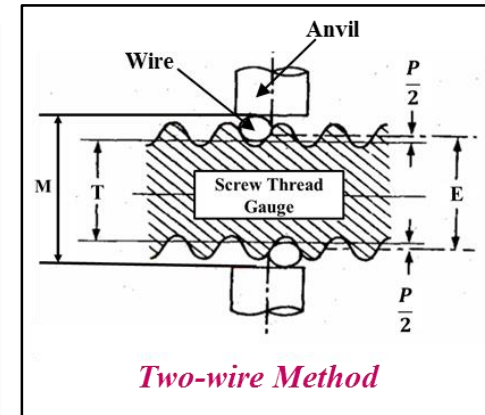
➤ Screw thread is mounted between the centers and wires are placed in the grooves and reading **M** is taken.

➤ Then the effective diameter **E** is calculated as: $E = T + P$

Where,

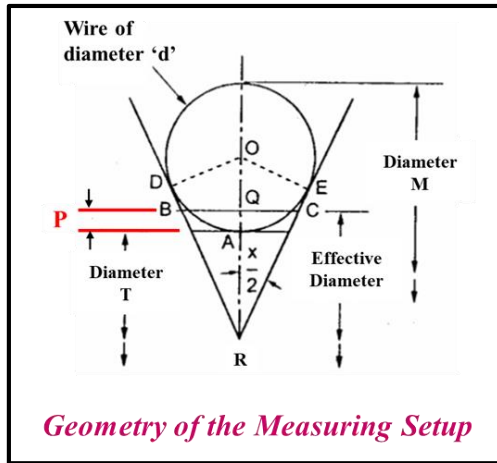
T = Dimension under the wires = $M - 2d$; M = Dimension over the wires;

d = Dimension of each wire; P = Difference between the effective diameter and the diameter under the wires (*explained on the next slide*).



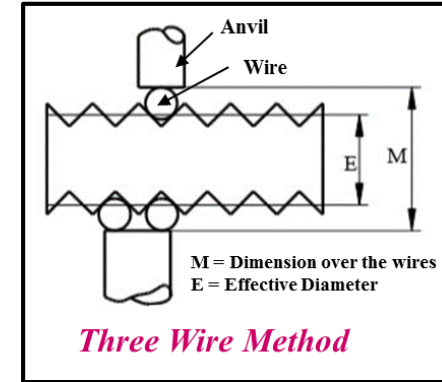
❖ Value of 'P':

- ✓ P is a value which depends on diameter of wire, pitch and angle of the screw thread.
- ✓ The P value can be derived in terms of pitch, diameter of wire, and thread angle using the geometry of the measuring setup.
- ✓ If $P' =$ pitch of thread, then
 - ❑ For **Whitworth** thread: $P = 0.9605 P' - 1.1657 d$
 - ❑ For **Metric** thread: $P = 0.866 P' - d$



c) Three-wire Method:

- Three wire method is the more accurate than the two wire method.
- In this method three wires of equal and precise diameter are placed in the grooves at opposite sides of screw.
- In this one wire on one side and two on the other side are used.
- This method ensures the alignment of micrometer anvil faces parallel to the thread axis.



Working Procedure:

- ✓ Basically, the principles of both two-wire and three-wire methods are same, hence same steps are followed to perform the measuring operation.

Applicability of Two and Three Wire Methods:

Two-wire Method is used when a **Floating Carriage Micrometer** is available for the measurement

When an **Ordinary Micrometer** is used for the measurement, a **Three-wire Method** should be used.

IV. Measurement of Pitch:

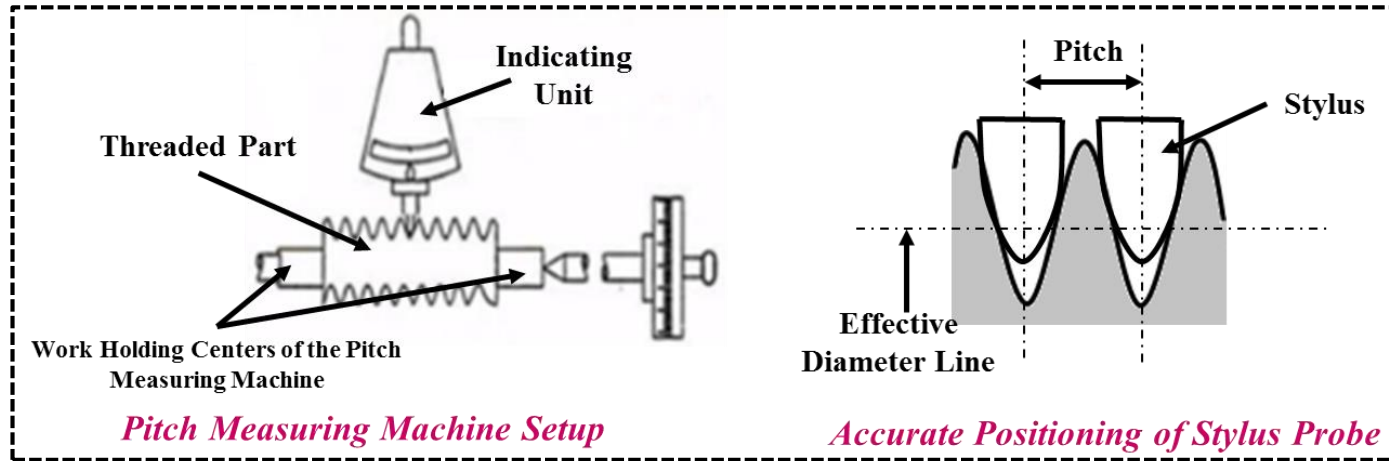
- Measurement of screw pitch can be done by following methods:
 - ❖ Pitch Measuring Machine
 - ❖ Tool Makers Microscope
 - ❖ Screw Pitch Gauge
 - ❖ Profile Projector

❖ Pitch Measuring Machine:

- A relatively accurate, simple and convenient method of measuring the pitch of a screw thread is by means of a pitch measuring machine.
- The screw to be measured is held between centers, and the machine is fitted with styles of such a size, that contacts the thread flanks approximately at the pitch line when it lies in the thread groove.
- Spring loaded head permits the stylus to move up the flank of the thread and down into the next space as it is moved along.

Working Procedure:

- ✓ The stylus is accurately positioned between the two flanks by ensuring that the pointer T is always opposite to its index mark when readings are taken.
- ✓ When the pointer is accurately placed in position, the micrometer reading is noted.
- ✓ The stylus is then moved along into the next thread space, by rotation of the micrometer, and a second reading is taken.
- ✓ The difference between the two readings is the pitch of the thread. Readings are taken in this manner until the whole length of the screw thread has been covered.

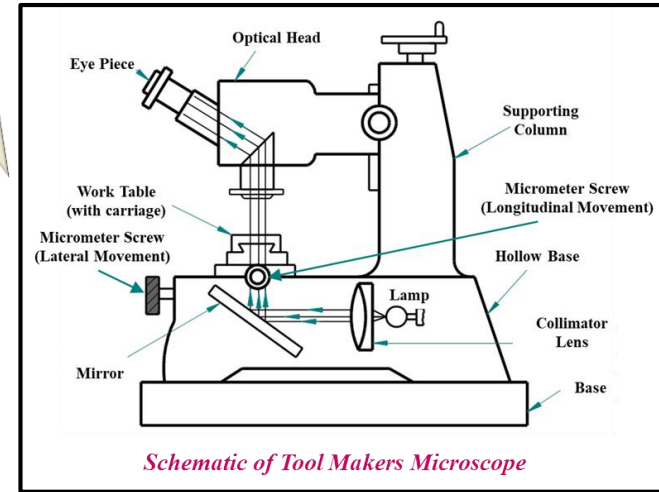


❖ Tool Maker's Microscope:

- It is an optical measuring machine equipped for all types of measurements for small parts.
- It creates an enhanced and accurate shadow of the part, which resembles the object.

Working Procedure:

- ✓ Worktable is placed on the base of the instrument.
- ✓ The optical head is mounted on a vertical column and it can be moved up and down.
- ✓ Work piece is mounted on a glass plate.
- ✓ A light source provides horizontal beam of light which is reflected from a mirror by 90 degree upwards towards the table.
- ✓ Image of the outline of contour of the work piece passes through the objective of the optical head.
- ✓ The image is projected on a ground glass screen on the work table.
- ✓ The measurements are made by means of cross lines engraved on the ground glass screen.



❖ Screw Pitch Gauge:

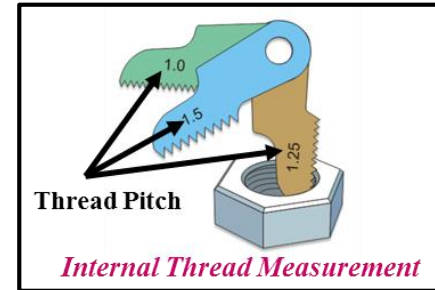
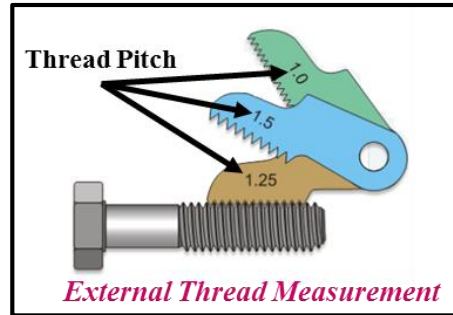
- This tool is not used as a precision measuring instrument.
- It allows the user to determine the profile of the given thread and quickly categorize the thread by shape and pitch.



