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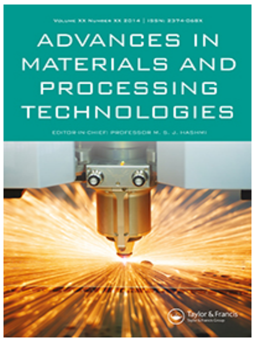

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Advances in applications of Non-Destructive Testing (NDT): A review

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ABSTRACT

Manufacturing processes such as casting, rolling, forging, extrusion, material removal processes, etc. are some of the common techniques used today in manufacturing industries. However, these processes must be carried out with utmost precision and precaution. Even the slightest negligence can give rise to anomalies which can be classified as defects or discontinuities depending upon their repairability. Non-Destructive Testing or NDT is amode of testing which has been adopted by industries for decades to test mass manufactured products for anomalies.

This paper discusses various NDT methods, such as Visual Testing, Magnetic Particle Inspection, Penetrant Testing, Ultrasonic Testing, Radiographic Testing, Acoustic Emission and Eddy Current Testing. The paper also discusses how technical advancements have broadened the scope of NDT even in industries that may not be manufacturing oriented, indicating that NDT is not limited to detection of anomalies. Even though these developments have made NDT more favourable, this paper highlights the fact that these techniques are mostly manual and heavily dependent upon inspectors' knowledge and experience, leaving room for errors. This paper also discusses the key challenges and future scope in the field of NDT.

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KEYWORDS
Non-destructive testing (NDT); manufacturing defects; eddy current testing; ultrasonic testing; acoustic emission

1. Introduction

One of the manufacturing industry's key objectives is to ensure product quality, that is, to make sure the product can perform its intended function for a long time. For a product to achieve this criterion, it is of utmost importance that the product is free of any defect and discontinuity. A defect is an imperfection in a product that can restrict its life by impeding its performance, eventually causing it to fail, even during operation under ordinary conditions. A discontinuity is similar to a defect, the only difference being that a discontinuity can be rectified whereas a defect cannot. These anomalies can arise during manufacturing stages or even during the operation of the product. These anomalies must be detected, studied and if possible, be rectified. Non-Destructive Testing or NDTconsists of a range of techniques that enable the detection and evaluation of said anomalies so that the product's condition is not exacerbated and can be rectified if possible. One of the most significant advantages of NDT is that they can be performed at all product life stages, even during their operation. This provides an accurate idea about the location and

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the properties (like dimensions, rate of propagation, etc.) and the severity of the defect or discontinuity.

The principles employed in various techniques of NDT are also employed in different fields. It is an implication that NDT is not only limited to manufacturing. For example, principles of NDT techniques are prevalent in medical diagnostics. X-Radiography used for detecting tumours, fractures, etc., and Remote Visual Testing used in procedures like endoscopy are some examples of NDT in the medical field. However today, major applications of NDT in manufacturing lie in automobiles, oil and gas, aerospace and so on. There are other fields that use the principles of NDT like geological exploration, architecture, etc. This paper aims at co-relating the principles of various NDT techniques with advances in applications in fields which may or may not be manufacturing-oriented.

2. Literature review

According to Cawley [1] eddy current, ultrasonic, magnetic particle, radiography and penetrant testing are the 'big five' techniques that dominate the NDT market. Thus, research is being done continuously to reduce the preparation required, increase the

Table 1. Capabilities and limitations of some of the key NDT Techniques.

NDT Technique	Capabilities	Limitations
Visual Testing	Suitable for surface inspection and monitoring manufacturing stages of a product.	1. Only restricted to surface flaws. 2. Highly dependent upon the inspector's experience.
Penetrant Testing	Suitable for surface inspection of mass-manufactured products.	1. limited to surface anomalies. 2. Too many variables affecting the test. 3. Messy process.
Magnetic Particle Inspection	Capable of detecting anomalies on or close to the surface in ferromagnetic materials.	1. Limited to anomalies in the vicinity of the surface. 2. Can be only used for testing ferromagnetic materials. 3. Testing of complex shapes may not be possible. 4. Removal of any coatings is required.
Radiographic Inspection	Capable of detecting surface and subsurface anomalies.	1. Safety hazards and waste disposal issues. 2. Time-consuming. 3. Expensive. 4. Dependent upon the orientation of anomalies.
Ultrasonic Testing	Capable of detecting surface and subsurface anomalies	1. Anomalies smaller than grain structure can go undetected. 2. Largely manual, therefore highly dependent upon the inspector's skill and experience. 3. Misinterpretations of signals can occur.
Eddy Current Testing	Capable of detecting flaws on or close to the surface in materials that are electrically conductive with or without coating (e.g. paint).	1. Limited to the testing of electrically conductive materials. 2. Assessment of subsurface anomalies in ferromagnetic materials is limited by this technique. 3. Theory of eddy currents, in general, is complicated.
Acoustic Emission	Capable of detecting surface and subsurface flaws with information about the propagation of the anomaly.	1. Structure under testing will attenuate stress waves. 2. Extrinsic sounds can cause misinterpretation.

speed of inspection and to inspect without shutting down the operation. How the process of using previous cases of data-interpretation to interpret new data can be helpful in solving the issue of NDT data interpretation is shown by Jarmulak et al. [2]. The article shows how Case-Based Reasoning (CBR) can be a successful alternative to expert systems and statistical classifiers. Zhijun [3] states that common defects and damages in composites can be effectively checked by ultrasonic inspection as compared to other methods of NDT. The author also introduces the development of studying and the applications of the ultrasonic method. According to G.S. Park and others [4], in a Magnetic Flux Leakage (MFL) type NDT system, the defect signals depend on the modification of the magnetic flux leakage in the area of defect. Thus, the authors describe a method to design a magnetic system which maximises the MFL in an NDT system.

