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CONTEMPORARY METHODS OF NONDESTRUCTIVE TESTING ON MECHANICAL CONSTRUCTION

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Summary: *Nondestructive testing has become an increasingly vital factor in the successful way of research and development, engineering and manufacturing. Only with appropriate use of nondestructive testing techniques can the benefits of advanced materials and engineering solutions be fully realized. On the other hand, application of the nondestructive testing as techniques of experimental mechanics to analysis stress state of machine components and engineering structures gives evaluation of the structure answers to loadings. The application areas and the roles of experimental analysis become more and more important according to the modern demand in mechanical engineering. It is not only a verification tool for a theory or a trial and error method to establish phenomenological relationship, but it is a speculative tool and engine of science evolution. This paper highlights the new area of nondestructive testing application on mechanical construction.*

Keywords: *nondestructive testing, integrity assessments, stress state, detection, measurement*

1. INTRODUCTION

Test methods which involve procedures used for examining an object, material or system without influence to its future usefulness has been defined as nondestructive testing. Nondestructive testing is concerned in a practical way with the performance and properties of the test samples [1]. While nondestructive testing answers if there is something wrong with the sample, various performance and proof tests, in contrast, answers if the sample is in satisfied working condition. Another area that provokes various interpretations in defining nondestructive testing is that of future usefulness of examined object. Some material testing involves taking a sample of the examined object for testing that is essentially destructive. For example a noncritical part of a pressure vessel may be worn out to get a sample for electron microscopy. Although future usefulness of the vessel is not defected by the loss of material, the procedure is essentially destructive and the worn out by itself, in one sense, the true "test object", has been removed from service permanently.
The idea of future usefulness is relevant to the quality control practice of sampling. Sampling is nondestructive testing method if the tested sample is returned to service. Nondestructive testing is not limited only to crack detection and involve also other discontinuities such as porosity, wall thinning from corrosion and many sorts of defects. Nondestructive material characterization is a growing area concerned with material properties including material identification and micro structural characteristics that have a direct influence on the life time circle of the examined object. Nondestructive testing has also been defined by listing or classifying the various methods. This approach is practical in that it typically highlights methods in use by industry.
Increased complexity of modern machines, however, could never have been achieved without parallel development in advances of nondestructive testing.

1.1. Increased demand on nondestructive testing

In the interest of reducing power consumption and rising costs of materials, the engineer is always under pressure to reduce weight. This can sometimes be done by substitute of steel or iron alloys by aluminum or magnesium alloys and composites materials, but such light weight solutions are not of the same size and shape as

those they replace. The tendency is also to reduce the geometric dimensions. These demands on the engineer have subjected parts of all sorts to increased stress levels. The stress to be supported is rarely static. It often fluctuates and reverses at low or high frequencies. Frequency of stress reversals increases with the speeds of modern machines and thus parts tend to fatigue and fail more rapidly.
Another cause of increased stress on modern machines is a reduction in the classical safety factor. Because of other considerations, a lower factor is often used, depending on the importance of lighter weight or reduced cost or risk to safety.
New demands on machines have also stimulated the development and use of new materials whose behaving characteristics, properties and performances are not completely known. These new materials create greater and potentially dangerous problems. Sufficient and proper nondestructive tests could have helped in investigation of structural integrity and assessments of the machine elements and systems made of such materials.
As technology improves and working characteristic requirements increases, machines are subjected to greater variations and to wider extremes of all kinds of stresses, creating an increasing demand for stronger and stronger materials.
Another motivation for the use of nondestructive tests is the engineer's demand for materials with better and better application properties. As size and weight decrease and the factor of classical safety is lowered, more and more emphasis is placed on better raw material control and higher quality of materials, manufacturing processes and workmanship.
Very often producer of raw materials or of half finished products does not improve quality and performance until that improvement is demanded by the high end customers. The pressure of the customers is transferred to implementation of improved design or advanced manufacturing processes. Nondestructive testing is frequently used to carry and support this new quality level.
The demands and expectations of the public for greater safety are obvious everywhere. This demand for safety has been another strong force in the development of nondestructive tests.
If rising costs are considered briefly with factors for the rising costs of mechanical failure, it could be found that costs are increasing for many reasons, for example: [12]

- greater costs of materials and labor;
- greater costs of complex parts;
- greater costs due to the complexity of assemblies;
- greater probability that failure of one part will cause failure of the others, due to provoked overloads;
- trend to lower factors of safety;
- probability that the failure of one part will damage other parts of high value and
- failure of a part within an automatic production machine may shut down an entire high speed, integrated, production line. When production was carried out on many separate machines, the broken one could be bypassed until repaired. Today, one machine is tied into the production with several others. Loss of such production is one of the greatest losses resulting from part failure.

