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A Review on Non-Destructive Testing (NDT) Techniques: Advances, Researches and Applicability

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ABSTRACT: The field of NDT is a very broad, interdisciplinary field that plays a critical role in evaluating the structural component and systems perform their function in a reliable manner. A review is presented of Non-Destructive testing methods for evaluating material characteristics, deformation in the materials without destroying the material. These testing methods are very important in determining and identifying the discontinuity and defects found on a material and parts of an object. There have been various NDT methods built upon different principles for Quality Assurance during the whole lifecycle of the product. Methods like Visual Inspection, Radiographic method, Optical techniques, Wave-based methods, etc. are used to analyze the defects on material and part of it. The Non-Destructive testing method has been widely used in different fields like in manufacturing, medical devices, packaging, marine industries, waste management, etc., but especially used in oil and gas industries, aircraft, and nuclear power plants. This paper reviews these NDT techniques and compares them in terms of intrinsic characteristics and their applications.

KEYWORDS: Life Cycle, Non- Destructive Method, Quality Assurance, Radiographic Method

1.0 INTRODUCTION

Destructive Testing (DT) is a testing method that analyzes the point at which a component, assert, or material fails. DT is also commonly called a Destructive Physical Analysis (DPA) [1]**.** Destructive testing is a qualitative analytical method that finds the material's quality like elasticity, hardness, tensile strength, impact resistance, etc. all the above-listed properties can't be found by Non-destructive testing (NDT) methods because to find these mechanical properties, it requires to apply load on the material. The load or weights deforms the material and make them not reusable. While NDT methods are used in a way that the material can be reutilized after testing. NDT is an industrial method for analyzing material characteristics or finding the deformation or discontinuities in the material without destroying or damaging the material. NDT is called Non -Destructive Evaluation- NDE or Non-Destructive Inspection- NDI.[2]

Non-Destructive techniques are highly esteemed in different fields and every field has data that is scientifically important. This NDT method focus on three major fields [3]:

1) **Rare items:** include fields like archeology (study of human activity through the recovery and analysis of material culture), space science, paleontology (the scientific study of life that existed prior).
2) **Environmental:** it includes analysis of rocks, soils, air particulates, and other environmentally related samples.
3) **Forensics:** it is a broad field where non-destructivity or destruction of samples is important or done. Other fields which are included in it is crime, illegal and fraud, terrorism, etc.

NDT is a mechanism used by engineers to detect, defects or damage in structure and materials, either during the manufacturing process or in service. The methods used are ultrasonics, radiography, magnetic particles, eddy's current, visual methods and dye penetrant, etc. As an industrial test method, this NDT method provides a cost-effective means of testing while protecting the object's usability for its designed purpose**.** NDT techniques provide cost-effectiveness of testing of samples for individual examination & investigation. Non-Destructive Evaluation (NDE) or NDT involves the identification & characterization of defects or damage on the surface and interior of materials without altering the material. [4,5]

Five major factors should be considered during the selection of the design of non-destructive testing survey [6-9];

1) The penetration capability of method,
2) The contrast in physical properties between the test compound or target and its surroundings,
3) The resolution requirements for measurements,

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4) Previous record or history of the method in its use in the construction of the structure and
5) The level of noise of the techniques which means whether the gathered information about the measured structure is valid or not.

Table 1: Basic difference between Destructive and Non-Destructive Testing[9]

Sr.no	Destructive Testing	Non-Destructive Testing
1	Purpose: This method is carried out to find properties and behavior of testing specimen under different loading condition	Purpose: This method is used to find the properties of the material and to identify and find out the defects.
2	Destructive testing is a qualitative as well as quantitative analytical method.	The non-Destructive Testing method is also a quantitative and quantitative analytical method.
3	Destructive Testing (DT) methods are generally mechanical tests where the particular characteristic of the material is evaluated by isolating a testing specimen of the structure in a controlled environment.	Non-Destructing Testing (NDT) is testing method that examine the defects in materials without damaging or destruction of the testing specimen.
4	The tested specimen is destroyed and cannot be either tested again or put into structure back.	The tested specimen isn't destroyed and examine the defects in materials without damaging the object or specimen being tested.
5	This method is quite costly as the testing specimen can't be reused.	NDT method is cost-effective overall
6	Example: Bending test, tensile testing, compression test, hardness, impact test, etc.	Example: ultrasonic testing, liquid dye penetrant method, infrared thermography, eddy's current testing, etc.

