Nondestructive Testing Methods

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Material failure may occur in a variety of situations dependent on stress conditions, temperature, and internal or external load conditions. Many of the latest engineered materials combine several material types i.e., metals, carbon, glass, resins, adhesives, heterogeneous and nanomaterials (organic/inorganic) to produce multilayered, multifaceted structures that may fail in ductile, brittle, or both cases.

composites engineering materials acoustic infrared thermography

1. Introduction

Recent technology development in engineered materials has been focused in a wide variety of sectors anywhere from biomedical to aerospace applications. The components used in these sectors are diversified materials specially designed using various modifications to perform a desired function in engineering operations. These novel engineering materials are essential for applications that require internal, external, static, dynamic load, mechanical load, extreme temperature, and corrosive exposure. The material structure plays a pivotal role in the upkeep of mechanical characteristics. These specially designed advanced materials/structures exhibit greater strength, weight reduction, modulus, and other properties including safety. Furthermore, these engineered materials also demonstrate advancement in the manufacturing process, efficiency, quality, and cost-effectiveness. Production of these engineering components includes several specific procedures including use of multilayered or multifaceted synthesis where several varieties of imperfections/inadequacies may be introduced to finished products. These materials generally contain cracking resistance under lightweight stress conditions. However, periodic testing and detection is required for tectonic coherence, defect diagnosis, and safety analysis of the refined/finished/polished products in their functional environment. Two primary methods are used to assess engineered material microstructures i.e., indirect and direct techniques. Indirect techniques measure structural parameters i.e., grain size, using other material parameters. For example, the average particle size can be measured from periodic multiplication of the lattice parameter. Direct techniques measure the desired structural parameters directly by a measurement technique [1]. Engineered materials are classified into five essential groups—metals, polymers, ceramics, composites, and semiconductors. Semiconductors are specifically charged materials while the other four groups are either structural or charged materials depending on their applications. Irrespective of above said group of materials the important material properties are affected by geometrical array and bonding type of molecules/atoms. There are generally three types of bonds in engineered materials i.e., metallic, ionic, and covalent bonds. Metals and alloys are comprised of metallic bonds; semiconductors form covalent bonds, and ceramics have both ionic and covalent bonds [2].

The structure of designed materials relates to the organization of its individual components at the nuclear level where the structure is fixed according to the molecular organization. In crystalline materials, the atoms are coordinated in repeating clusters known as a lattice structure. Although there are numerous potential crystal structures, some of the more commonly observed structures in metals are face-centered cubic (fcc), body-centered cubic (bcc), hexagonal closed-packed (hcp), and tetragonal [2]. Numerous metals and their alloys exist in more than one crystal structure depending on composition and temperature, but the majority fall within these four gem structures. The engineering material structure can be categorized as macrostructure, microstructure, crystal structure, electronic structure, and nuclear structure. The microstructure of most specialized alloys for a given engineering application includes different stages that may contrast in their physical properties, setup, morphology, estimate, volume division, etc. Although the material choice for a particular application may focus on a particularly important useful property, often an auxiliary property such as solidifying extend, toughness, corrosion, creep resistance, or organic compatibility will play an overpowering part within the effective use of the material [3]. For engineered materials production using multiple material types (multi-components) in various layers (multi-layers), various angles (multi-facets) may be one of the failure causes for the material in the finished or operating state. These NDT methods are applying in the testing the quality of pipes, tubes, aerospace, automobile, storage tank manufacturing, in military and defense, and in nuclear industries. The above reasons necessitate discussing various advanced techniques enabling adequate diagnosis/testing of engineered materials to ensure they fulfil their desired technological applications with superior performance.

2. Survey on Various Nondestructive Methods

This review of advanced NDT methods for engineered material research over the past 10 years focuses on different aspects and general methods. During engineered material manufacturing, various defects or inadequacies may occur, making it imperative that the material quality and safety concerns during active performance be assessed [1]. The basis of nondestructive testing methods is to assess the quality of the structure without risk of damage to the specimen. Most legislative guidelines for NDT depend on the suggestion of autonomous worldwide organizations, such as ISO and ASTM standards. These autonomous organizations base their guidelines in portion on the investigation of producers and a few national and universal exchange affiliations. These exchange affiliations incorporate the Universal Committee for Nondestructive Testing (UCNDT), the American Society for Nondestructive Testing, and the Nondestructive Testing Management Association [4][5]. Comparing different types of NDT techniques can be troublesome; each method is interesting and outlined for its application. The chart below (**Figure 1**) supplies a wide range of various kinds of NDT tests over several years according to the principle type of technique. The year-wise number of publications on each particular NDT technique was consolidated, although the annual total number publications are also clearly enumerated in **Figure 1**. The advanced techniques i.e., terahertz, neutron imaging and digital correlation were the most mostly used NDT technologies.