Tschelisnig [5] presents the principles of hyperbolic triangulation and the basis of propagation of waves. The author also explains the AE inspection systems by taking an example from TUV Vienna's 32 channel software and equipment. The results gained after the tests performed on the TUV Vienna are discussed in integrity analysis and leakage tests. Crostack et al. [6] state that the ability to measure internal and induced stresses or to differentiate between structures of materials can be provided by Non-destructive testing. This, in turn, provides the data for the calculation of potential lifetime and reliability. They also state that the materials may be better understood by observing fast-moving processes like crack propagation when they are under impact load. Carlomagnoet et al. [7] examine the application of infrared thermography in the field of architectural restoration by taking three samples made of support of tuff, marble or brick and covering them with a layer of plaster. This layer of plaster is given inclusions to simulate cracks and detachments in frescoes. To detect the artificially induced flaws, various techniques, such as lateral heating thermography, pulse thermography, pulse phase thermography and modulated thermography are used. Bollas et al. [8] discuss the monitoring of defects in the wheelsets of locomotives using the Acoustic Emission (AE) monitoring method of NDT. The authors present the results of AE measurements performed on the wheelsets of the locomotives with and without defects, with varying speed and directions. The conclusions drawn show that the AE monitoring method can be an efficient method for monitoring the wheelsets of the trains.

Opportunities for the inspection of rock bolt in applications such as reinforcement of coal mine roofs are limited to destructive techniques like pull-out testonly. Thus, Beard et al. [9] tried to develop an NDT technique for monitoring the condition of rock bolts. Drinkwater et al. [10] reviewed the most relevant works on the use of ultrasonic arrays for non-destructive evaluation applications, in addition to which the author also discusses its future direction. The author also reviews the most relevant papers on the application of ultrasonic arrays in medical and sonar fields. On the other hand, Lim et al. [11] explain how one NDT technique is not sufficient for evaluation. Every technique has certain limitations which restrict their efficacy under different situations. The authors do so by differentiating the results between UT and ultra-response method for evaluation of defects in a concrete structure. A disadvantage of NDT is that most evaluations are heavily dependent upon the inspector's knowledge and experience. This is most relevant to magnetic particle inspection and penetrant testing, which also happen to be the most used inspection techniques. Luk et al. [12] research on some human factors which may affect the accuracy of an evaluation and provide some suggestions in order to tackle these issues.

Tasca et al. [13] explain how the evaluation of complex parts can be done using NDT. Although x-ray provides accurate data about a defect and is mostly p`referred over other techniques, sometimes UT can provide better results. The authors also provide better insight as to how UT can provide more information other than just the nature of the defect or discontinuity but also how it occurred. Cau et al. [14] worked on the detection of defects in pipes using UT. They evaluated the problem with the help of appropriate Artificial Neural Network models. Numerical Techniques like FEM have been used to evaluate problems in pipes by studying the echoes produced by ultrasonic waves. Eddy Current testing has many variables that affect evaluations made by this method. Martin et al. [15] provide a summary on these variables as well as recent advancements in this mode of NDT. The authors also explain how development in electronics and data evaluation systems have made Eddy current testing more effective. One of the advantages of NDT is that it can be done simultaneously while operating a machine. For example, Pohl et al. [16] illustrated that Eddy current testing could be done on rail tracks simultaneously to trains travelling on them. The authors also emphasised other applications of NDT, such as the use of ultrasonic testing on railroad gauges and wheels.

Singh et al. [17] illustrate the application of magnetic particle separation techniques used in the Indian mining industry. The authors provide an insight as to how this process has made inspection simple and cost-effective as well as discuss the disadvantages of this technique. Advancements in NDT have resulted in better evaluation of defects and discontinuities. Bracun et al. [18] proposed a laser-based technique for 3-D modelling of defects which use advanced algorithms to produce 3-D images with the help of electronic visual aids, such as cameras. Most of the principles employed in NDT techniques are employed in other fields as well. In fact, some of these techniques can be incorporated into improvising existing technology. One such example has been illustrated by Benenson et al. [19] where they emphasise the issues with self-navigating cars. A combination of techniques such as ultrasonic waves and thermography can assess surrounding environments more accurately, thus increasing reliability. An advantage of NDT is that it can be conducted at any stage of production. Lattice defects which are microscopic in nature, arise during material manufacture and affect the overall physical integrity of any component. Dobmann et al. [20] show that NDT, if incorporated at every stage of material production, helps in making sure that these properties are uniform throughout.