Screw Pitch Gauge

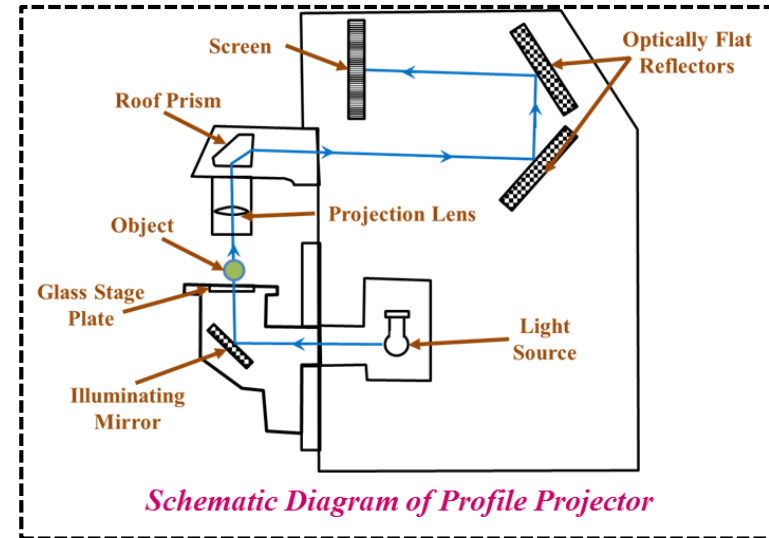
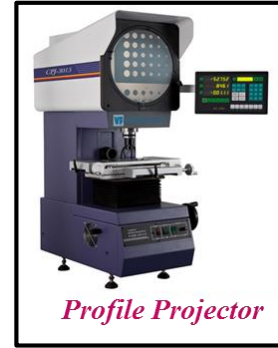
Working Procedure:

- ✓ To use a thread gauge, the user must first match the type of thread to the gauge.
 - ❑ **For example:** attempting to measure metric threads with an imperial gauge will not return accurate results.
- ✓ To determine the correct gauge, a process of trial and error may be needed if the screw is of unknown origin.
- ✓ Once the correct gauge is determined, the user should extend one of the leaves of the tool and press it against the threaded portion of a screw.
- ✓ If the teeth (cut into the leaf) match the spacing of the thread, then the user can read off the thread pitch stamped into the leaf.
- ✓ If the fit is not good, the user should try a different leaf.



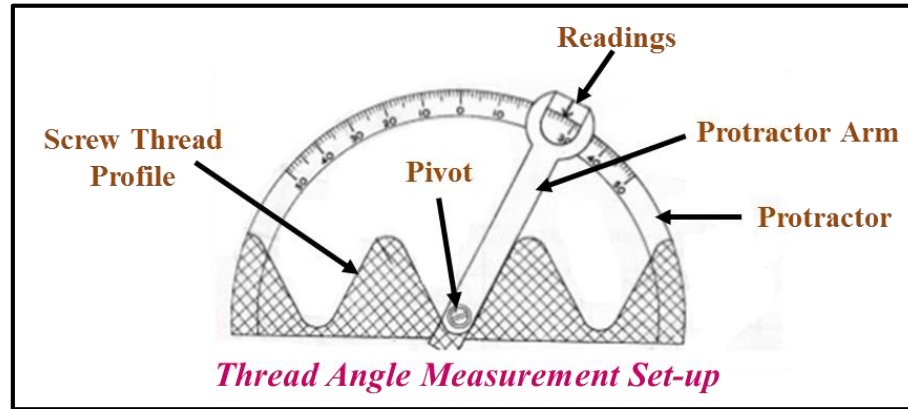
❖ Profile Projector:

- In this method, projector magnifies the profile of the specimen, and displays this on the built-in projection screen.
- On this screen there is typically a grid that can be rotated 360° so the X-Y axis of the screen can be aligned with a straight edge of the machined part to examine or measure.
- This projection screen displays the profile of the specimen and is magnified for better ease of calculating linear measurements.
- An edge of the specimen to examine may be lined up with the grid on the screen.
- From there, simple measurements may be taken for distances to other points.



V. Measurement of Thread Angle:

- Thread angle can be measured by using following instruments:
 - ❖ *Tool Makers Microscope*
 - ❖ *Profile Projector*
- In these methods optical projection / shadow is used to check the thread angle by using protractor.
- For better accuracy of results, it is necessary to project along the direction of the screw thread, i.e., along the helix angle.



Summary:

- Screw threads measurement is required for dimensional control to ensure a certain consistency of fit.
- Screw thread inspection is performed by using the thread gauges and some individual measuring instruments for measuring different thread elements.
- Different methods for measuring major diameter, minor diameter, effective diameter, pitch, and thread angle of threaded elements have been discussed.
- Tool makers microscope and profile projector can be used to perform all types of linear/angular measurements for small threaded elements.

THANK YOU





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CERTIFICATION COURSE

INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 19: Gear Measurement



Dr. Kaushik Pal

Associate Professor

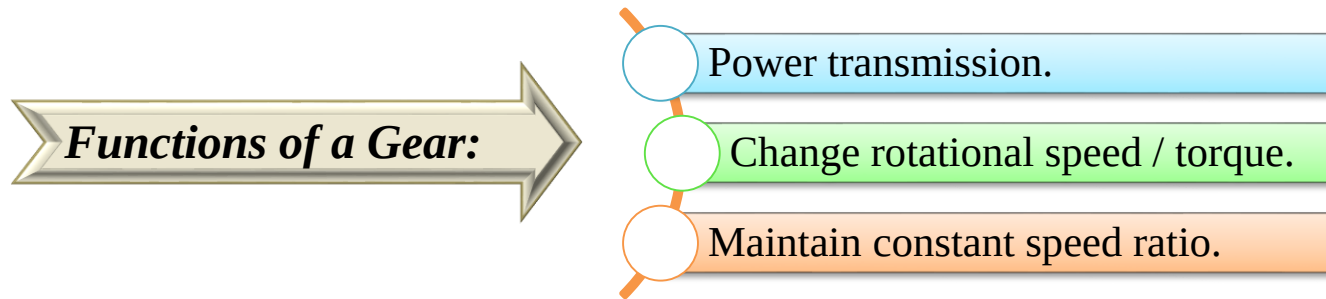
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What is Gear?

- A gear is a toothed wheel, which meshes with another toothed wheel to transmit power / motion from one shaft to another.
- They have advantage over friction and belt drives in that they are positive in action, a feature which most machinery require.
- In order to have perfectly uniform relative motion between driving and driven shaft, it is essential that both gears be of perfect geometrical form.
- Hence, during manufacturing the inspection process is included to ensure high degree of accuracy of gears.



Gear Terminology:

❑ Pitch Circle:

- It is an imaginary circle which by pure rolling action, would give the same motion as the actual gear.

❑ Pitch Circle Diameter or Pitch Diameter:

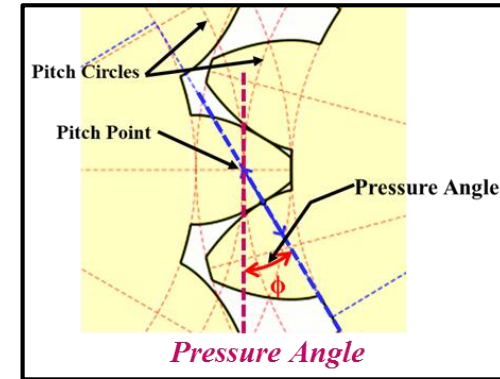
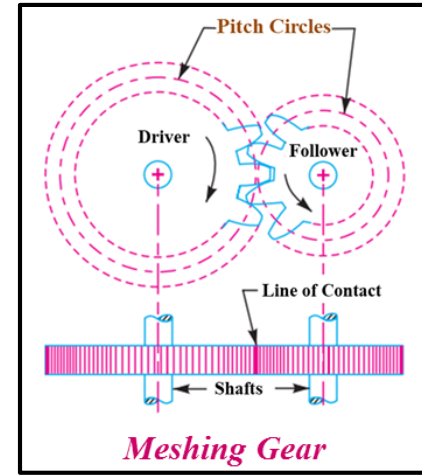
- It is the diameter of the pitch circle.
- The size of the gear is specified by the pitch circle diameter.

❑ Pitch Point:

- It is a common point of contact between two pitch circles.

❑ Pressure Angle or Angle of Obliquity:

- It is the angle between the common normal to two gear teeth at the point of contact and the common tangent at the pitch point.
- It is usually denoted by ϕ . The standard pressure angles are $14\frac{1}{2}^\circ$ and 20° .



❑ Addendum:

- It is the radial distance of a tooth from the pitch circle to the top of the tooth.

❑ Dedendum:

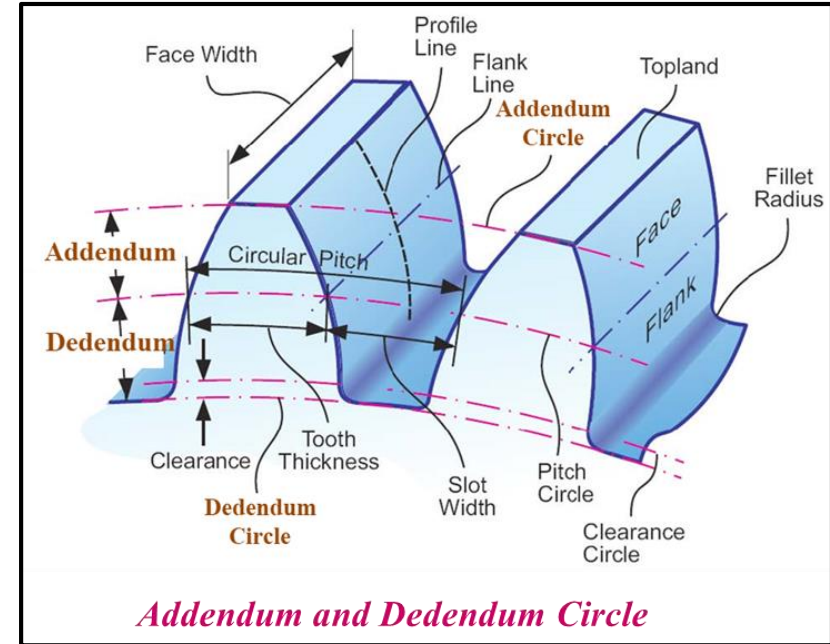
- It is the radial distance of a tooth from the pitch circle to the bottom of the tooth.

❑ Addendum Circle:

- It is the circle drawn through the top of the teeth and is concentric with the pitch circle.

❑ Dedendum Circle or Root Circle:

- It is the circle drawn through the bottom of the teeth.