2. CLASSIFICATION OF NDT METHODS

Nondestructive testing is an area of the testing that is concerned with all aspects of the uniformity, quality and serviceability of machine materials, elements and structures. The science of nondestructive testing incorporates all the technology for detection and measurement of significant properties, including discontinuities, in objects ranging from research specimens to finished mechanical structures and products. By definition, nondestructive techniques are the means by which materials and structures may be tested without disruption or harm to future usefulness and characteristics.
However, the information required for appreciating the large range of nondestructive testing is widely evaluated in a many publications and reports. Tables 1 and 2 summarize data about nondestructive testing methods and procedures to show their purposes and similarities [11].
Method refers to the specialized procedures, techniques and instruments associated with each nondestructive testing approach. There are usually many techniques or procedures associated with each method. The following paper describes these methods without details on application or procedure, providing a resume of each method in a single place, for very quick reference.
Nondestructive testing usually can be classified into six major categories: visual, penetrating, radiation, magnetic - electrical, mechanical vibration, thermal and chemical - electrochemical. A version of the classification system is presented in Tab.1. with additional categories included to cover newly developed methods. The first six categories involve basic physical processes that require transfer of matter or energy to the object being tested. Two auxiliary categories describe processes that provide transfer and accumulation of information, and evaluation of the signals and images common to nondestructive testing methods.

Table 1: Nondestructive testing method categories [11]

Basic Categories	Objectives
Mechanical and optical	color, cracks, dimensions, film thickness, gauging, reflectivity, strain distribution and magnitude, surface finish, surface flaws, through-cracks
Penetrating and radiation	cracks, density and chemistry variations, elemental distribution, foreign objects, inclusions, micro porosity, misalignment, missing parts, segregation, service degradation, shrinkage, thickness, voids
Electromagnetic and electronic	alloy content, anisotropy, cavities, cold work, local strain, hardness, composition, contamination, corrosion, cracks, crack depth, crystal structure, electrical and thermal conductivities, flakes, heat treatment, hot tears, inclusions, ion concentrations, laps, lattice strain, layer thickness, moisture content, polarization, seams, segregation, shrinkage, state of cure, tensile strength, thickness, disbands
Sonic and ultrasonic	crack initiation and propagation, cracks, voids, damping factor, degree of cure, degree of impregnation, degree of sintering, delaminations, density, dimensions, elastic moduli, grain size, inclusions, mechanical degradation, misalignment, porosity, radiation degradation, structure of composites, surface stress, tensile, shear and compressive strength, disbands, wear
Thermal and infrared	bonding, composition, emissivity, heat contours, plating thickness, porosity, reflectivity, stress, thermal conductivity, thickness, voids
Chemical and analytical	alloy identification, composition, cracks, elemental analysis and distribution, grain size, inclusions, macrostructure, porosity, segregation, surface anomalies
Auxiliary Categories	**Objectives**
Image generation	dimensional variations, dynamic performance, anomaly characterization and definition, anomaly distribution, anomaly propagation, magnetic field configurations
Signal image analysis	data selection, processing and display, anomaly mapping, correlation and identification, image enhancement, separation of multiple variables, signature analysis

Each method can be completely characterized by five principal factors [12]:

- energy source or medium used to probe the test object (such as X - rays, ultrasonic waves or thermal radiation);
- nature of the signals, image or signature resulting from interaction with the test object (reduction of X - rays or reflection of ultrasound, for example);
- means of detecting or sensing resulting signals (photo emulsion, piezoelectric crystal or inductance coil);
- method of indicating or recording signals (meter deflection, oscilloscope trace or radiograph) and
- basis for interpreting the results (direct or indirect indication, qualitative or quantitative, and relevant dependencies).