One of the major advances in NDT is that these methods are no longer limited to detection but also play a major role in preservation. X-radiography is normally preferred for this application because of its ability to scatter, which can be used to study the deterioration of concrete. Kamal and Boulfiza [21] studied this by observing penetration in alkalis using X-radiography technique. Pulsed eddy current techniques are capable of providing detailed information about a specimen. However, a major drawback lies in its sensitivity to external factors which may cause deviations in results. Tian et al. [22] provide a way of reducing the problem of lift-off in ECT by using normalisation, also making it suitable for measuring the thickness of metal with various coatings. Shrivastava et al. [23] discuss the role NDT can play in advances in medical research. They also provide information regarding the current applications of NDT and discuss the advantages of AE techniques in the biomedical field. NDT techniques today are being majorly used for evaluating mega structures like bridges. Sahama et al. [24] performed NDT on different parts of a bridge which include hangar sockets, welded joints and various concrete parts by using techniques such as PT, RT, MPT, etc.

One of the disadvantages of NDT techniques that depend upon magnetic behaviour is that they are not effective for metals with low magnetic permeability. One such material is Aluminium and its alloys. Hu et al. [25] used magnetic sensors and proposed a way for detecting anomalies in thin-plate aluminium alloys. Development in computation and electronics have provided NDT engineers with a brilliant and tricky opportunity for the development of this field. Bieder et al. [26] provide a solution to this problem by proposing quantification or classification of NDT results in terms of common parameters like type, location and size of the anomaly. NDT techniques enable measurement of those properties of materials which cannot be measured by other testing methods. For example, Hasar [27] measured microwave reflection from cement and mortar specimens which help in determining the electrical properties of the specimen. This is useful information which is used in the preservation of structures. Product quality over the years has improved largely due to automation of industries like CNC machines, die casting, rolling, etc. However, for further improvement and a greater level of satisfaction, Wolter et al. [28] suggest incorporation of NDT techniques during manufacturing stages. This can enable detection of any irregularities in machine settings or irregularities in the material.

Composites are a relatively new introduction in the field of material technology. Like metals, composites are also prone to defects like voids, cracks, etc. Banarjee et al. [29] discuss inspection of jute–polypropylene composite using a new technique called frequency-modulated thermal wave imaging (FMTWI). He et al. [30] discusses applications of pulsed eddy current testing, a relatively new form of eddy current testing, in the detection of subsurface defects using a rectangular PEC sensor. Automation has provided high rates of production. Bergmann et al. [31] discuss the requirement of rapid testing techniques that can keep up with the rate of production and provide the same sense of satisfaction ensuring customers quality products. They also discuss the applications and limitations of X-Ray computer tomography. FRP reinforced concrete is becoming an increasingly popular material for components, such as beams, slabs, etc. One of the problems with this material is that a proper surface examination cannot be done until the FRP layer is removed completely. A beam of this material may not even show signs of any anomalies when tested. Büyüköztürk et al. [32] provide a laser-acoustic NDT method for evaluating bonding in FRP reinforced concrete products.

Concrete has a unique self-healing ability. When concrete is exposed to the environment, it reacts with water to form grains. Tittleboom et al. [33] provide an NDT method that utilises AE for analysing self-healing capability of concrete. Evaluation of water pipelines is not only limited to studying the extent of the damage but also the type of flow. Open-type pipelines are usually placed under the surface; therefore, VT is not an option. Suzuki et al. [34] conducted experiments which showed that AE could be used to evaluate fluid flow conditions in these pipelines. The microstructure of metals is crucial as it determines many properties of a metal. It is usually determined by destructive techniques, such as hardness tests and other metallurgical techniques. Gür [35] discusses Magnetic Barkhausen Noise method, which is a form of NDT technique that has a high potential for classifying microstructures of steel. Ribeiro et al. [36] provide an

NDT method for the evaluation of non-ferromagnetic materials by providing an algorithm to model variation in ECT voltages. Usually, this method would involve the use of a probe for detecting readings. However, these readings are complex.

Mazal et al. [37] studied AE in cyclically loaded AlMg alloys and studied the changes in these AE through X-Ray diffractions. Modern NDT methods have been enhanced by advancements in technology. VT is the oldest mode of NDT. However, it was not considered to be as reliable as other modes of testing. Zhu et al. [38] discuss and review developments in optical technology used in NDT. Applications of NDT are prevalent in aerospace engineering. Sato et al. [39] discussed how planar defects in graphite are detected using UT technique which is used for quality assurance in rockets. Residual stresses in materials post-manufacturing or post-operation of a product can hinder its performance. Xu et al. [40] discuss how ultrasonic critical refracted longitudinal waves can be used to detect and evaluate residual stresses non-destructively and confirmed the accuracy of UT LCR wave method experimentally.

Mori et al. [41] present a new method for detection of defects in a concrete structure. This method is based on the dynamic response generated by concrete structures having flaws and are subjected to impact loading. Experimental and numerical results presented in the paper suggest that this method is effective as compared to the similar methods like impact-echo method. Pohl et al. [42] discussed that the ultrasonic inspection of the disc and the wheel rim of trains should be done without dismantling the wheel. While the inspection of track surface of railroad with a train speed of approximately 70 km/h should be carried out using eddy current method of NDT. N.P. Avdelid et al. [43] presents the applications of transient thermal NDT in assessing the aircraft composites. Pulsed thermography is used to monitor all the features in real-time. But, in the cases involving repair of composites, thermal modelling is also used in addition to pulsed-phase thermography to provide supplementary results. Maierhofer et al. [44] show that the impulse thermography is a good method for the detection of voids in concrete covers up to 10 cm and more. A computer program is also developed for investigation of the influence of various environmental conditions, parameters of the material and geometry on the thermal behaviour.