2.0 NON-DESTRUCTIVE TESTING METHODS

These Non-Destructive testing methods plays important role in the testing of complex materials. Numbers of techniques or methods are used in the complex NDT field including, Radiographic Testing, Visual Testing (VT) or visual inspection (VI), ultrasonic testing, thermographic testing, infrared thermography testing (IRT), acoustic emission testing (AE), acoustic-ultrasonic, electromagnetic testing, stereography testing, optical testing, liquid/ dye penetrant testing and magnetic particle testing. Damage to complex materials can occur during material processing, manufacturing of the component, or in-service activities. In which porosity, cracks, and exfoliation are very common defects. [4]

Non-Destructive Testing (NDT) techniques or methods mainly depend on four criteria:
1) Type of material
2) Type of defect or damage
3) Defect size
4) Location of a defect.

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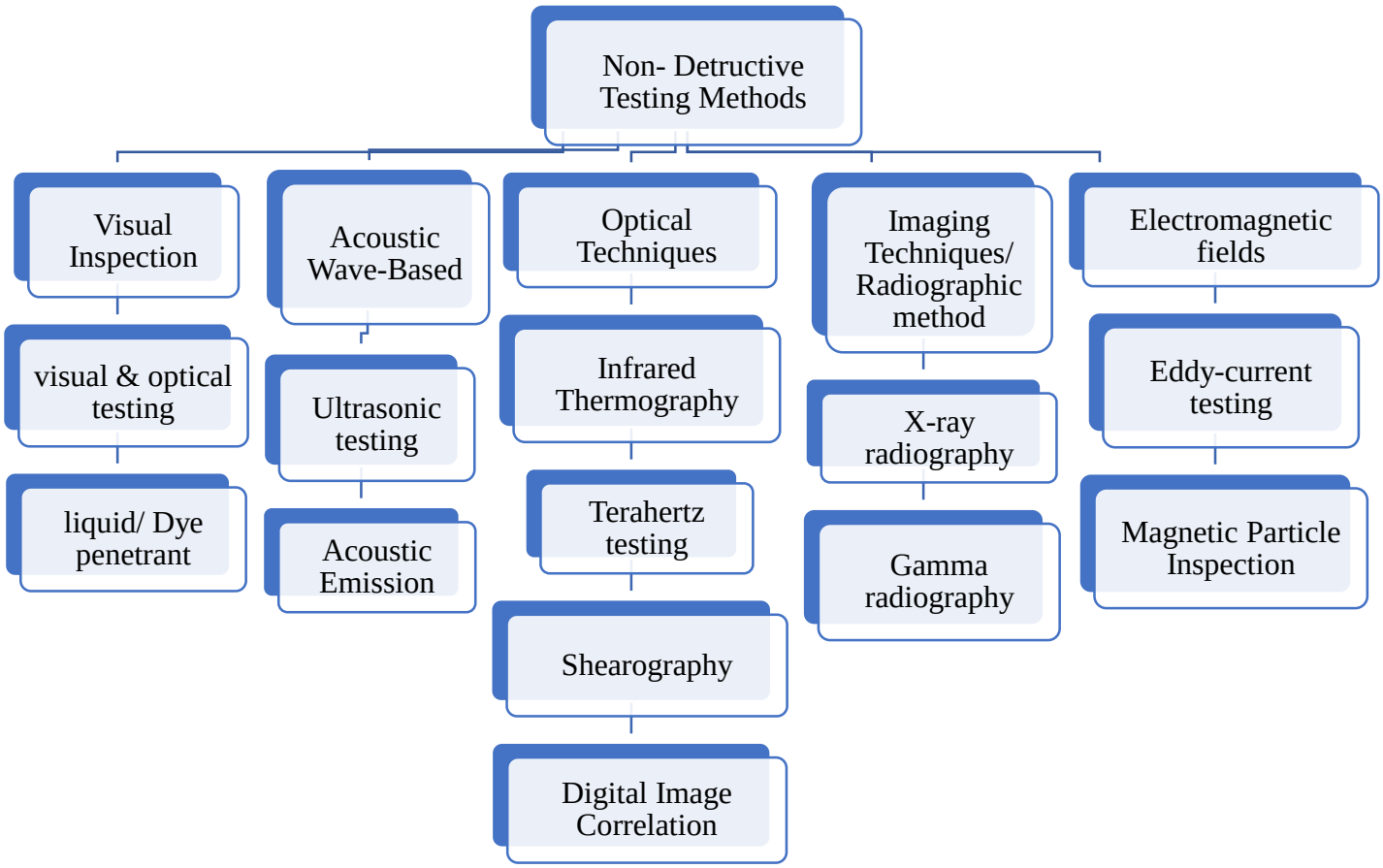