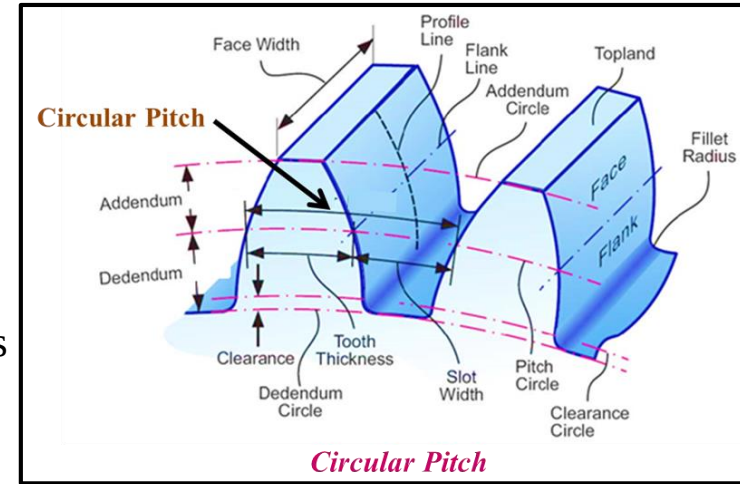
□ Circular Pitch (p_c):

- It is the distance measured on the circumference of the pitch circle from a point of one tooth to the corresponding point on the next tooth.
- It is usually denoted by p_c .

$$\text{Circular Pitch} = p_c = \pi D / T$$

Where, D = Diameter of the pitch circle, and
 T = Number of teeth on the wheel.

- Two gears will mesh together correctly, if the two wheels have the same circular pitch.



□ Diametral Pitch (p_d):

- It is the ratio of number of teeth to the pitch circle diameter in millimetres.

$$\text{Diametral Pitch, } p_d = \frac{T}{D} = \frac{\pi}{p_c}$$

Where, D = Diameter of the pitch circle, and
 T = Number of teeth on the wheel.

❑ Module (m):

- It is the ratio of the pitch circle diameter in millimetres to the number of teeth.

$$m = D/T$$

❑ Clearance:

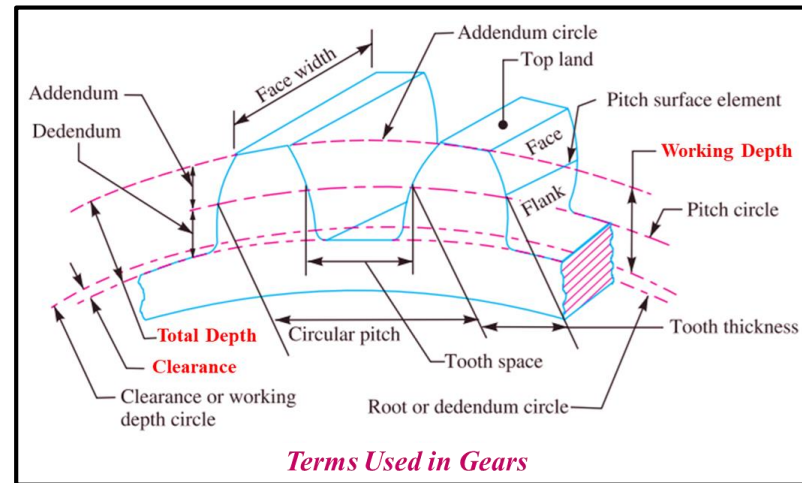
- It is the radial distance from the top of the tooth to the bottom of the tooth, in a meshing gear.
- A circle passing through the top of the meshing gear is known as clearance circle.

❑ Total Depth:

- It is the radial distance between the addendum and the dedendum circle of a gear.
- It is equal to the sum of the addendum and dedendum.

❑ Working Depth:

- It is radial distance from the addendum circle to the clearance circle.
- It is equal to the sum of the addendum of the two meshing gears.



❑ **Tooth Thickness:**

- It is the width of the tooth measured along the pitch circle.

❑ **Tooth Space:**

- It is the width of space between the two adjacent teeth measured along the pitch circle.

❑ **Backlash:**

- It is the difference between the tooth space and the tooth thickness, as measured on the pitch circle.

❑ **Face of the Tooth:**

- It is surface of the tooth above the pitch surface.

❑ **Top Land:**

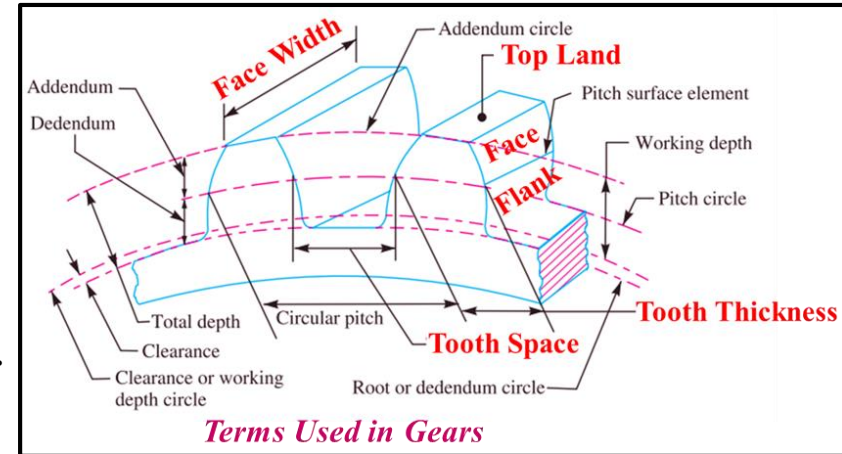
- It is the surface of the top of the tooth.

❑ **Flank of the Tooth:**

- It is the surface of the tooth below the pitch surface.

❑ **Face Width:**

- It is the width of the gear tooth measured parallel to its axis.

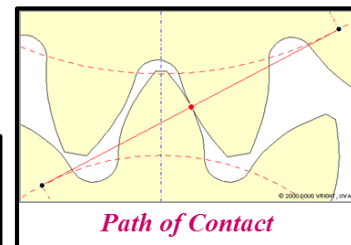
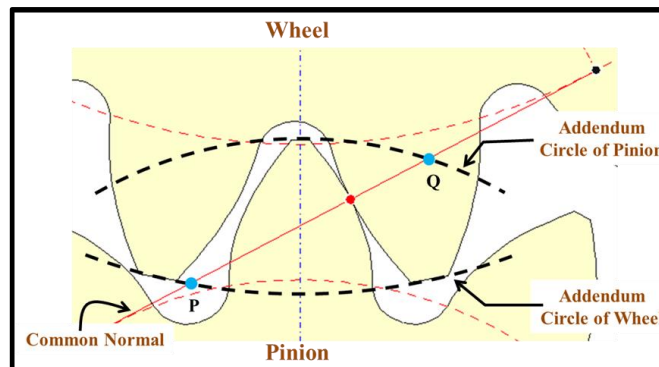


□ Path of Contact:

- It is the path traced by the point of contact of two teeth from the beginning to the end of engagement.

□ Length of the Path of Contact:

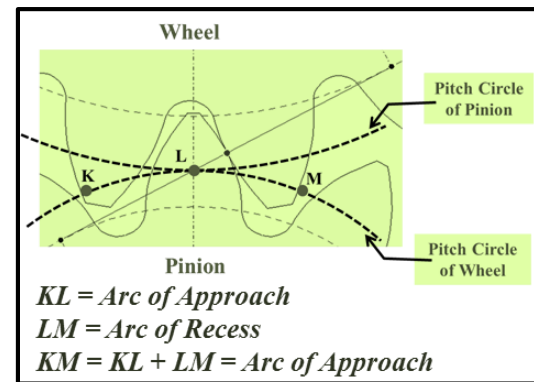
- It is the length of the common normal cut-off by the addendum circles of the wheel and pinion.



PQ = Length of Path of Contact

□ Arc of Contact:

- It is the path traced by a point on the pitch circle from the beginning to the end of engagement of a given pair of teeth.
- The arc of contact consists of two parts, i.e.
 - ❖ **Arc of Approach:** It is the portion of the path of contact from the beginning of the engagement to the pitch point.
 - ❖ **Arc of Recess:** It is the portion of the path of contact from the pitch point to the end of the engagement of a pair of teeth.



$KL = \text{Arc of Approach}$

$LM = \text{Arc of Recess}$

$KM = KL + LM = \text{Arc of Approach}$

Forms of Teeth:

- There are mainly two types of profiles are used in manufacturing of gear teeth. They are:

Involute Profile

Cycloidal Profile

□ Involute Profile:

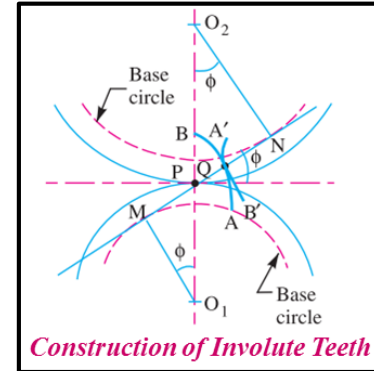
- ✓ Involute is defined as the locus of a point on a straight line which rolls around a circle (base circle) without slipping.
- ✓ In an involute gear, the profiles of the teeth are involutes of a circle.

□ Cycloidal Profile:

- ✓ It is the curve traced by a point on the circumference of the circle which rolls without slipping on a fixed straight line.
- ✓ Cycloid gear tooth profile is based on the epicycloid and hypocycloid curves, which are the curves generated by a circle rolling around the outside and inside of another circle, respectively.

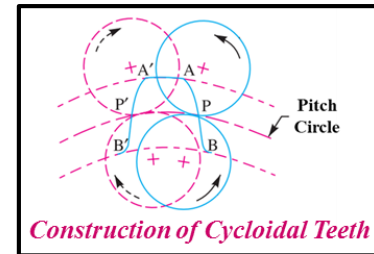


Involute of a Circle



Construction of Involute Teeth

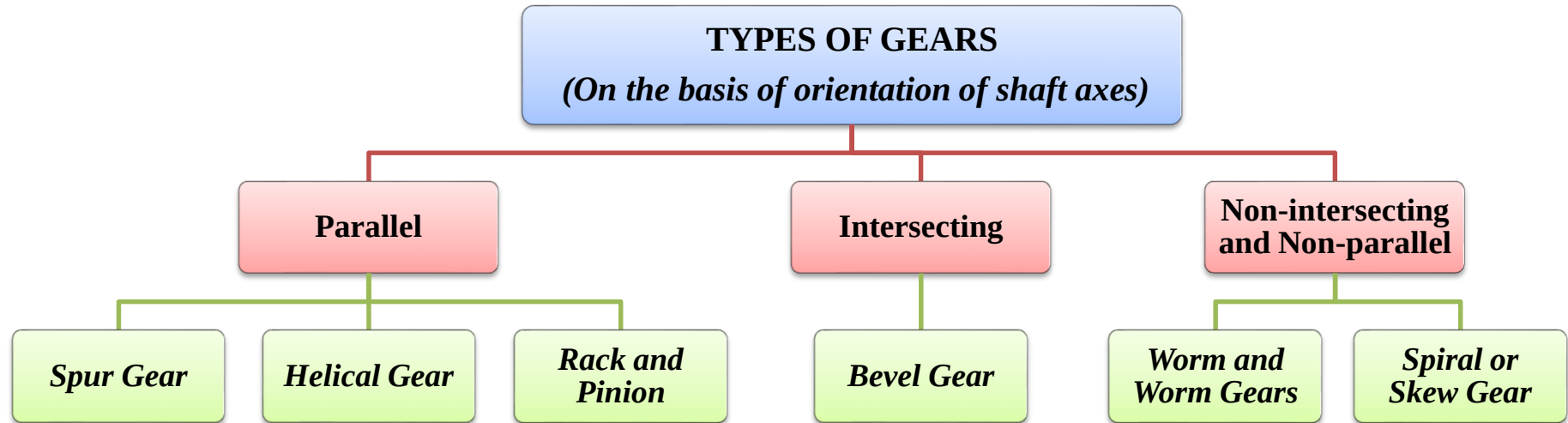
Cycloid



Construction of Cycloidal Teeth

Classification of Gears:

- Gears are commonly classified according to the position of the axes of the shafts between which the motion is to be transmitted.