Mao et al. [45] propose a technique for determination of the location and the extent of defects and cracks which occur in oil pipelines using the time-frequency analysis of Hilbert-Huang. A signal processing technique developed by Hilbert–Huang which is based on direct extraction of the energy associated with the intrinsic time scales in the signal is used to process the signals from the oil pipelines with and without defects. Schajer et al. [46] present an NDT method for estimation of grain direction, dry density and moisture density of orthotropic materials like wood. This method is developed using the measurements of complex attenuation of microwaves which are transmitted via the material. These attenuations possess tensor characteristics like that of stress, strain, etc. Davis et al. [47] explain the usage of NDT methods in examining the tunnel lining grouting programs' efficiency with a focus on the impulse radar and impulse response methods. Kohl et al. [48] introduce the various scanning systems which are developed for on-site applications of Non-Destructive methods by presenting the results obtained from calculations which were performed at the laboratory at BAM as well as on-site at various bridges.

Shah et al. [49] present the results obtained from non-destructive ultrasonic testing of concrete specimens which are in the form of a cube. This testing is done using different frequency transducers. Orbán et al. [50] give an overview of the available methods of NDT, minor destructive and monitoring along with their applicability and efficiency in the testing of masonry arch railway bridges. Kornmeier et al. [51] discuss the appropriateness of various methods of non-destructive analysis to characterise Ci/SiC components like satellite nozzles. For characterisation of 3-D fibre orientation and integrity, matrix homogeneity, dimensions and distribution of micropores and synchrotron radiation using tomography at a fibre scale was used. A comparative study is given by Bayraktar et al. [52] for the developments in non-destructive controls of composite materials and manufacturing engineering applications. A review about the advantages, performance and usage at multiple scales of XR-CT (X-Rays Computed Tomography) medical scanner is also given.

Monitoring of seven-wire steel strands 15.7 mm in diameter is done by Chaki et al. [53] by using the guided ultrasonic wave procedure. For the optimisation of the measurement, the configuration was done by accounting the geometrical and mechanical properties of the prestressed strands followed by choice of mode of guided ultrasonic procedure at a suitable frequency. Capability and performance of shearography, ultrasonic, X-ray CT and thermography methods for the wind turbine blades inspection and delamination have been analysed by Amenabar et al. [54]. Recent advances in NDT with a focus on ultrasonic and electromagnetic techniques are reviewed along with ideas about the risk-based inspection by Abeele et al. [55]. Fatigue failure in offshore structures is predicted by using fracture mechanics-based damage models. A survey of NDT techniques for testing of building structures along with their application is done HOŁA et al. [56]. The major focus is given on the acoustic emissions method of NDT due to a lot of development in recent years and the ability to acquire important information on the tested structure using software and algorithms.

3. Methods of non-destructive testing

3.1. Visual Testing (VT)

VT is the oldest mode of NDT. This method involves a surface examination by visual aids, mainly the eye. The human eye is the most important visual aid that is required for conducting VT inspection. Light is an important requirement for conducting VT. The amount of light entering the eye determines the quality of the image. Several factors such as surface condition, brightness, temperature, size and shape of the object can affect the amount of light that is being reflected into the eye. Human factors such as physiological and environmental factors also affect the results of VT inspection.

There are two types of VT methods, Direct VT (or DVT) and Remote VT (or RVT). Direct VT is carried out when the eye can be placed within 25 inches and at a minimum angle of 30 degrees to the surface of the specimen that is to be evaluated. Remote VT (as shown in Figure 1.) is done for sites which do not have proper accessibility and no illumination. In this mode, light is supplied by an external source via cable along with a camera which transmits images or a live feed on to a monitor.

3.2. Penetrant Testing

PT is an application of capillary action. When a special liquid, called a penetrant, is applied on the surface of a component, usually by an aerosol, it fills any discontinuity that may be present by virtue of capillary action.

There are mainly two types of penetrants, fluorescent and visible dye penetrants. However, due to the better contrast ratio of fluorescent dyes, they are typically used for PT. The component to be inspected is immersed in the penetrant (as shown in Figure 2(a)) for some time and is then washed, dried and then observed under black light (fluorescent dyes). The set-up for PT can be manual and/or even automatic. However, for simplicity in field inspection, dye penetrants (which do not require complicated setups) are used. PT done with dye requires an additional liquid called developer (as shown in Figure 2(b)). The developer draws out the dye which may be entrapped in a discontinuity, making it visible. Factors such as wettability, capillary action, dry concentrate and viscosity determine the choice of the penetrant to be used. Before any PT is done, there are certain prerequisites that should be noted: 1) temperature, if the surface is too cold a longer period of immersion is required and if it is too high the penetrant may evaporate, 2) environmental considerations which include flammability, fumes, etc., 3) lighting and 4) surface condition such as coatings or rust should be addressed as it can affect the action of the penetrant.