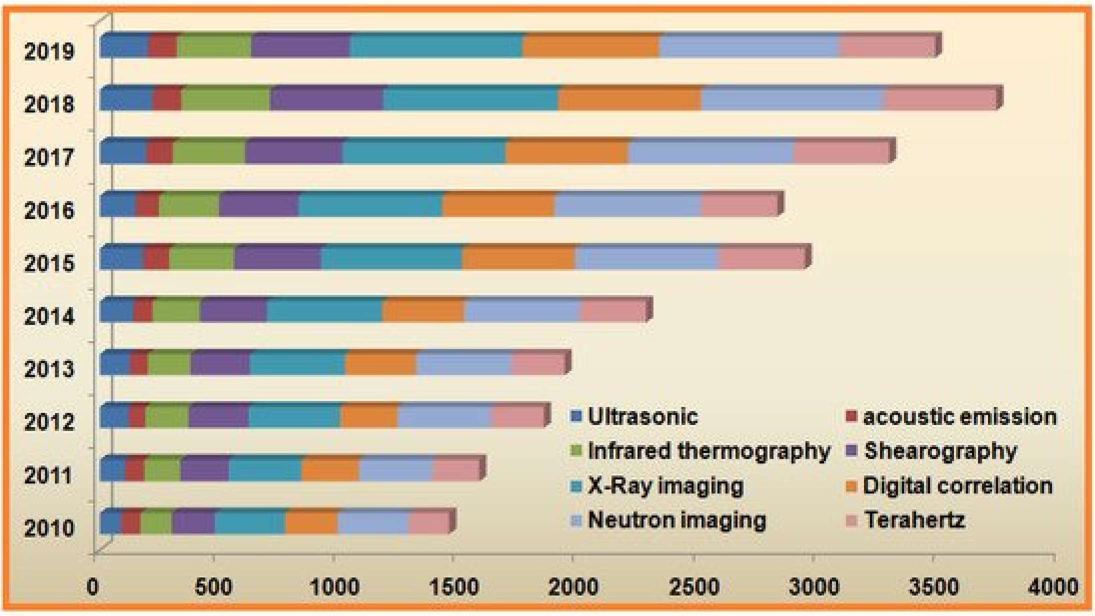

Figure 1. An assessment of publication numbers on various nondestructive methods and their applications for the last 10 years.

Nondestructive testing explains the broad range of assessment and evaluation techniques for inspection of chemical and physical properties of material, component, and systems without any sample damage. These methods broadly include ultrasonic, X-ray radiography, neutron radiography, acoustic emission, nonlinear acoustic, infrared thermography, terahertz, shearography, and magnetic flux leakage testing. Nondestructive testing methods are routinely practiced in several industrial sectors including manufacturing of pipes, storage tanks, tubes [6], aerospace products [7], military and defense materials [8], nuclear industrials, automotives [9], stress testing in a rock bolt [10], biomedical materials, and composites [11]. As per the practice reported in a recent survey, NDT analytical tools are mainly terahertz, neutron imaging, digital correlation, X-ray imaging, and infrared imaging, and either one or more of these methods were typically used for inspection and evaluation of samples in a variety of industries. We found that in recent years several modifications were established on these sampling methods, type of analysis, and critical image analysis for the assessment of samples. Several developments were reported for NDT equipment including techniques, acquisition techniques, image processing, and computing power to upgrade practices.

In image-based techniques such as X-ray radiography, neutron radiography, micro-tomography, optical techniques, infrared thermography, terahertz testing, digital imaging, and shearography the upgrades and modifications were focused in the assessment of deformities, cracks and delamination, etc. The various NDT techniques along with their explained testing areas, applications, advantages, and disadvantages are tabulated in **Table 1**.

Table 1. Review survey on NDT testing methods with their applications.

NDT Methods	Testing Area	Applications	Advantage	Disadvantages
Acoustic emission (AE)	Cracking, debonding and delamination	Composite, fiber materials	Easy detection of fatigue racks, fractures, interface debonding, microcracks in matrix and delamination	Time consumed in data processing, required skills and experience in distribution of amplitudes in overlapped areas.
Ultrasonic (UT)	Material surface and internal defects	Elements, nonmetals, forging material and glued joints	Easy to detect, precession to find defects and adaptable defect area	Testing process on complex objects is complicated and more process time.
X-ray	Internal material defects	Material casting, non-metal parts and composites	Material defects i.e., porosity, slags, material abnormal penetration	Crack finding is not possible in perpendicular axis, not possible to find depth of crack, on-site online detection and the cost also high.
Eddy current	Material surface and small defects	Electrically conductive material	The operational equipment is advanced technology, testing object surface is not required to clean and less time to complete the test	Delicate in signals owing edge effect, suddenly alter, easy to allow the wrong display.
IRT	Calculated damage thickness, interlayers, and surface	Metallic and Nonmetallic materials	Noncontact of testing object, working area is large	To detect the material defect depth, complex algorithm is required such as mathematical calculations.
Magnetic Particle	Material surface and small defects	Ferromagnetic materials	It is low cost, portable and subsurface defects also detected	Restricted to ferromagnetic materials.