Spur Gear:

- If the teeth of gear wheels are parallel to the axis of wheel, the gears are called spur gear.
- They transmit power from one shaft to another parallel shaft.



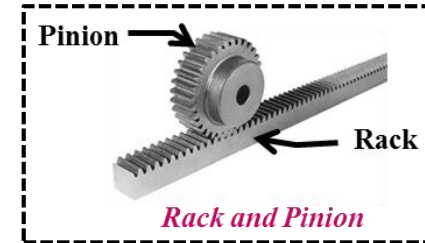
Helical Gear:

- In helical gears, the teeth are inclined to the axis of wheel.
- Their gradual engagement makes them operate much smoothly and quietly than spur gears.



Rack and Pinion:

- It is a special case of spur gear in which one gear is having infinite diameter called rack.
- They are used to convert rotation into linear motion.



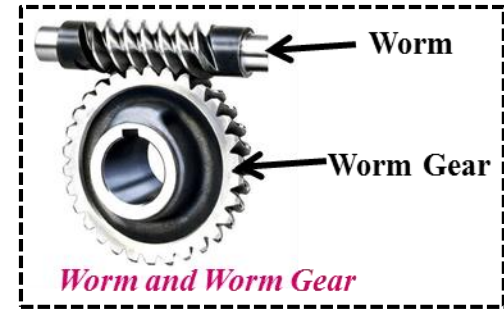
Bevel Gear:

- Teeth of bevel gear are cut on conical surfaces.
- They are useful when direction of the shaft's rotation needs to be changed.
- Bevel gears are generally used to transmit power at perpendicular direction.



Worm and Worm Gear:

- It is a gear arrangement also known as worm drive, in which a worm meshes with a worm gear.
- They are used when large gear reductions are needed.



Spiral or Skew Gear:

- Spiral gears are also known as crossed helical gears.
- They have high helix angle and transmit power between two non-intersecting non-parallel shafts.



Measurement of Gears:

- The Inspection of the gears consists of determining dimensional accuracy during manufacturing using following methods:

- ❖ General Tests:

- ☐ Gear Profile Inspection
 - a) Involute Measuring Machine
- ☐ Rolling Gear Test (Parkinson Gear Tester)

- ❖ Measurement of Individual Elements:

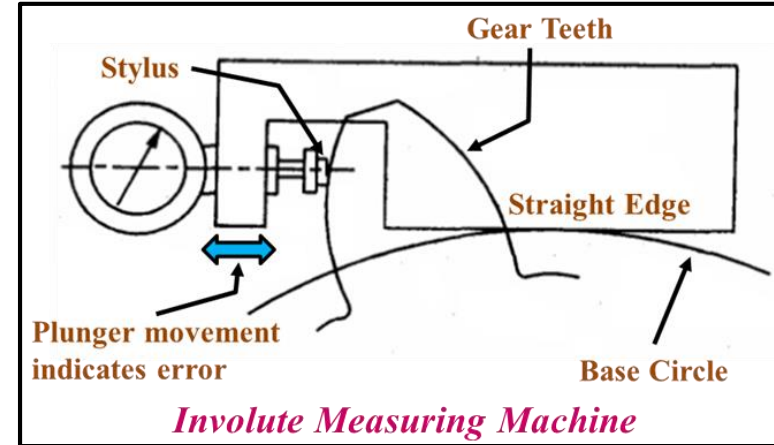
- ☐ Measurement of Gear Tooth Thickness
 - a) Gear Tooth Vernier Method
 - b) Constant Chord Method
 - c) Base Tangent Method
- ☐ Measurement of Pitch Diameter and Tooth Spacing
- ☐ Measurement of Gear Pitch



❖ General Tests:

❑ *Involute Measuring Machine:*

- In this method the gear is held on a mandrel and circular disc of same diameter as the base circle of gear for the measurement is fixed on the mandrel.
- After fixing the gear in the mandrel, the straight edge of the instrument is brought in contact with the base circle of the disc.
- Now, the gear and disc are rotated and the edge moves over the disc without slip.
- The stylus moves over the tooth profile and the error is indicated on the dial gauge.

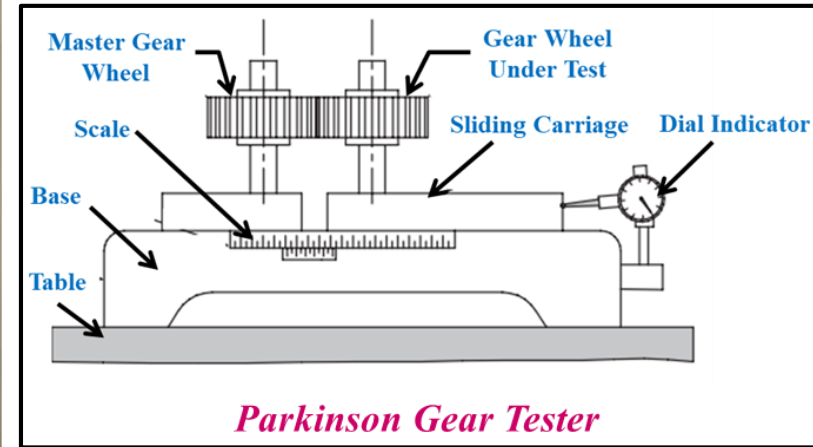


❑ Rolling Gear Test:

- It is a popular gear testing machine used in metrology laboratories and tool rooms.
- The gear being inspected will be made to mesh with a standard gear (master gear), and a dial indicator is used to capture radial errors.
- This test is generally performed on a most commonly used machine Parkinson Gear Tester.

Working:

- This test is used to detect any errors in
 - ✓ Tooth form
 - ✓ Pitch
 - ✓ Concentricity of pitch line
- When two gears are in mesh with each other, then any of the above errors will cause the variation of centre distance.
- Radial variations of the gear being inspected are indicated by the dial indicator.
- This variation is plotted on a chart or graph sheet, which indicates the radial variations in the gear for one complete rotation.

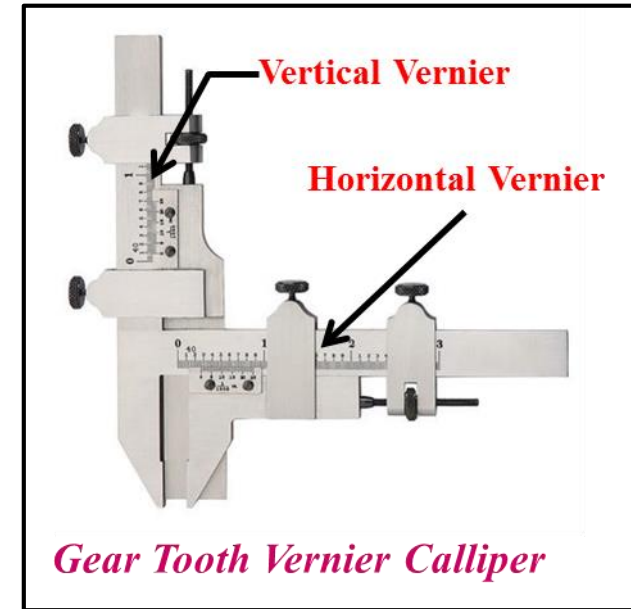


❖ Measurement of Individual Elements:

❑ Measurement of Gear Tooth Thickness:

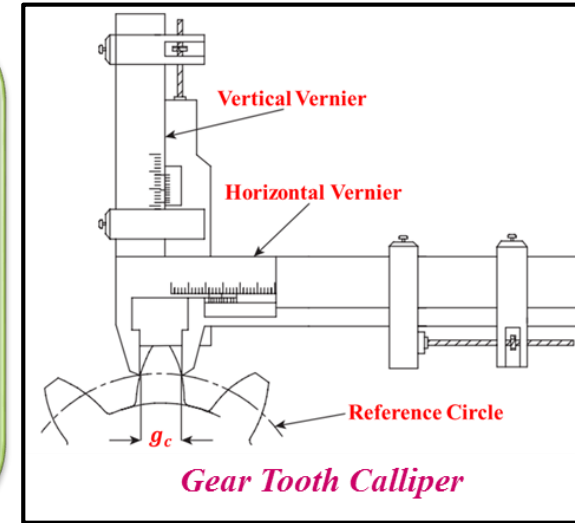
a) Gear Tooth Vernier Method:

- This method uses gear calliper to measure gear tooth thickness.
- Gear Calliper has two vernier scales, one horizontal and the other vertical.
- Horizontal vernier scale reading gives chordal thickness (g_c) and vertical vernier gives the chordal addendum (h_c) by measuring position of a blade, which can slide up and down.



Working:

- First, the blade position is set to a value equal to the addendum of the gear and locked into position with a locking screw.
- The calliper is set on the gear in such a manner that the blade surface snugly fits with the top surface of a gear tooth.
- The two anvils are brought into close contact with the gear, and the chordal thickness (g_c) is noted down on the horizontal vernier scale
- The theoretical value of g_c can be found out by considering one tooth in the gear and it can be verified.