3.3. Magnetic Particle Inspection

MPI (Figure 3) is a test based upon the behaviour of ferromagnetic materials when exposed to a magnetic field. Due to their high magnetic permeability, the domains align themselves in the direction of the applied magnetic force creating continuous lines. The underlying principle of MPI is studying the continuity of these lines of force; if the material is uniform, then the lines are continuous. Whereas the lines distort in the case of a discontinuity because they tend to follow a path where they experience the least reluctance (the ability of a domain to resist alignment in the direction of applied magnetic force). In order to do so, these lines bend around the discontinuity creating a ‘distorted’ field. Sometimes if discontinuities are large enough, these lines tend to exit

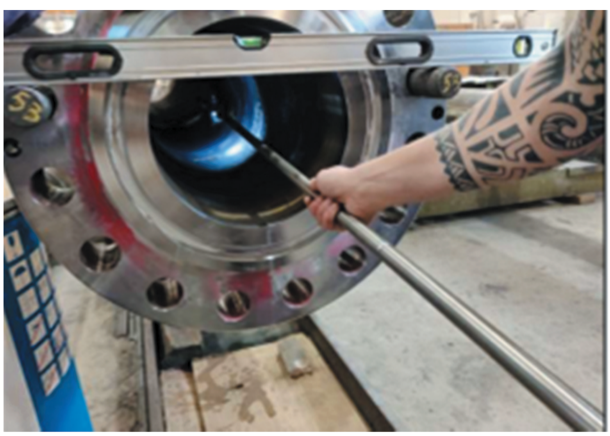

Figure 1. RVT of a pipe using borescopes with lighting source.

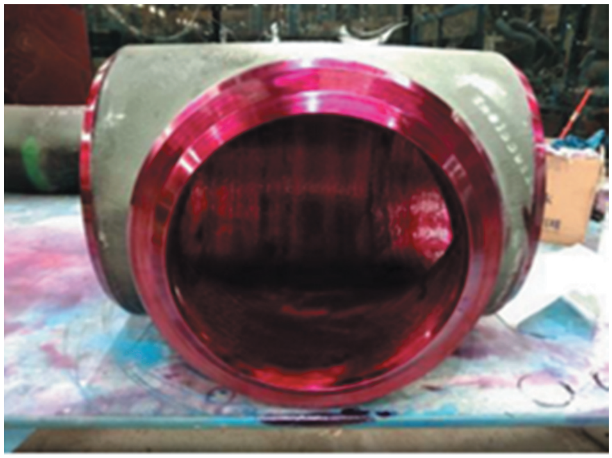

Figure 2. (a). Application of penetrant in PT.

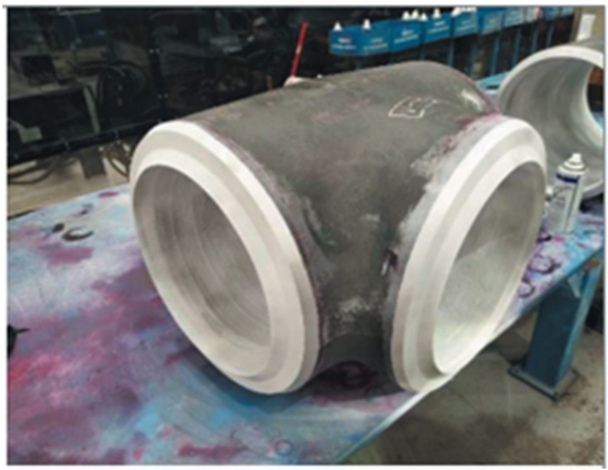

Figure 2. (b). Application of developer after removal of penetrant.

the surface and form through the air over the discontinuity. This is known as leakage of magnetic fields. This leakage can be made visible by applying a ferromagnetic powder. The powder gets accumulated, and a visible indication is observed.

Usually, iron filings are used, but for improved visibility, ferric oxide powder is used. The detection is, however, affected by physical factors, such as thickness (thicker the material stronger the field required), material (different components affect the permeability of the material) and internal stresses (effect on magnetic conductivity) of the component. Some other testing factors, which include distancing between the magnetic poles and speed of the detector, also affect the results of MPI. Test results of MPI are instantaneous and easy to interpret.

Figure 3. Magnetic particle inspection.

3.4. Radiographic Testing

RT is based upon the characteristics of radiation. Radiation is nothing but waves or particles emitted from a source passing through a medium. Radiography is the practice of capturing images by employing the characteristics of radiation. One of the key characteristics of radiation is that it can be absorbed by materials and the amount absorbed varies with the thickness of the material. When radiation is made to pass through a component, it is attenuated by the material. In regions of discontinuities, these rays experience lesser attenuation and travel faster in comparison to rays in uniform regions. The area of the film in the vicinity of the discontinuity experiences more spotlight, and therefore a unique image is obtained, making the discontinuity visible. There are mainly two types of radiations used in radiography, X-radiation and gamma radiation. While gamma rays are produced from a radioactive source and X-rays in a vacuum tube, characteristics of radiation apply to both.

3.5. Ultrasonic Testing

UT is based on the behaviour of sound waves. Sound is nothing but the disturbance of particles in solid, liquid or gas. This disturbance is propagated at different frequencies in different media. In UT, a pulse generated by a piezoelectric material is propagated through a component (as shown in Figure 4(a)). The frequency of this pulse is usually in the order of 106 Hz to facilitate longer transmission distances. As long as the pulse travels through uniform regions, its properties will not be altered. Changes in properties of the pulse (like velocity) are indicative of a present discontinuity. The changes are detected by a transducer which converts sound energy into visual signals that can be displayed on LCD (as shown in Figure 4(b)) or CRT. The transducer can also detect sounds of inaudible frequencies, making UT accurate and reliable. The accuracy of UT depends upon variables like temperature, which can affect the attenuation of waves and even the dimensions of the component. Surface condition is an important variable as

Figure. 4 (a). UT of a pipe segment.