Figure 1: Classification of Non-Destructive Testing methods. [8]

2.1) Visual Inspection Method

2.1.1 Visual and Optical testing: [6], [11-14]

The Visual Inspection method is a very common and basic method to inspect damage or defects. This method is fast, economical, and flexible. VI method depends on the detection of defects on a surface using an eye. This method is normally applied without using any additional equipment but can be improved by using a magnifying glass that improves its effectiveness and opportunity. The main limitation of this method is that it is only capable of analyzing defects or discontinuities on the surface of the material or part. VT is most fruitful when it is performed at all stages of any new manufacturing. VT is the main method that is used during the investigation of pressure equipment.

VT method requires 3 primary conditions; these are:

- Good sight to see what you are looking for,
- Adequate lighting,
- Experience to identify and solve problems.

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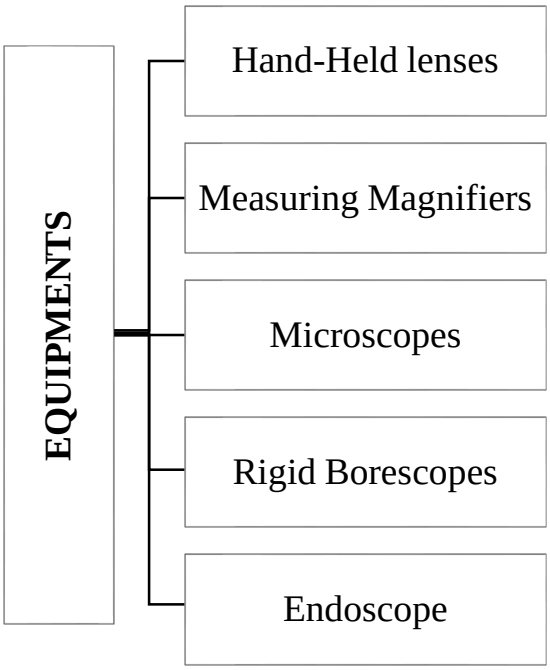
Equipment used for Visual and Optical testing methods



Advantages:

- This method is used in non-porous material to analyze defects including cracks, surface porosity, leakage in new products, in-process cracks in the material, etc.
- VT method is a visual observation of the surface to investigate the presence of surface defects like corrosion, improper alignment of parts, physical damage is some of the defects that are detected by this Visual Inspection method.

2.1.2 Liquid/ Dye Penetrate Method: [4], [8], [13-15]

Liquid/Dye penetrate testing is an easy Non-Destructive Testing (NDT) method used to find surface defects in metals and many non-metals by penetrating liquid. Materials that are analyzed by this method are metals (aluminum, copper, titanium, steel, and so on.), glass, rubber, and plastics.

Working:

Liquid/ Dye penetrant testing discloses surface defects by the **" bleed-out"** of a penetrating medium against an opposite background. The Process is as follow;

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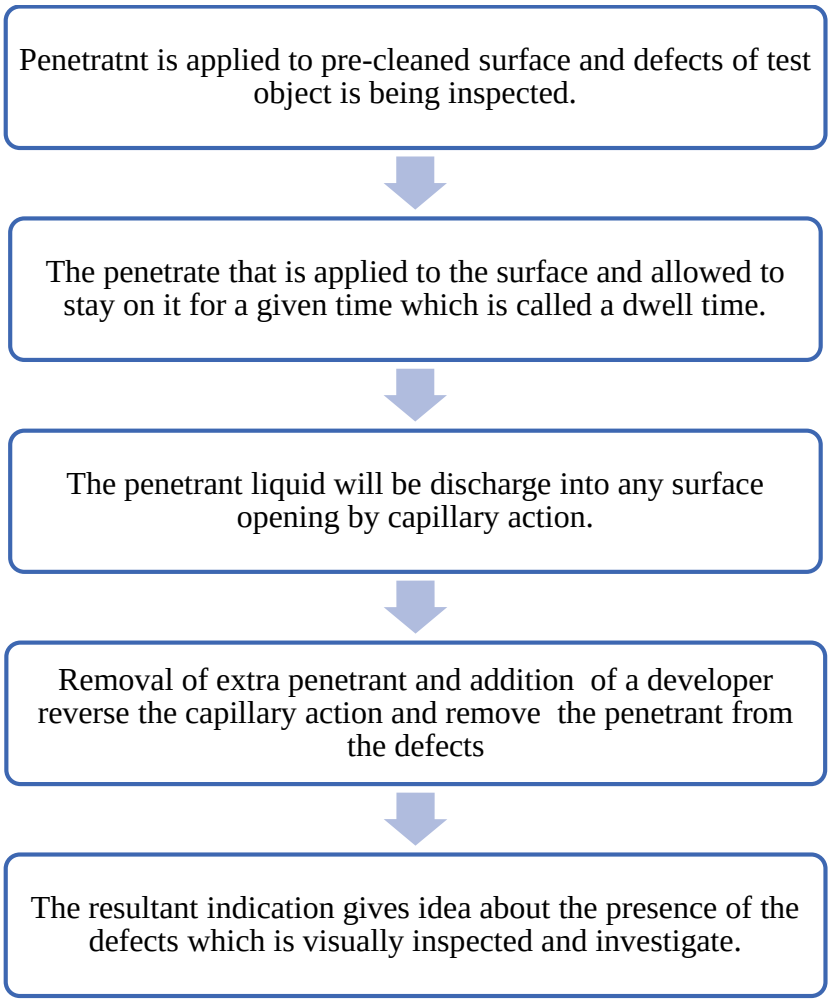
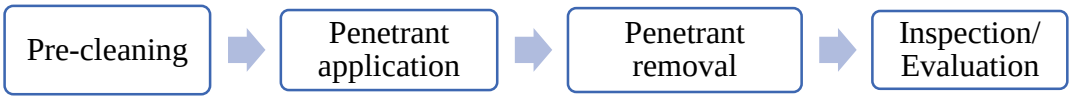