Theoretically,

$$g_c = mz \sin(90^\circ/z)$$

$$h_c = \frac{mz}{2} \left(1 + \frac{2}{z} - \cos(90^\circ/z) \right)$$

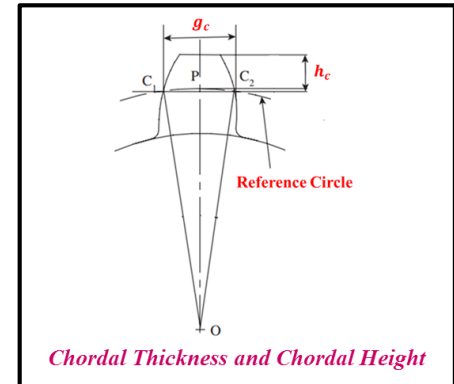
Where,

g_c = Chordal thickness of gear tooth along pitch circle

h_c = Chordal height

m = Module

z = Number of teeth on the gear



b) Constant Chord Method:

- This method of checking gear tooth thickness measures the tooth width at the points of contact of a symmetrically placed close meshed rack.
- The length of chord AB is constant for all gears of the same module and pressure angle irrespective of the number of teeth.
- A single calculation and comparator setting will suffice when checking a set of meshing gears with different numbers of teeth.
- It is an efficient method for measuring a large number of gears, each having different number of teeth but the same module.

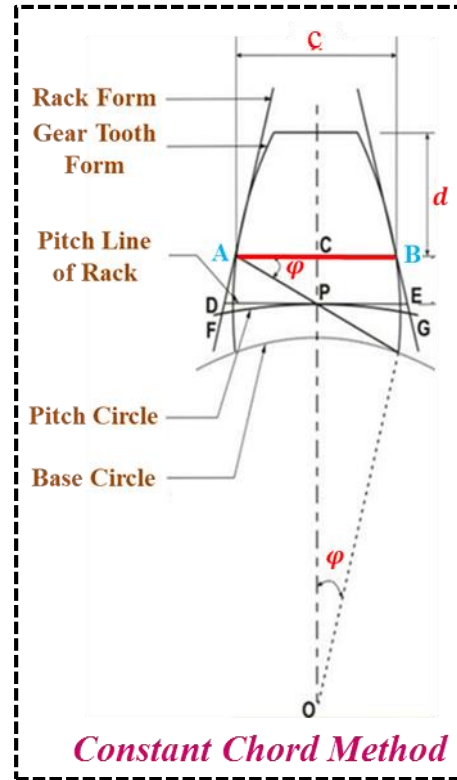
Length of constant chord AB is given by:

$$c = AB = \frac{\pi}{2} m (\cos^2 \varphi)$$

Chordal height is given by:

$$d = m \left[1 - \frac{\pi}{4} \cos \varphi \sin \varphi \right]$$

Where, m = module, and
 φ = pressure angle of the gear



Constant Chord Method

c) Base Tangent Method:

- In this case, tooth thickness is measured by measuring the chordal distance over a number of teeth by using a tooth span micrometer, also called a flange micrometer.
- The base tangent length is the distance between the two parallel planes which are tangential to the opposing tooth flanks.

Base tangent length (span width) across s number of teeth for a involute gear is given by:

$$W_s = mz \cos \varphi \left[\tan \varphi - \varphi + \frac{\pi}{2z} + \frac{\pi S}{2z} \right]$$

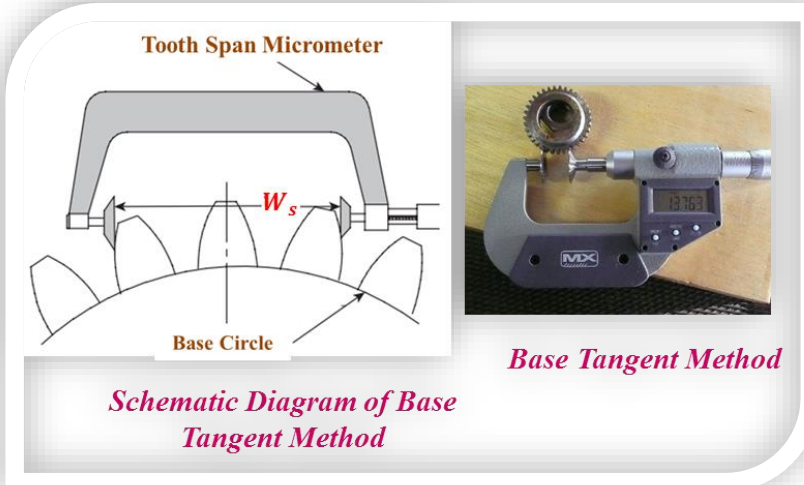
Where,

m = module,

z = no. of teeth,

φ = pressure angle,

S = no. of tooth spaces in W_s



Tables for the span width for given values of module, number of teeth and pressure angle are used for faster inspection.

❑ Measurement of Pitch Diameter:

- Pitch circle diameter and tooth spacing of a gear is measured by checked by inserting cylinders (plugs) in the tooth spaces so that their axes lie on the pitch circle.
- The cylinder (plug) diameter can be found by considering a rack in mesh with the gear.

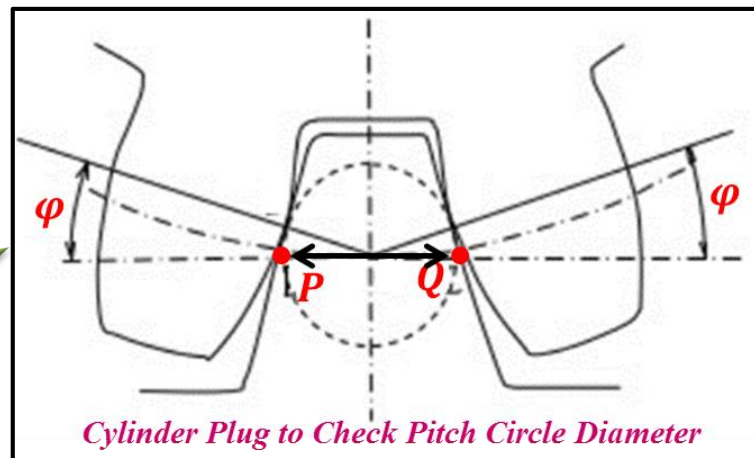
❖ Cylinder plug diameter is given by:

$$PQ = \frac{\pi m}{2} \cos \varphi$$

Where,

m = module

φ = pressure angle

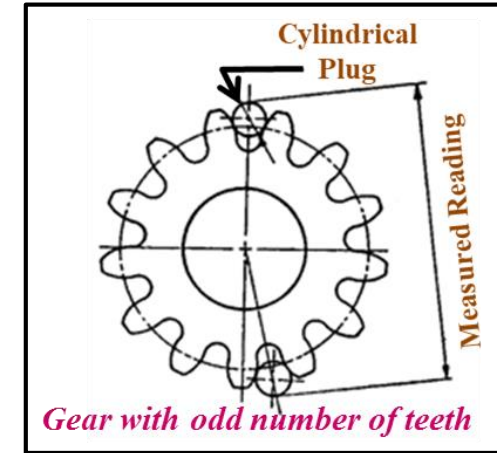
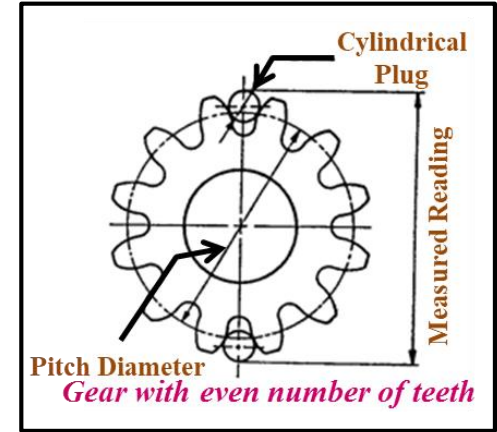


Note:

- ✓ The plug size remains the same for all gears having the same pitch and pressure angle.
- ✓ A correction will again have to be made in this plug size for backlash.

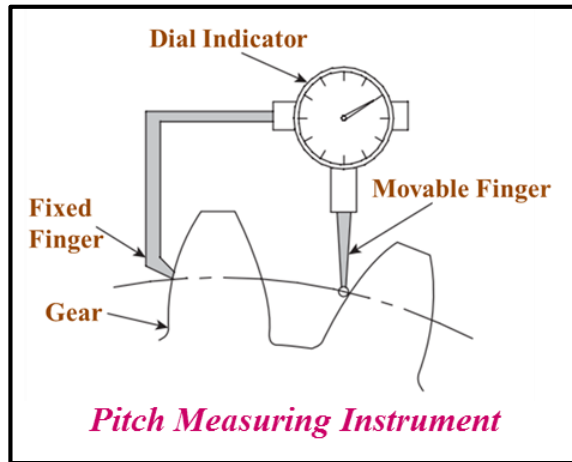
Working:

- ❖ If a gear has an even number of teeth:
 - Cylinders can be placed in diametrically opposite tooth spaces and a measurement taken over them.
 - The pitch diameter is obtained by subtracting one cylinder diameter from this measurement.
- ❖ If a gear has an odd number of teeth:
 - Gears with an odd number of teeth can also be checked for pitch diameter by the two-cylinder method.
 - In this method, a calculation is needed to find the pitch diameter.



❑ Measurement of Gear Pitch:

- Pitch is the distance between corresponding points on equally spaced and adjacent teeth.
- The two types of instruments that are usually employed for checking pitch are:
 - i. Pitch-measuring Instrument
 - ii. Pitch-checking Instrument



i. Pitch-measuring Instrument:

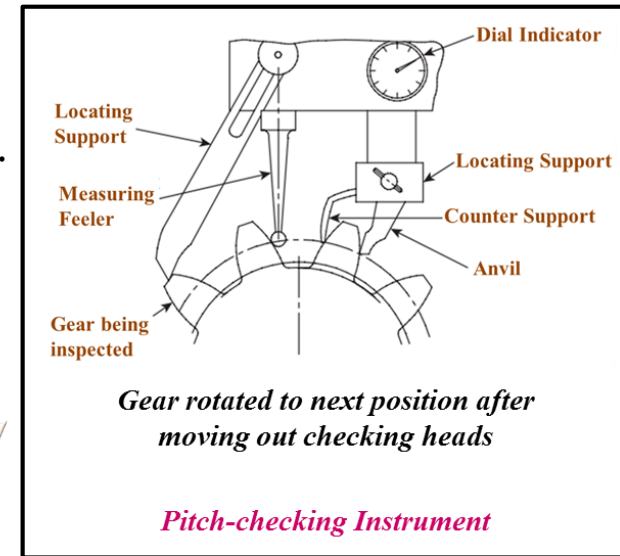
- ✓ These instruments enable the measurement of chordal pitch between successive pairs of teeth.
- ✓ The instrument comprises a fixed finger and a movable finger, which can be set to two identical points on adjacent teeth along the pitch circle.
- ✓ The pitch variation is displayed on a dial indicator attached to the instrument.

ii. Pitch-checking Instrument:

- ✓ A pitch-checking instrument is essentially a dividing head that can be used to measure pitch variations.
- ✓ The instrument can be used for checking small as well as large gears due to its portability.
- ✓ It has two probes:
 - a. Anvil (fixed)
 - b. Measuring feeler (movable)
- ✓ Measuring feeler is connected to a dial indicator through levers.