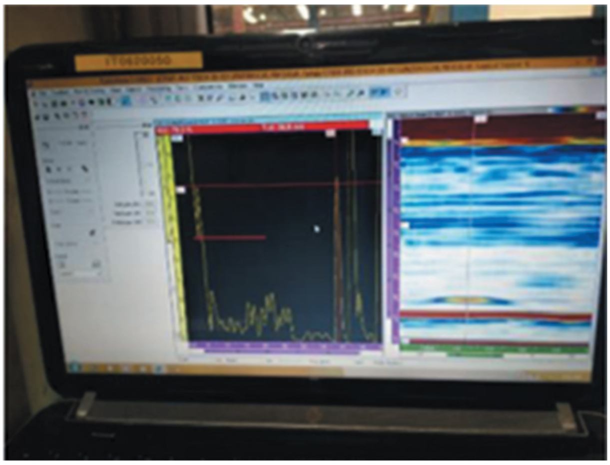

Figure. 4 (b). Real-time feed of UT on the pipe segment.

tighter bound coatings facilitate better pulse transmission. The orientation of the discontinuity is, however, the most important factor in detection by UT.

3.6. Eddy Current Testing

ECT is based on the fluctuation of the magnetic field induced due to eddy currents. When a metal is placed in a fluctuating magnetic field produced by alternating current in a loop, the current is generated in the metal which is swirly in nature. These currents are called eddy currents. A typical ECT set-up consists of two circuits, a primary and a secondary circuit. The primary circuit is connected to an AC supply which sets up a primary fluctuating magnetic field which induces eddy currents in the test specimen. These eddy currents set up a secondary magnetic field that interferes with the primary magnetic field, thereby affecting the current flowing through the coil. Therefore, if eddy currents are altered then the current set-up due to the second magnetic field is also affected, thus changing the primary current. This change will produce a change in the impedance reading, indicating a discontinuity. There are two types of ECT, pulsed ECT and Remote ECT. Pulsed ECT is used to detect defects in conductive materials, and the latter is used for ECT in remote regions.

3.7. Acoustic Emissions

AE is based on the principle that when a material undergoes deformation, energy is released in the form of elastic waves of high frequency. These waves travel outwards to the surface. Deformations continue to release energy when they are subjected to further loading. These waves are called acoustic emissions. These acoustic emissions are then detected by sensors, and the data is transmitted to a transducer which amplifies and converts the signals into interpretable data. One major difference between AE and other modes of NDT as discussed above is that in AE, the disturbance is originating from the material and not from an external source. Normally, in other modes, a disturbance is generated and transmitted through the specimen, and the response is studied. AE can provide information about the origin of the discontinuity and propagation of the same. Attenuation and wave velocity are two important factors which affect the wave propagation process, ultimately influencing detection.

3.8. Summary

4. Advances in applications of NDT

4.1. Diagnostics and Protection of Cultural Heritage

The requirement for the preservation of historic buildings involves a great knowledge of materials and structures, possible states of damage and their causes. The most arduous problems of unseen situations or detection of the mechanical behaviour of various structural elements like iron tie rods, timber roofs and floors, load-bearing walls, etc., can be solved using the Non-Destructive Testing techniques.

In the instance of masonry, the most often utilised NDTs techniques are thermovision, radar and sonic tests and as Minor Destructive techniques, the flat jack tests. Binda [57] and Suprenat [58] outline the main investigation techniques and their physical principles.

Significant information about the glass manufacturing technique employed can be extracted by using the Non-Destructive Technique of Environmental Scanning Electron Microscopy and Fibre Optics Microscopy with an Energy Dispersive X-Ray analysis on glass fragments obtained from archaeological excavations [59].

A new Non-Destructive Technique which is Adaptable Neural Network Architecture was introduced by Doulamis [60] in 2012 is capable of recognising the artistic styles incorporated in paintings. This technique can be very useful in preserving and restoring cultural paintings.

4.2. On-site Measurement and Monitoring of Concrete by NDT

Concrete is extensively used in various structures. Defects in concrete structures can lead to severe damages and loss of life. Deterioration of Concrete structures often goes unnoticed, and in many cases, initial damage is not visible until there is huge damage which is beyond repair. Thus, structural failure can be prevented by using Non-Destructive Tests to check for defects during the initial stages only.

To improve the brittle behaviour, steel fibres are introduced into concrete after which chemical coating of the fibres is done in order to attain maximum mechanical properties mainly toughness. For monitoring structures, Acoustic Emission (AE) provides a way to identify between various fracture stages which are pre-peak and post-peak. Acoustic Emission test also reveals the efficiency of chemical coating [61].

NDT can act as a powerful tool providing valuable information about the current condition of a structure. Using NDT during the initial stages of building construction can help in identifying errors beforehand allowing easy repair as the error will be limited to a specific area, as proved by Clausen [62]. This helps in averting grave situations like loss of life and prevent them from happening in future.