This review reports state of the art developments with respect to frequently used advanced NDT techniques used for assessment of engineered materials from a perspective paradigm. Engineered materials such as composites and components used in aviation, aerospace and automotive, and biomedical applications are evaluated using advanced NDT tests to examine the purity/quality, diagnose structural health, and estimate the residual life span under specific mechanical loading situations.

It should be noted that the nondestructive technologies used in assessment and evaluation of various engineered materials are reported for developments occurring over the past 10 years (2010–2019). Therefore, related published scientific research papers were found using several search engines with a significant increase in number regarding modifications and developments over the last decade. These reported research results and development of various modifications have caused an enormous increase in number of research papers on nondestructive testing methods, and this vast number of publications served as the basis for this critical review (**Figure 2**). Primarily, this paper describes the comprehensive parameters i.e., safety, cost, time and applications, along with their principle and uses. These parameters were taking into consideration for the comparative studies and described. Descriptions are also provided as necessary to discuss how material failure occurs in the production process, how one can assess material strength, and lastly how NDT methods can be used to evaluate material efficiency. Various reasons are noted for damage/defects of engineered material properties and their integrity. Secondly, NDT techniques are classified according to their application, and advanced NDT techniques are discussed from a case approach. Lastly, combined and simultaneous methods approached as per the application requirements will be explained.

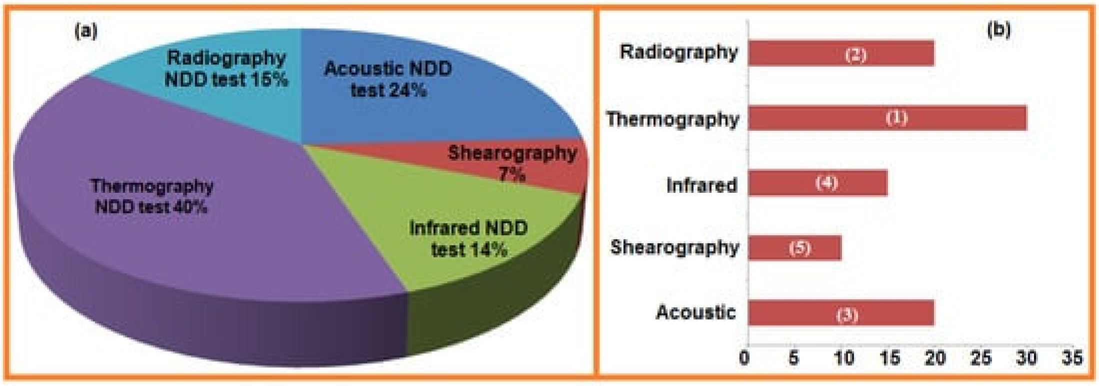

Figure 2. Recent development in the most practiced NDT techniques (**a**); number of papers reported and studied (**b**).

Failure Criteria of the Engineering Materials

Material failure hypothesis is the science of anticipating conditions under which strong materials will fail under the activity of outside loads. Essentially, engineered material failure criterion is distinguished as brittle (fracture) and ductile feature (yield). Material failure is dependent on different conditions such as temperature, stress, and internal or external load conditions. In many cases, engineered materials can fail in ductile, brittle, or both cases. Material failure criteria can be classified as macroscopic and microscopic failures. Bending moment failures, meanwhile, are often caused due to phenomenological and linear elastic fracture mechanical failure [12]. Composite polymers are widely used in railways, aerospace, and automotive industries owing to their resistance to harsh environment, bearable pay loads, and extreme mechanical properties. These composites may contain fibers, matrices, polymeric resin, and interfacial bonding in the micro- or macroscale [13]. These components may provide better mechanical properties, load bearing, and corrosive resistance. Composites commonly suffer from fatigue damage where sequential damage propagates throughout the matrix, producing cracking and debonding that can lead to major material failure. This delamination mechanism does not occur in polymer composites due to short fiber 3-D distribution [13]. Fiber breakage and delamination are considered high energetic damage while matrix cracks are least energetic damage [14].

There are several types of testing processes available in advanced composites or components for efficiency and safety evaluation. Material defects are the most common issues in composites and engineering components, and defect detection is crucial in the strategic maintenance of these structures. Defects that lead to malfunction of composite materials are composite cracking, fiber fracture, debonding, and pull-out [15]. Moreover, the NDT method is preferred for defect diagnosis without destruction and reduction of the diagnosis operational cost.

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