Working:

- The instrument is located by two adjacent supports resting on the crests of the teeth.
- A tooth flank is butted against the fixed anvil and locating supports.
- The measuring feeler senses the corresponding next flank.
- The instrument is used as a comparator from which we can calculate the adjacent pitch error, actual pitch, and accumulated pitch error.



Summary:

- Gears are the main elements in a transmission system.
- For efficient transfer of speed and power, gears should conform perfectly to the designed profile and dimensions.
- During manufacturing the gears are inspected to ensure high degree of accuracy using different methods.
- All methods comprising general testing methods and measurement of different elements of gears are discussed.

THANK YOU





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INSPECTION & QUALITY CONTROL IN MANUFACTURING

Lecture 20: Miscellaneous Measurements



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Joint faculty: Centre of Nanotechnology



Introduction:

- Miscellaneous metrology includes certain instruments, measuring machines, and techniques, which are difficult to label under earlier discussed headings.
- It is an interesting mix of various topics that are essential in a modern manufacturing system.
- It also deals with the standard procedure for ensuring accuracy and precision of manufacture by carrying out acceptance test on machine tools.
- Some of the most commonly used miscellaneous measurement techniques are:
 1. *Laser-based Instrumentation*
 2. *Coordinate Measuring Machines*
 3. *Automated Inspection*
 4. *Machine Vision*



1. Laser-based Instrumentation:

- These techniques are increasingly being used in applications like machine tool assembly to ensure perfect alignment of machine parts.
- Traditionally, lasers were more used by physicists than engineers, since the frequencies of lasers were not stable enough.
- **LASER (Light Amplification by Stimulated Emission of Radiation)** is an intense emergent beam of light that can be parallel to a high degree or can be focused onto a very small area.
- Although a number of materials may be used to produce lasers, helium-neon gas laser is the most popular for applications in metrology.



Properties of LASER:

- For the purpose of measurement, laser has some additional properties that are not possessed by ordinary light:

❖ Monochromatic:

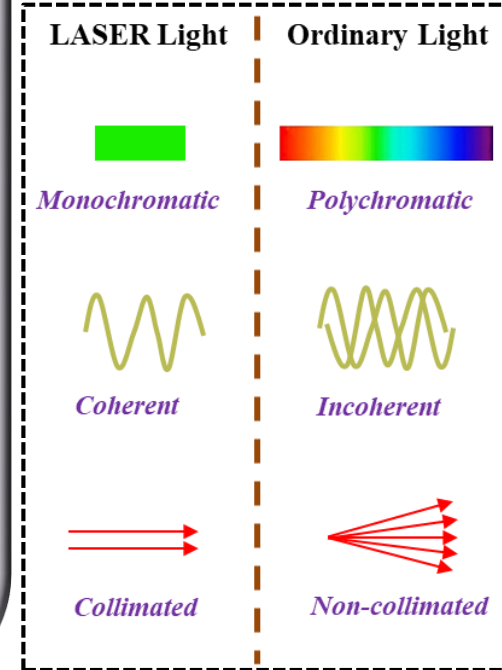
- ✓ Laser light is monochromatic.
- ✓ It has bandwidth in the range of $0.4 - 0.5 \mu m$.
- ✓ Stabilised lasers have still narrower bandwidths, with the result that very high resolution can be achieved during measurement.

❖ Coherent:

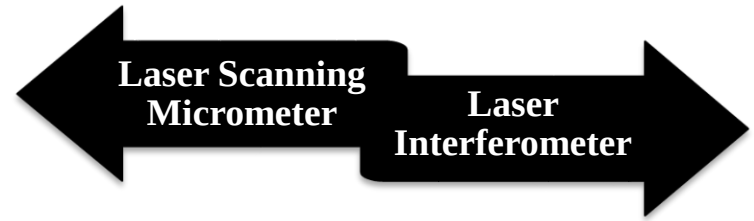
- ✓ In normal light, the rays are randomly phased, resulting in partial interference within the beam.
- ✓ In contrast, laser rays are all in phase, producing a coherent beam of light.

❖ Collimated:

- ✓ The rays in a laser beam are perfectly parallel with little divergence and scatter.



Instrumentation Based on Laser Principles:

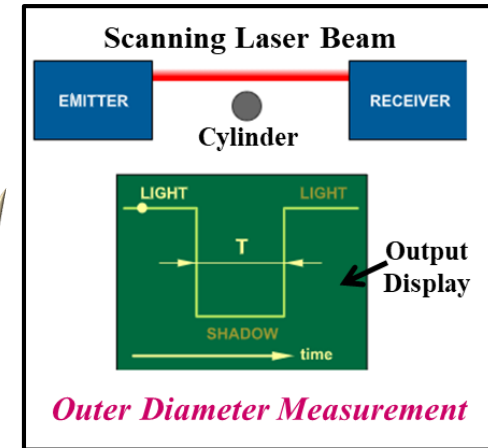


a) Laser Scanning Micrometer:

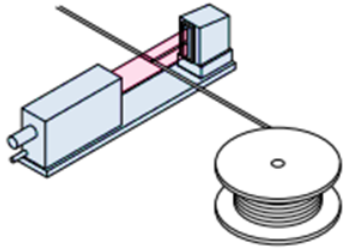
- It features a high scanning rate which allows inspection of small workpiece even if they are fragile, at high temperature, in motion or vibrating.

Working:

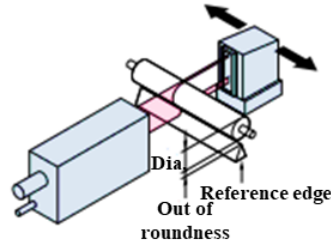
- ✓ A transmitting unit emits a laser beam that scans at a very high and known speed across the measuring range.
- ✓ Every object placed in the measuring field interrupts the laser beam and casts its shadow into the receiver.
- ✓ By measuring the shadow time, the outside diameter of the part can be exactly computed.
- ✓ In addition to the diameter measurement, by checking other combinations of light / shadow segments, it is possible to measure any other dimension related to the shadow cast by the part.



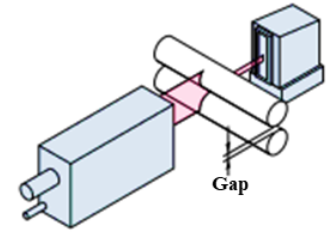
Applications:



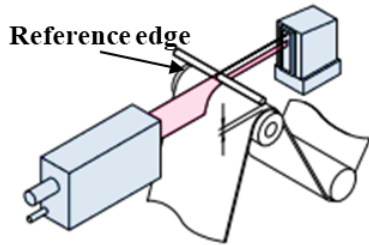
In-line glass fiber or fine wire diameter



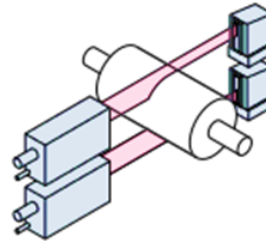
Outer dia. and roundness of cylinders



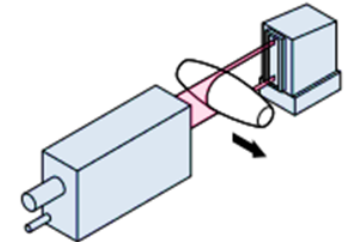
Gap between rollers



Thickness of film and sheet



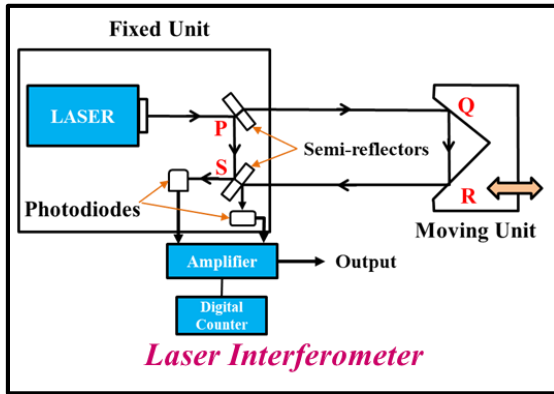
Dual system for measuring a large outside diameter



Taper and form measurements

b) Laser Interferometer:

- In recent times, laser-based interferometers are becoming increasingly popular in metrology applications.
- The fixed unit called the laser head consists of laser, a pair of semi-reflectors, and two photodiodes.
- The sliding unit has a corner cube mounted on it.

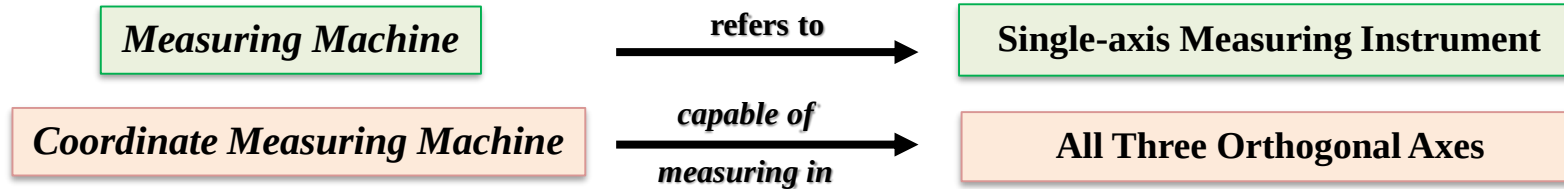


Working:

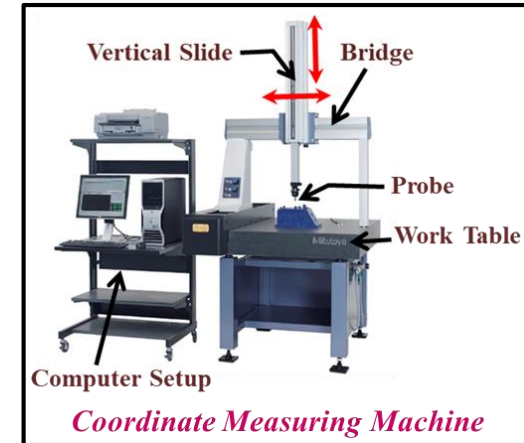
- ✓ Laser light first falls on the semi-reflector P, is partially reflected by 90° and falls on the other reflector S.
- ✓ A portion of light passes through P and strikes the corner cube.
- ✓ Light is turned through 180° by the corner cube and recombines at the semi-reflector S.
- ✓ Now, if $PQRS - PS = \text{odd number} \times (\lambda/2)$ [Destructive Interference]
 $PQRS - PS = \text{even number} \times (\lambda/2)$ [Constructive Interference]

- ✓ Each time the moving slide is displaced by a quarter wavelength, the path difference (i.e., $PQRS - PS$) becomes half a wavelength and the output from the photodiode also changes from maximum to minimum or vice versa.
- ✓ This sinusoidal output from the photodiode is amplified and fed to a high-speed counter, which is calibrated to give the displacement in terms of millimetres.