To perform this method, there are several steps to follow and each step must be performed in the right manner:



Advantages:

- Easy to learn, economical, and analyze a wide range of materials and compounds.
- This method can be used to analyze metals and non-metals and very sensitive to detect small surface cracks and defects.
- Post-emulsifiable system can analyze broad, shallow defects.
- Good for high volume production.

Disadvantages:

- Pre-cleaning is compulsory.
- This method will not detect defects below the surface.
- Uneven surface or surface with porosity produces so much backdrop, which will interfere with evaluation.
- Fluorescent penetrants are sensitive to contaminants which will affect their performance.
- Various approach requires for surface preparation and cleaning.
- It will only analyze surface defects.

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2.2) Wave- based Method: [4],[8], [13-17]

The wave-based method is a pre-deterministic prediction technique to resolve steady-state potent problems and is developed to solve some of the frequency limitations established by element-based prediction methods.

2.2.1) Acoustic Emission (AE): [4],[8]

Acoustic emission is a sound wave generated when a testing material undergoes stress condition. AE occurs in for high mechanical loading generating sources of elastic waves and this occurrence is the output of a small surface displacement of a material produced due to stress waves produced when the energy in a material or on its surface is released spontaneously. this energy releases stress waves resulting in fiber destruction, matrix cracking debonding, and so on.

Acoustic Emission (AE) based NDT methods detect and track these spontaneous releases of stress waves through the arrangement of highly sensitive sensors or transducers.

There is also a combined method of AE and Ultrasonic Testing (UT), called the Acousto-Ultrasonic technique (AUT) which is introduced by Vary in 1981.

Limitation of AE method: - Difficult to understand and explain
- Expensive instruments are required.

2.2.2) Ultrasonic Testing (UT): [4], [13-17]

Ultrasonic testing is a non-destructive inspection method that uses higher frequency sound waves.

Table 2: Categories of Ultrasonic measurements and their application [17]

Sr.no	Measurement category	Measured parameters	Applications
1	Time-domain	Times of flight and velocities of longitudinal, surface, and shear waves	Used to measure density, flaw detection, thickness, interface analysis, mechanical properties, dimensional analysis, robotics, etc.
2	Frequency domain	Frequency-dependence of ultrasound amplitude or ultrasonic spectroscopy	Microstructure, porosity, surface characterization, phase analysis, etc.
3	Attenuation domain	Fluctuations in reflected and transmitted signals at a given frequency and beam size	Flaw characterization, surface, and internal microstructure interface analysis, etc.
4	Image domain	Time of flight, velocity, thickness, discrete point analysis by C-scanning, linear, 2D, etc.	Surface and internal imaging of flaws, microstructure, density, mechanical properties 2-D and 3-D imaging.

❖ **Basic equipment** uses for typical ultrasonic inspection:
1) Ultrasonic Flaw detector:
2) Probes:
3) Probe lead:
4) Couplant

❖ **Advantages of Ultrasonic Inspection:**

The main advantage of UI compared to other NDT methods are:

- Very sensitive method and can find small defects
- UT is more sensitive to defects that are perpendicular to the sound beam
- Flaws can be sized and the location of the internal defects within the component can be detected, the nature, shape, and direction of the flaws can be determined.
- Very portable method with flaw detectors and probes being light and compact which allow an on-site analysis of difficult access component possible.