From research done by Tatsis, et al. [63] ultrasonic methods of NDT can also be used to estimate the condition of the structural elements and the extent of damages caused by a fire in a building.

Shrinkage cracking is one of the major problems during the early stages in the concrete industry. It occurs primarily due to the usage of low-quality aggregate, which results in volumetric contraction of coarse aggregate. The detection of shrinkage cracking is very important and can be done by using the Acoustic Emission method, which shows some promising results in the identification of shrinkage cracking, according to Ohtsu [64].

4.3. Application of Ultrasonics

Surface waves as described by Rayleigh are waves which move along the solid surface, and their motion is restricted to a region close to the surface whose depth is akin to the wavelength. The surface waves have distinctive characteristics which help in characterisation and detection of anomalies. Depending upon the defect size relative to the wavelength of the surface wave, they are diffracted, scattered and reflected by the surface defects. Surface waves have been used to characterise cracks in aluminium (Al) bars (Edwards et al. [65], Palmer et al. [66], Edwards et al. [67]).

After a specific period of time, fouling deposits start developing on industrial pipes. These deposits are hard to prevent and pose a serious problem to plant operators. There are a lot of varieties of fouling that may occur, entailing different chemical structures and elemental composition. The presence of fouling in pipes results in corrosion, blockage, rupture and deformation, which leads to substantial increase in operation cost and contamination of products. Pipe inspection can be done by involving ultrasonic guided waves, Withers [68], Mc Cements [69], Hay & Rose [70], Lohr & Rose [71], da Silva et al. [72] and da Silva et al. [73]. This technique which is capable of long-range identification with great reliability, has been shown to identify not only fouling but also particular defects in pipes. As experimented by de Carellan [74], due to the potential of conventional ultrasonic cleaning baths to eliminate hard deposits there is a possibility to break the bond between the fouling deposits and the steel pipe by using guided waves of sufficient magnitude.

4.4. Application of Acoustic Emission

Acoustic Emission monitoring is very useful in evaluating the quality of laser cutting, a process of cutting a material using a laser which is defined mainly by the state of the laser cut surface and existence of the re-solidified material occurring as dross at the lower cut edge. Changes in quality of the beam, the surface of materials and gas flow can lead to a reduction in the quality of laser cut. While laser cuts the material, AE signals are emitted due to the interaction between the cutting gas, laser light and plate material. These AE signals can be captured during or immediately after the cutting process, and the dross formation along with the degradation of the laser cut surface can be detected thus helping control the cutting process and ensuring high laser cut quality. Kek [75] proved by experimenting that this method of capturing AE signals to control the laser cutting process is applicable to unalloyed as well as alloyed steel (austenitic stainless steel) with different thicknesses.

Surface rail transportation is one of the most significant and important discoveries of modern technology. With time trains have been improving even if we exclude magnetic levitation technology. Due to the dynamic nature of loading and frequent working of the trains, deformations develop in the wheels and the axles. One of the major factors that lead to the deterioration of the wheel is the emergency braking, which produces a lot of heat due to friction, leading to small or large surfaces of the tyre to be flattened. These flattened surfaces can lead to misalignment, bad rolling quality, fatigue, lower speed, etc. This defect can be detected by using AE monitoring. As the wheels produce transient elastic waves to which AE monitoring is sensitive, thus detecting the defects when the train passes.

Wind turbine blades are one of the most vulnerable and exposed parts of the turbine. They are continuously in contact with gushes of wind and are often exposed to severe weather conditions. This leads to deterioration of the blades. Damaged blades are not acceptable for continued service. Thus, there is a need for monitoring these blades, which can be done by using AE monitoring. Tsopelas [76] summarises the first successful long-term AE monitoring of the full-scale in-service Wind Turbine.

4.5. Other Applications

Ultrasonic methods of NDT can be used in Quality Control of the Ground Improvement for setting up crude oil storage tanks. This method involves the production of vertical impulses by the surface waves on the ground surface. The dispersive characteristic of the incoming wave after being reflected by the ground is calculated, which gives layer stiffness of the layered ground. This procedure permits measuring of shear modulus for profiles of the ground-based on depth, with very small deformations before and after the improvement of the ground. The ratio of shear modulus before and after improvement represents an extent of ground improvement, which is then used as an estimate of successfulness for the conducted groundworks. Using the ultrasonic method of NDT ensures the safety and stability of the oil storage tank [77].

The Radiographic Inspection method of NDT can be used to scan porous construction materials for moisture content. Excess moisture content in construction materials will affect the physical properties of building structures. This leads to dampness and thus weakening the structure. Radiographic Inspection provides continuous and swift measurement and increased metering on a single sample without the influence of human factor [78].

An application of NDT in quality control can be seen in a technique called Positive Material Identification as shown in Figure 5(a,b) which uses the principle of X-Ray diffraction to determine compositions of alloys in mills post manufacturing.

Aircrafts construction involves usage of carbon fibre laminates which are usually long fibre-enforced composite materials. Quality assurance activities are considered very important because separated fibres are regarded as weak areas. Thus, Structural Health Monitoring is becoming increasingly important nowadays. This structural health monitoring is done using Guided Waves, that is, Ultrasonic method of NDT and also by Acoustic Emission Monitoring technique of NDT [79].