2. Coordinate Measuring Machines (CMM):



- A CMM enables the location of a point coordinates in a three-dimensional (3D) space.
- It simultaneously captures both dimensions and orthogonal relationships.
- Another remarkable feature of a CMM is its integration with a computer.
- The computer provides additional power to generate 3D objects as well as to carry out complex mathematical calculations.
- Complex objects can be dimensionally evaluated with precision and speed.



Comparison between Conventional and Coordinate Measuring Technology:

- A comparison of coordinate metrology with conventional metrology shows the important advantages of CMMs.

Conventional Metrology

- Manual, time-consuming alignment of the test piece
- Single-purpose and multi-point measuring instruments making it hard to adapt to changing measuring tasks
- Comparison of measurements with material measures, i.e. gauge blocks or kinematic standards
- Separate determination of size, form, location and orientation with different machines

Coordinate Metrology

- Alignment of the test piece not necessary
- Simple adaptation to the measuring tasks by software
- Comparison of measurements with mathematical or numerical models
- Determination of size, form, location and orientation in one setup using one reference system

When to use CMM?

Multiple Features:

- More the number of features (both dimensional and geometric) can be controlled.

Flexibility:

- No additional accessories (such as jigs and fixtures) needed.

Automated Inspection:

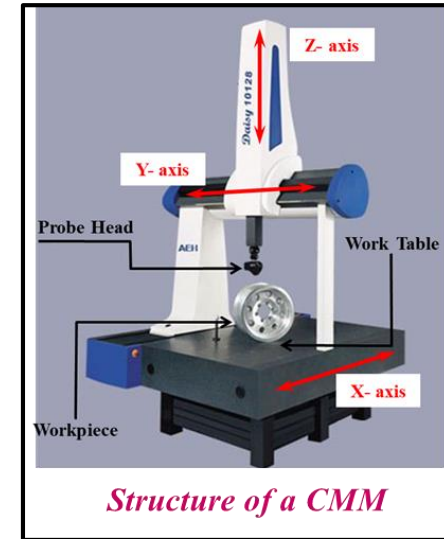
- Inspection can be done in fully automated environment.

High Unit Cost:

- If rework or scrapping is costly.

Structure of CMM:

- ✓ The basic version of a CMM has three axes, along three mutually perpendicular directions.
- ✓ A carriage is provided for each axis, which is driven by a separate motor.
- ✓ The three carriages of a CMM form a Cartesian reference coordinate system.
- ✓ The work volume is cuboidal.
- ✓ Each axis is fitted with a precision measuring system, which continuously records the displacement of the carriage from a fixed reference.
- ✓ The third axis carries a probe.
- ✓ When the probe makes contact with the workpiece, the computer captures the displacement of all the three axes.

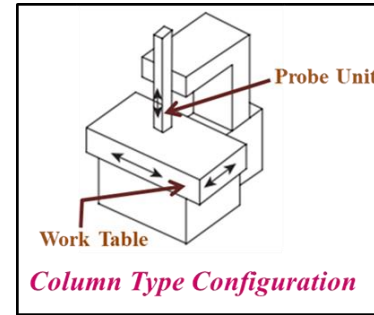
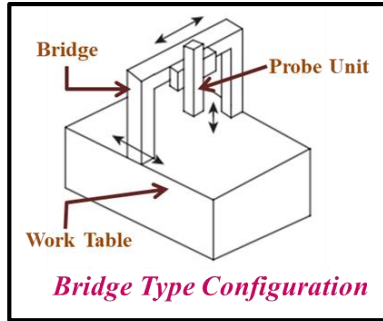


Basic CMM Configurations:

- Configurations of CMMs play an important role in meeting measurement requirements like accuracy, flexibility, time (throughput) and cost.
- Depending on the geometry of the workpiece being measured, they are categorized into five popular physical configurations:
 - i. *Bridge*
 - ii. *Column*
 - iii. *Cantilever*
 - iv. *Horizontal Arm*
 - v. *Gantry*

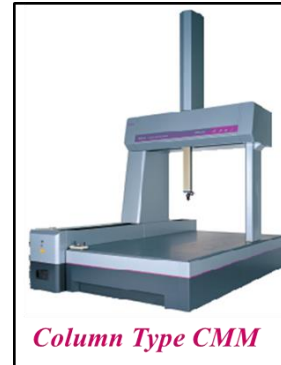
i. Bridge:

- A bridge-type configuration is a good choice if better rigidity in the structure is required.
- The probe unit is mounted on a horizontal moving bridge, whose supports rest on the machine table.



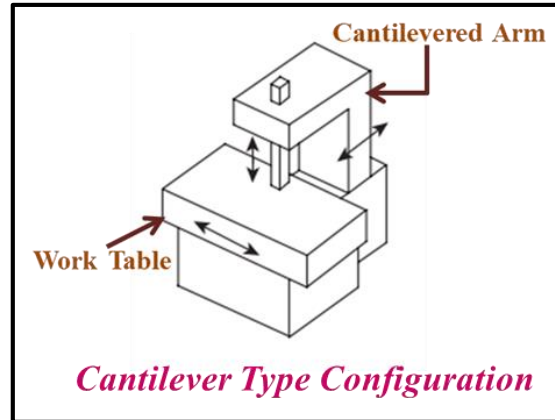
ii. Column:

- This configuration provides exceptional rigidity and accuracy.
- It is quite similar in construction to a jig boring machine.
- Machines with such a configuration are often referred to as universal measuring machines.



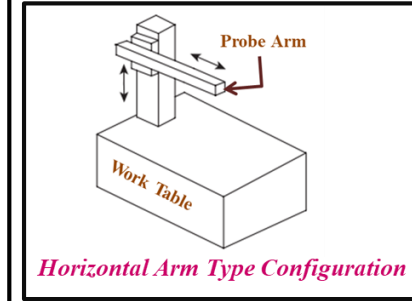
iii. Cantilever:

- The vertically positioned probe is carried by a cantilevered arm.
- The probe moves up and down along the Z-axis, whereas the cantilever arm moves in and out along the Y-axis (lateral movement).
- The longitudinal movement is provided by the X-axis, which is basically the work table.
- This configuration provides easy access to the workpiece and a relatively large work volume for a small floor space.



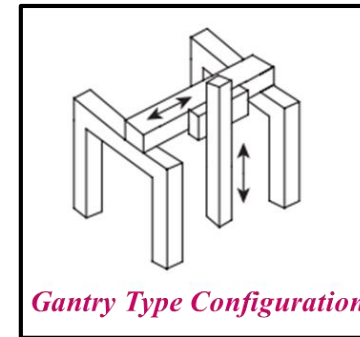
iv. Horizontal Arm:

- In this type of configuration, the probe is carried by the horizontal axis.
- The probe assembly can also move up and down along a vertical axis.
- It can be used for gauging larger work pieces since it has a large work volume.



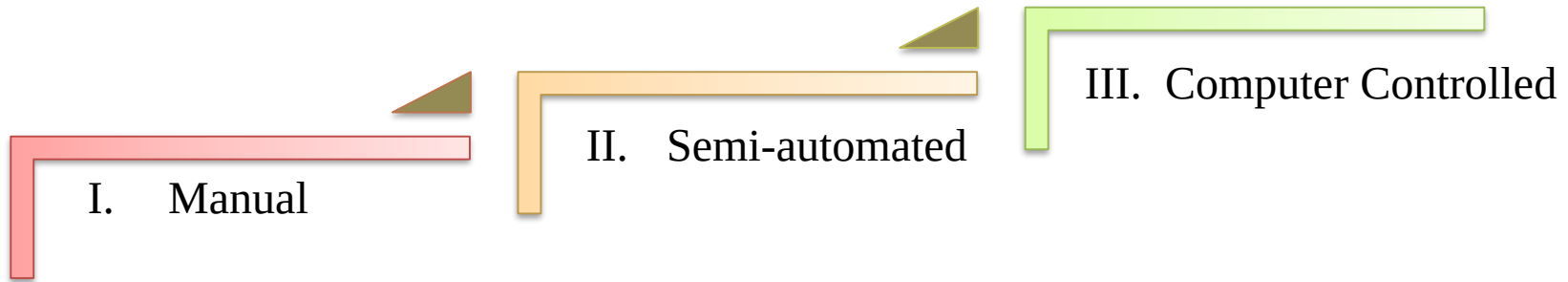
v. Gantry:

- In this configuration, the support of the workpiece is independent of the X- and Y-axis.
- Both these axes are overhead and supported by four vertical columns from the floor.
- The operator can walk along with the probe, which is desirable for large work pieces.



Modes of Operation:

- Modes of operation are quite varied in terms of type of construction and degree of automation.
- CMMs can be classified into the following three types based on their modes of operation:



I. Manual:

- The manual CMM has a free-floating probe that the operator moves along the machine's three axes to establish contact with part features.
- The differences in the contact positions are the measurements.

II. Semi-automated:

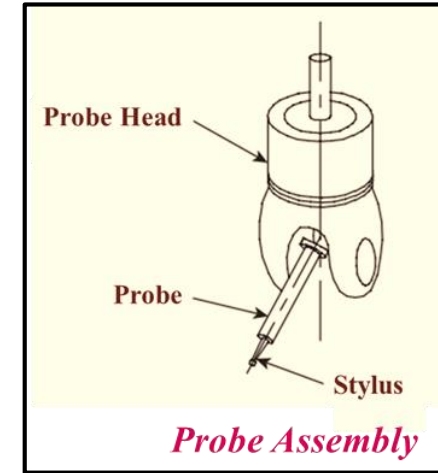
- A semi-automatic machine is provided with an electronic digital display for measurement.
- Many functions such as setting the datum, change of sign, and conversion of dimensions from one unit to another are done electronically.