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- The ultrasound reflects from the flaws is displayed and permit immediate on-site analysis and utilized for an automatic system, production monitoring, and process control.
- Entire component is scanned from the front to the back surface
- This method differs from other wave-based methods as it does not require sample preparation and is used to determine mechanical properties, microstructure, microscopy, imaging, etc.
- Ultrasonic equipment is transportable and cost-effective except plasma and vacuum.

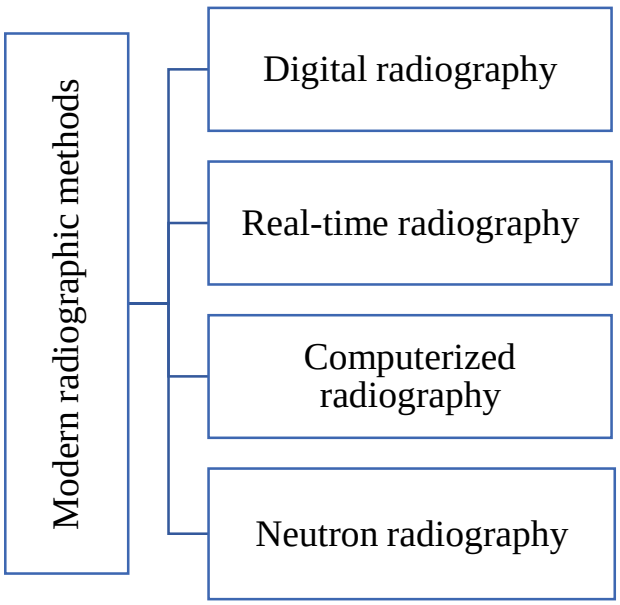
❖ **Disadvantages of UT:**

- Many times it is difficult to interpret a defect signal
- It requires experienced and trained personnel to operate and perform the method
- Good technical knowledge is required
- Rough surfaces such as In-service components are difficult to analyze.
- Single-crystal probes have a dead zone in which flaws cannot be detected.
- Whereas twin-crystal probes can only be used over a certain depth range.
- Couplant must be used to allow the effective transfer of ultrasonic energy between the probe and the component. Loss of Couplant can lead to wrong interpretation.
- Reference standards are required to characterize flaws and calibrate the equipment
- Test surface must not be rough or uneven otherwise it is not applicable.
- The Couplant can be a contaminant that requires replacement before further processing can be done.

2.3 Radiographic Method: [4],[13],[14],[15]

- It is one of the earliest NDT techniques however, due to health and safety measures alternative methods are replacing it for some applications in the industry. This method is suitable for the determination of internal defects in ferrous and nonferrous metals and other materials.
- It works by generating short-wave X-ray or gamma radiation and pointing it towards the object. Radiation penetrates to a certain extent and if this penetration is sufficient to pass through the testing object this will be captured on a photographic film. if the testing object has a high density it absorbs more radiation and less radiation will reach the film resulting in lighter image generation. And if the testing object has a low density like slag, it will absorb less radiation and more radiation will reach the film and produce a darker image.

2.3.1 Modern Methods:



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a) Digital Radiography:

This method is advanced and progressed after speed and memory storage growth of computers that allow the production of digital images and covert, stored and displayed on relatively. It permits the use of large digital X-ray images.

Use: at hospitals, at airports for scanning of luggage also at industrial radiography.

b) Real-time Radiography:

In this method, conveys the radiographic image to a screen display and looks as it occurs in real-time. it converts the radiation into light by the fluorescent screen. Therefore, it is called fluoroscopy.

Use: the airport system used digital radiography are real-time system.

c) Computerized Tomography:

Used in medical applications and in the industry.

d) Neutron Radiography:

Neutron radiography uses neutrons in place of X-rays or gamma rays to pass from the object and expose the film. In X-ray and gamma rays, radiation is absorbed with more dense material and pass-through lighter materials, whereas in neutron radiation it absorbs light materials and passes through the dense materials.

❖ **Use:** For locating light materials inside dense materials, water entrapment, and corrosion in aircraft wings.