Ground transportation vehicles can also be monitored using Structural Health Monitoring. The wheelset of these vehicles produce sound signals which can be detected by using the Acoustic Emission Monitoring technique of NDT. If there is any damage in the wheel treads such as pitting (formation of cavities or holes), sound signals produced change, and these changes can be detected by integrating AE monitoring system in the wheelset hollow shaft [79].

5. Challenges and future scope

One of the greatest advantages of NDT is that principles utilised in testing have been derived from existing technologies. Development of electronics over the past few decades has largely contributed to advancements in this field. Introduction of LCD in visual testing has facilitated the formation of clearer images, which has made RVT a more reliable technique. Another major advantage of LCD is its portability and durability in the field. Introduction of electronic gauges and sensors has definitely reduced the risk of any misinterpretations and errors. The automated setup used in PT has made this technique not only more suitable for mass manufacturing but has also reduced the risk of human error during the application process. Digital advancements in RT have eliminated the use of films in X-radiography and replaced them with special sensors that are used to process digital images, providing better contrast than films, thus reducing the risk of misinterpretation. Digitalisation in RT has also contributed to better documentation of recorded data. Advancement in electronics has also introduced CT or Computed tomography, which has facilitated the formation of 3D images from 2D figures. Modern UT systems, though manual, are now incorporated with computer-aided systems which have also helped in improving image quality. Another major advancement in the field of NDT is that components can now be simultaneously tested in the field during their operational period. Techniques such as infrared imaging can study stresses induced in a component.

Even though all these advancements have made NDT techniques more favourable, there are certain limitations associated with them. All of the above techniques require highly trained personnel; even then there is no guarantee of zero misinterpretation. Slightest negligence can end in a major catastrophe. Techniques such as VT and RT are especially dependent upon the inspector's knowledge. In RT, sometimes it is possible faults may not be detected due to their orientation with X-Ray beams, it is therefore

Figure. 5 (a). Positive Material Identification (PMI) is an application of X-Ray diffraction. The technique is used to identify materials by checking their content using an X-Ray diffraction machine.

Figure. 5 (b). Material content displayed on the monitor of an X-Ray diffraction machine.

imperative that these techniques require highly trained personnel. It is also important to note that no single technique is sufficient to determine a component's structural integrity.

In some cases, operational costs of equipment used are high, and usually, a minimum of two techniques are required to approve a component safe for operation, making NDT not only time-consuming but expensive as well. VT, PT, RT and UT typically face this issue. Sustainability is another aspect that has to be kept in mind while studying the drawbacks of these techniques. With growing concerns of the rapid depletion of resources, sustainable materials such as composites, glass, fibres, etc., are becoming increasingly popular. Aviation and automobile industries are now switching over to composites as they are lighter and provide better strength than alloys. Composites are

Figure. 6 (a). Often more than two techniques have to be implemented in order to approve a product. Here VT is being done on the internal section of the pipe using a borescope after PT.

Figure. 6 (b). Pinhole defect emerging on the LCD monitor post PT.

also resistant to corrosion and hence provide greater durability. Increasing the use of composites in production would make methods such as ECT and MPI obsolete. Use of liquid penetrants and toxic materials in PT and RT, respectively, also elude NDT technology from achieving sustainability.

Like any other field, manufacturing or non-manufacturing, NDT should also aim for sustainability. This will involve the use of technology that produces minimum life cycle carbon emissions and minimum by-products. Toxic wastes generated in PT and RT pose a risk of contamination. Elimination of the toxic nature of this waste is a scope of interest. Pacana et al. [80] propose methods of choosing fluorescent penetrants in FPI. Although modern radiographic testing technologies have reduced the risk of exposure, waste management still remains a major issue. Another drawback discussed in the previous paragraph was the employment of highly trained personnel to conduct NDT procedures. However, Artificial Intelligence and Machine Learning show promise in this regard. AI systems can be generated, which can potentially detect flaws that may not be perceptible to an inspector. These systems can particularly hold major advantages in VT, PT, RT and UT, where the risk of misinterpretation is relatively high. Digital Image processing software can be programmed to detect discontinuities in structures through digital images that may be processed in VT, UT, RT or AE. Machine Learning algorithms can also reduce the time of inspection and processing. Robotics also shows promising advancements in NDT. Automated set-ups can be created, which can be integrated with AI systems mentioned previously can greatly improve the effectiveness of NDT techniques.

6. Conclusion

Principle of Non-Destructive testing is simple, to make sure a product conforms to its requirements physically and operationally by conducting a series of tests which do not tamper with the overall viability of the final product. One of the bigger disadvantages of NDT is that a single technique is not sufficient for total satisfaction. However, combining two or more techniques can ensure a greater sense of satisfaction. The underlying working principles of various NDT techniques have proved to be effective in every situation, making NDT a relatively mature field. Scope of development in NDT lies in its application and technology. Development in material technology has broadened the field of application of NDT along with the development of electronics over the last few decades which has provided the field with enhanced and sophisticated equipment (with underlying working principles remaining unchanged) making NDT more reliable and cost-effective. This paper described the various methods involved in NDT and identified as well as compiled the advances in the applications of NDT, showing that the field is not only limited to the identification of an issue but also its classification and rectification followed by preservation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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