III. Computer Controlled:

- A computer-controlled CMM has an on-board computer, which increases versatility, convenience, and reliability.
- Such machines are quite similar to CNC machines in their control and operation.
- Computer assistance is utilized for three major functions:
 - i. *A programming software directs the probe to the data collection points.*
 - ii. *Measurement commands enable comparison of the distance traversed to the standard built into the machine for that axis.*
 - iii. *Computational capability enables processing of the data and generation of the required results.*

Probe:

- The probe is the main sensing element in a CMM.
- Various types of probes are used in CMMs, including mechanical, optical, laser, and white light.
- These probes can be categorized as:
 - ✓ *Contact Type*
 - ✓ *Non-contact Type*



Contact Type:

- These probes are in physical contact with the workpiece when the measurements are taken.
- Contact probes may be either 'hard' probes or 'soft' probes.

Non-contact Type:

- Most non-contact probes employ a light beam stylus.
- The distance from the point of measurement is known as standoff and is normally 50 mm.

Operation of CMMs:

- A modern CMM is very similar in operation to a computer numerical control (CNC) machine, because both control and measurement cycles are under the control of the computer.
- The software providing functional features comprises the following three components:
 - a. Move* commands (which direct the probe to the data collection points).
 - b. Measurement* commands (which result in the comparison of the distance traversed to the standard built into the machine for that axis).
 - c. Formatting* commands (which translate the data into the form desired for display or printout).
- Machine is programmed using readily available subroutines, mathematical operations and library programs already stored in its memory.

Major Applications:

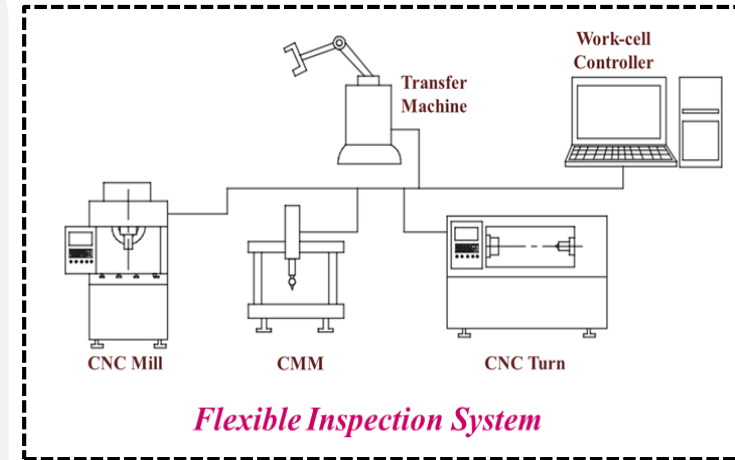
- ✓ A CMM can easily be integrated into an automated inspection system.
- ✓ A CMM may be interfaced with a CNC machine so that machining is corrected as the workpiece is inspected.
- ✓ *Reverse Engineering*: A complete 3D geometric model with all critical dimensions can be built where such models do not exist.

3. Automated Inspection:

- Automated inspection, in a general sense, means automation of one or more steps involved in the inspection procedure.
- The example of a manufacturing system with automated inspection is flexible inspection system.

Flexible Inspection System:

- ✓ This system is formed by integrating production and inspection equipment into fully automated systems (FMS or CIM) to achieve high production rate as well as to improve productivity.
- ✓ A typical FIS comprises one or more CNC machines, a transfer machine (a robotic handling system), and a CMM.
- ✓ The controller continuously monitors the function of the CNC machine and, directs the transfer machine to shift the work part to the CMM to carry out on-line/post-process inspection.



4. Machine Vision (MV):

- Machine vision is the technology and methods used to provide imaging-based automatic inspection and analysis in industry.
- It extracts information from an image on an automated basis.
- The information extracted can be a simple data (good-part/bad-part signal) or complex set of data (identity, position and orientation of each object in an image).

Stages of Machine Vision:

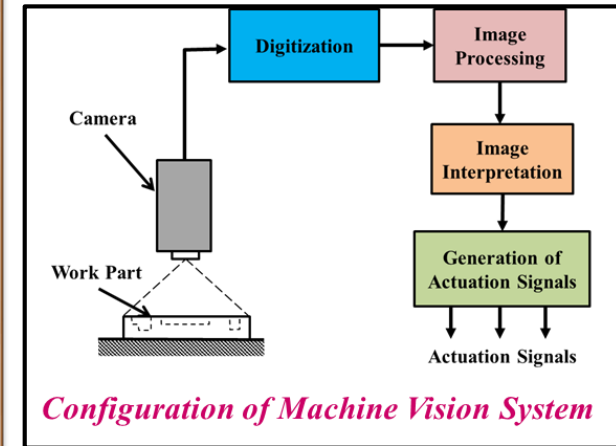
- ✓ The principal applications in inspection include dimensional gauging, measurement, and verification of the presence of components.
- ✓ The operation of a machine vision system involves the following four important stages:

I. Image generation and digitization

II. Image processing and analysis

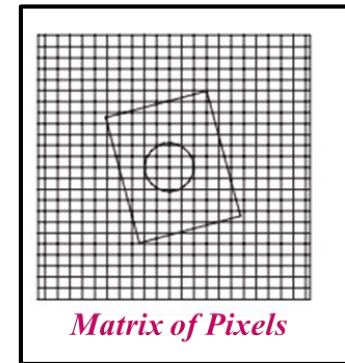
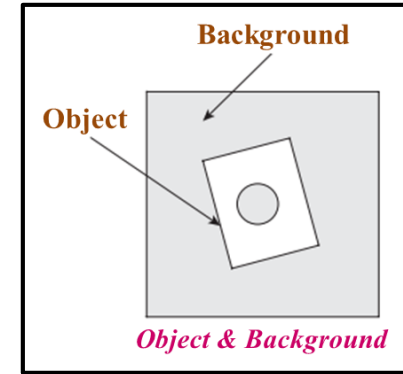
III. Image interpretation

IV. Generation of actuation signals



I. Image Generation and Digitization:

- The primary task in a vision system is to capture a 2D or 3D image of the work part.
- A 2D image captures either the top view or a side elevation of the work part.
- The work part is placed on a flat surface and illuminated by suitable lighting, which provides good contrast between the object and the background.
- The camera is focused on the work part and a sharp image is obtained.
- The image comprises a matrix of discrete picture elements popularly referred to as pixels.
- Each pixel has a value that is proportional to the light intensity of that portion of the scene.
- The intensity value for each pixel is converted to its equivalent digital value by an analog-to-digital converter.
- This digitized frame of the image is referred to as the *frame buffer*.



II. Image Processing and Analysis:

❖ Pre-treatment:

- Information available in the frame buffer is refined and processed to facilitate further analysis; e.g. noise removal, contrast enhancing.

❖ Segmentation:

- It involves two stages:
 - **Thresholding:**
 - ✓ **Binary Vision System-** (Converts each pixel value into white or black, depending on a given threshold value)
 - ✓ **Grey-scale System-** (Stores different shades of grey/colour information of each pixel)
 - **Edge Detection:**
 - ✓ To distinguish the image of the object from its surroundings.

❖ Feature Extraction:

- Size: length, width, area, and perimeter
- Shape: size dependent/independent
- Colour: mean and variance
- A combination of them

III. Image Interpretation:

❖ Template Matching and Pattern Recognition:

- Computer program has to match the extracted features with the features of templates already stored in the memory.
- This matching task is popularly referred to as template matching.
- Whenever a match occurs, an object can be identified and further analysis can be carried out.
- The interpretation function that is used to recognize the object is known as pattern recognition.

❖ Feature Weighting:

- In order to eliminate the possibility of wrong identification when two objects have closely resembling features, feature weighting is used.
- In this technique, several features are combined into a single measure by assigning a weight to each feature according to its relative importance in identifying the object.

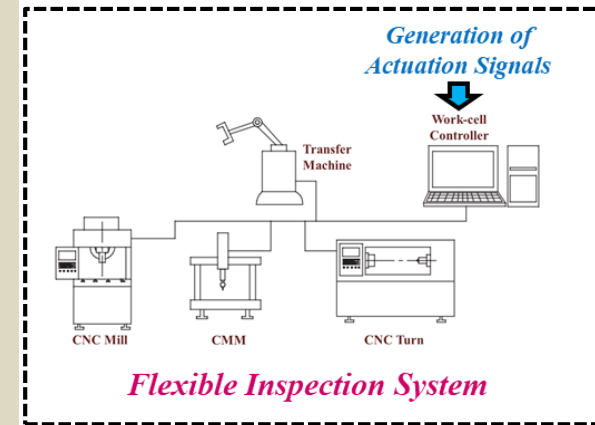
IV. Generation of Actuation Signals:

- Once the object is identified, the vision system should direct the inspection station to carry out the necessary action.

Example:

In a flexible inspection environment,

- The work-cell controller generates the actuation signals to the transfer machine to transfer the work part from machining stations to the inspection station and vice versa.
- Clamping, declamping, gripping, etc., of the work parts are done through actuation signals generated by the work-cell controller.



Applications of Machine Vision in Inspection:



a) Dimensional Gauging and Measurement

b) Identification of Surface Defects (scratch marks, tool marks, pores, and blow holes)

c) Verification of Holes (the count of number of holes; the location of holes with respect to a datum)

d) Identification of Flaws in a Printed Label (text errors, numbering errors, and graphical errors)

Summary:

- Laser-based instrumentation is the best choice for precise measurement due their monochromatic, coherent and collimated behaviour.
- A computer controlled CMM increases the versatility, convenience, and reliability of measurement operations.
- In automated inspection, a computer serves as a real-time controller to integrate the functions of several machines with the inspection station.
- A machine vision system enables the identification and orientation of a work part within the field of vision, and has far-reaching applications.

Brief Outline of the Course:

- ❖ In manufacturing, **quality control** is a process that ensures customers receive products free from defects and meet their requirements.
- ❖ **Inspection** and **measurement** is needed during production for checking the products for its required specifications.

Destructive Tests

- To understand a specimen's performance or material behaviour under different loads.

Non-destructive Tests

- To evaluate the properties of material or component without causing damage.
- To perform in-service inspection to avoid any catastrophic failure.

Metrology

- For complete evaluation of manufactured products.
- Reducing the cost of rejects and rework through application of statistical quality control techniques.

THANK YOU