❖ **Advantages of industrial radiography:**

- Radiography can be used with solid materials
- It has the ability to detect internal defects
- It gives a permanent record of the test
- It indicates require corrective action
- Pictorial presentation of the information
- Provides sensitivity on each film
- Preferable for any material

❖ **Disadvantages of industrial radiography:**

- This method has a problem in detecting very small defects
- It can only detect flaws that are in a specific direction
- This method is carried out in a proper manner with safety measures, if it is used wrongly, it can be extremely dangerous
- Basically, radiography is a highly costly NDT method and required more manpower
- Equipments are costly and time consuming
- May not detect critical defects
- Experienced person is required to interprets the data
- Gamma rays are less sensitive than X-ray, especially on thin materials
- Testing area required to be controlled environment
- There are possible health hazards

2.4) Optical Techniques: [8],[13],[18]

- Optical NDT has attracted more attention in recent years, mainly because of its non-destructive imaging properties with high sensitivity and precision.
- **2.4.1) Infrared Thermography NDT:**
- It monitors the variations in temperature of the objects in the infrared portion of the electromagnetic spectrum.
- Recently, IR thermography widely used in aviation, aerospace, machinery, petrochemical, medical and other fields.
- This IR thermography is based on temperature variation. There are two types of thermography:

  a) Active Thermography (AT): is defined as applying a stimulus to a testing object to cause the testing target to heat or cool in such a way that the characteristics of the target are observed when viewed by thermal image.

  b) Passive Thermography (PT) is defined as measuring the temperature variations between the testing object surroundings under various ambient temperature conditions.

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- In current years, the development of thermography method has been an increasing interest in Ultrasonic Lock-in Thermography (ULT).

❖ **Specific Applications:**

- In the military: they used this system for several years for reconnaissance, target acquisition, heat demanding missiles, fire control and navigation.
- Civil: they use in law enforcement, fire-fighting and building integrity.
- In medical: uses depend on the fact that damaged biological tissues are hotter than normal tissue, so IR can be used for mammography, injury of soft issue and arterial constriction.
- Environmental applications: include earth resources, pollution control and conservation of energy.
- Industrial uses: include predictive maintenance and in manufacturing of products.

❖ **Advantages** of thermal and infrared testing:

- Both active and passive techniques can be used for various components or assemblies to detect various conditions
- Inspections under high temperature is possible
- Thermal testing can be carried out on materials such as composites which are tough to test with other NDT methods

❖ **Disadvantages** of thermal and IR testing:

- Expensive instruments
- Reflective surfaces can give a false hot-spots
- Careful spectral filtering is necessary to image material that is partially transparent to IR energy.
- Emissivity value must be known to accurately measure the component's temperature.
- Interpretation of data can be difficult due to many variables, for that experience person is essential.

2.4.2) Terahertz (THz) Technology:

- THz waves refer to electromagnetic waves with frequencies ranging from 0.1 THz to 10 THz. Terahertz wavelength ranges approximately 0.03 mm to 3 mm, in between microwave and IR.
- The internal structure of the testing object is determined by analyzing changes of the THz signal. THz imaging has advantages in the detection of internal flaws for non-metallic material. The THz wave can pass through opaque materials (like fabrics and plastics) and detect internal flaws which visible light cannot detect.

Application of THz techniques:. Most important application for THz technology is in the area of THz time-domain spectroscopy or T-ray imaging. The system induces THz short waves into a material, which interact with different phases, defects or damage. Internal structure within the material is determined by detection and analysis of reflected or transmitted THz waves. The THz- based NDT technique is usually implemented through,

2.4.3) Shearography:

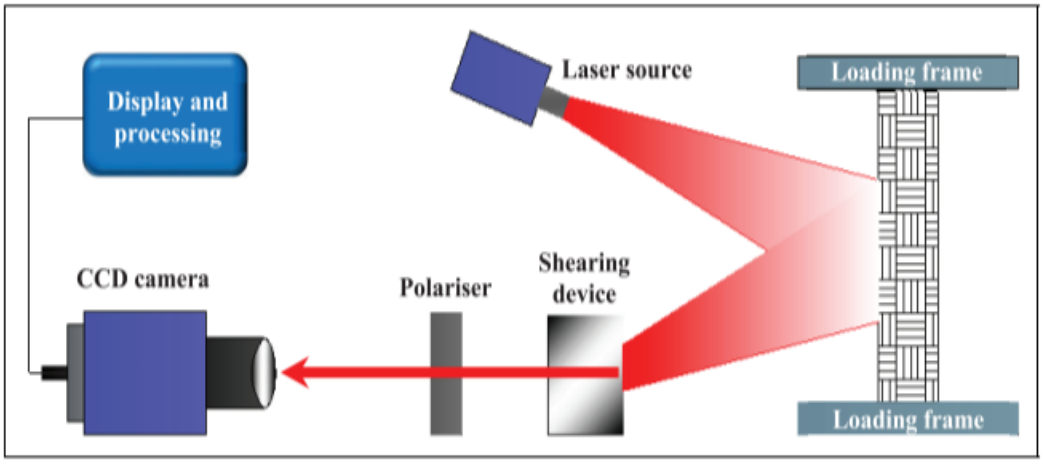

Figure-2 A Shearography system **[8]**

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This method was first described and applied by Leendertz and butters in the 1970s.
A typical shearography setup is shown in figure-2. A laser beam light up a sample surface and the beam is then scattered and reflected. The speckle pattern is imaged through a shearing device (Michelson interferometer) which divides it into two clear images with one being monitored during deformation. A controlled stressing method is necessary and is applied through thermal, vacuum, vibration, microwaves or mechanical loading. This interferometric pattern is then captured and recorded by a CCD (Charge Coupled Device) camera, which results in a periphery pattern that contains structural information.

2.4.4) Digital Imaging Correlation (DIC):

DIC is a simple and economic optical NDT technique for analyzing strain & displacement. Through DIC technology one can measure mechanical properties of different materials break up even at a high temperature. It is useful for non-contact and remote measurement; various types of materials in different temperatures; from RT (Room Temperature) to high-temperature measurement and can be used at the micro, macro, and nano-scales.

2.5) Electromagnetic Fields:

2.5.1) Eddy's Current Testing: [4],[13],[7],[15],[19],[14]

Michael Faraday, an English scientist, first discovered Eddy Currents in 1832. Eddy currents are generated through a process called electromagnetic induction.

Uses: Eddy Currents can be used for crack detection, material thickness, coating thickness, conductivity measurement for material identification, heat treatment monitoring.

❖ **Advantages**:

- It can be used to locate and measure various physical properties
- This method can be used as an automated high-speed testing process i.e., encircling coils.
- It will give excellent reproducibility of the results
- Unwanted signals can be suppressed
- This method does not require Couplant
- No need to contact the part under analysis

Disadvantages:

- This method can only be used on electrically-conductive materials.
- Permeability of ferromagnetic materials gives false readings
- Limited depth of penetration because of the skin effect of AC fields.
- Only AC fields generate eddy currents.
- Encircling or internal coils when used, the part or coil needs to be accurately centered.
- Highly trained personal required

2.5.2) Magnetic Particle Testing: [4],[7], [13-15]

This method is a comparatively simple NDT method that can be used in the detection of surface and sub-surface flaws in magnetic materials. If the magnetic particles are introduced to this surface, they will be held in place by the flux leakage to give a visual indication.

Specific Application:

This testing method is widely used in the industry for final evaluation of manufactured components, receiving inspection, and in-process evaluation for quality control.

Advantages of Magnetic Particle Testing:

- It is a sensitive method for locating surface and sub-surface flaws in ferromagnetic materials
- This method is easy and simple to learn
- Components of any size and shape can be tested
- Cracks that are filled with foreign material can be detected
- Non-metallic inclusions may be located
- Very rapid method for detection
- An indication of defects is formed virtually instantaneously

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Disadvantages:

- Only ferromagnetic parts can be detected
- It is often required to apply two magnetic fields 90 º apart in separate operations to ensure a part is fully tested
- Demagnetization is often required as residual magnetic fields may be a problem
- High currents may lead to arcing between the part and electrical contact, which can burn the part.
- Permeability of material or part can affect the final results

3.0 ADVANCED NDE TECHNIQUES FOR INDUSTRIAL APPLICATION [24]

Advancement in science & technology has brought forth several NDE techniques with enhanced capabilities for identification, characterization, and sizing of discontinuities.

Table 3: Advanced NDE techniques for Industrial Application

Sr.no	Method	Description
1	Infrared Thermography	• Infrared thermography is a technique for non-contact measurement or mapping of spatial distribution of temperature over the surface of any component. It is based on the principle that any object above absolute zero temperature emits electromagnetic radiations. • IR thermography has got the unique distinction among NDT techniques because of its fast results, adaptability to inspect hostile/ inaccessible areas, free from any unsafe radiations, and ability to provide both qualitative and quantitative information on the inspection.
2	Phased Array Ultrasonic Technique (PAUT)	✓ Conventional ultrasonic instruments employ single or dual transducers to transmit and/or receive sound waves. Hence, they suffer the constraints of fixed angle scanning, longest inspection periods due to multiple angle scans, and a risk of missing defect signals. ✓ Phased array ultrasonic testing technique works on the same principle and a single frequency but contains an array of transducers that can be pulsed in groups for phased transmission of sound waves and propagation of sound waves in a range of angles covering a wider path. ✓ Scan time is considerably reduced; the probability for detection of defect improves and is extensively used in rail, aerospace, and chemical/petrochemical industries.
3	Ultrasonic Time of Flight Diffraction Technique (TOFD)	✓ The conventional ultrasonic testing technique is versatile in the detection of defects and their orientation but is inadequate in precise characterization and sizing of defects. ✓ Time of Flight Diffraction (TOFD) technique derived on the same ultrasonic principle is more appropriate for precise measurement of dimensions of defects for repair/ remedial actions. ✓ When an ultrasonic pulse encounters a defect, the pulse is diffracted at the edges of the defect. The difference in time of flight of initial pulse and echoes diffracted from the edges

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		of defects is measured for location and precise sizing of defects and this technique is known as time-of-flight diffraction technique. ✓ By measuring the transit time between diffracted echoes from the top and bottom of defect, we can assess the depth and size of defects. Both Phased Array Ultrasonic Testing and Time of Flight Diffraction techniques provide real time image with precise location and are non-hazardous.
4	Impact -Echo Testing technique	✓ This technique is based on the use of mechanical impact-generated compression waves that travel through the structure and are reflected by internal flaws and external surfaces. ✓ Impact Echo can be used to measure the thickness of slabs, plates, columns and beams, and hollow cylinders. It can also be used to determine the location and extent of flaws such as cracks, de-laminations, and voids, honeycombing and de-bonding in concrete structures. Impact Echo testing consists of measuring both the time record and frequency spectrum associated with a mechanical impact on the surface of a structure. It is non-destructive and requires only one surface of the structure to be exposed.
5	Remote Visual Inspection	✓ Remote Visual Inspection is a Non-Destructive Testing technique used to detect and examine a variety of visible flaws; such as cracks, corrosion, contamination, structural integrity, and other discontinuities in inaccessible, remote locations. ✓ Remote visual inspection technique has made extensive advancements from simple bore scope, endoscope to video scope. We have miniature cameras and optical lens which can be used to access even very small-bore locations such as heat exchangers, drain headers and stacks. ✓ The benefits of RVI include inspection at confined spaces, lesser operational& safety risks, enhanced image resolution and permanent documentation.

4.0 APPLICATION/ USE OF NON-DESTRUCTIVE TESTING [11], [20-23]

This method is fast and easy to use at a site. NDT is comparatively less expensive and can be used for,

- The actual condition of reinforcement can be evaluated
- The main objective of the assessment is to ensure that structure and its parts do not fail under its loading conditions
- Assessment is carried out to observe its maximum resistance capacity
- Flaws like cracks, void space, fractures and weak locations can be detected
- Minimize the local damage affecting the lifespan of the structures
- Overall stability of the structure can be evaluated
- To reduce the cost and accident prevention
- To improve reliability of the product
- In aerospace: testing castings
- In automotive: to test the durability of piston heads

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- In manufacturing: to check the quality of the components before it goes into production
- In medical devices: to check durability and composition of stents
- In packaging: to test the structure and chances of leakage for packages
- In marine industries: to identify corrosion
- In agricultural and food products Quality Inspection
- In waste management: to identify convertible metals in waste
- In petrochemical industry: to check pipelines used to transport oil
- NDT methods can be used at any stage in the production or life cycle of the components
  - To assist in product development
  - To screen incoming materials
  - To monitor or control manufacturing processes
  - To verify proper processing like heat treating
  - To evaluate in-service damage
- For Quality assurance purposes: to assure the quality of the output of the production.
- NDT method can be used to determine:
  - Size, shape, or orientation of a flaw like cracks or porosity
  - Coating thickness or material thickness
  - Hardness of the material
  - Composition of the material
  - Electrical conductivity of the material

CONCLUSION

Non-Destructive Testing methods are invaluable as a tool for testing and analysis, as may be required during various stages within the lifetime of a composite product. It is clear that each technique has its own potential but rarely achieves the capabilities for a full-scale diagnosis of possible defects and damage evaluation in a composite system. So, the combination of two or more techniques is used in order to get better result and increase the effectiveness of investigation. NDT can be performed on metals, plastics, ceramics, composites and coating in order to detect cracks, internal voids, surface cavities, delamination and any type of flaws that could lead to premature failure. The reliability and confidence level of non-destructive test is typically increased by using multiple test methods.

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