The objective of each test method is to provide information and data about the following material parameters and properties [10]:

- discontinuities (such as cracks, defections, inclusions, delaminations);
- structure or microstructure (including crystalline structure, grain size, segregation, misalignment);
- dimensions and metrology (thickness, diameter, gap size, discontinuity size);
- physical and mechanical properties (reflectivity, conductivity, elastic modulus, sonic velocity);
- composition and chemical analysis (alloy identification, impurities, elemental distributions);
- stress and dynamic response (residual stress, crack growth, wear, vibration) and
- signature analysis (image content, frequency spectrum, field configuration).

The limitations of a method include conditions required by that method such as conditions to be met for technique application (access, physical contact, and preparation) and requirements to adapt the sample or sample medium to the test object. Other factors limit the detection or characterization of discontinuities, properties and other attributes and limit interpretation of signals or generated images.

3. OVERVIEW OF MAIN NONDESTRUCTIVE METHODS AND PROCEDURES

Nondestructive testing is an analysis technique used in scientific and industry areas to determine the state or function or properties of a system without the use of invasive approaches. Because nondestructive testing does not require the disabling or sacrifice of the system of interest, it is a valuable technique that saves both money and time in product evaluation, troubleshooting and research.

Table 2: Objectives of nondestructive testing methods [12]

Objectives	Attributes Measured or Detected
Discontinuities	
Surface anomalies	roughness, scratches, gouges, crazing, pitting, inclusions and imbedded foreign material
Surface connected anomalies	cracks, porosity, pinholes, laps, seams, folds, inclusions
Internal anomalies	cracks, separations, cold shuts, shrinkage, voids, lack of fusion, pores, cavities, delaminations, disbands, poor bonds, inclusions, segregations
Structure	
Microstructure	molecular structure, crystalline structure and strain, lattice structure, strain, dislocation, vacancy, deformation
Matrix structure	grain structure, size, orientation and phase, sinter and porosity, impregnation, filler and reinforcement distribution, anisotropy, heterogeneity, segregation
Small structural anomalies	leaks (lack of seal or through holes), poor fit, poor contact, loose parts, loose particles, foreign objects
Big structural anomalies	assembly errors, misalignment, poor spacing or ordering, deformation, malformation, missing parts
Dimensions and metrology	
Displacement, position	linear measurement, separation, gap size, discontinuity size, depth, location and orientation
Dimensional variations	unevenness, nonuniformity, eccentricity, shape and contour, size and mass variations
Thickness, density	film, coating, layer, plating, wall and sheet thickness, density or thickness variations
Physical and mechanical properties	
Electrical properties	resistivity, conductivity, dielectric constant and dissipation factor
Magnetic properties	polarization, permeability, ferromagnetism, cohesive force
Thermal properties	conductivity, thermal time constant and thermoelectric potential
Mechanical properties	compressive, shear and tensile strength (and module), Poisson's ratio, sonic velocity, hardness, temper and embrittlement
Surface properties	color, reflectivity, refraction index, emissivity
Chemical composition and analysis	
Elemental analysis	detection, identification, distribution and profile
Impurity concentrations	contamination, depletion, doping and diffusants
Metallurgical content	variation, alloy identification, verification and sorting
Physiochemical state	moisture content, degree of cure, ion concentrations and corrosion, reaction products
Stress and dynamic response	
Stress, strain, fatigue	Heat treatment, annealing and cold work effects, residual stress and strain, fatigue damage and life (residual)
Mechanical damage	wear, erosion, friction effects
Chemical damage	corrosion, stress corrosion, phase transformation
Other damage	radiation damage and high frequency voltage breakdown
Dynamic performance	crack initiation and propagation, plastic deformation, creep, excessive motion, vibration, damping, timing of events, any anomalous behavior
Signature analysis	
Electromagnetic field	potential, strength, field distribution and pattern
Thermal field	isotherms, heat contours, temperatures, heat flow, temperature distribution, heat leaks, hot spots
Acoustic signature	noise, vibration characteristics, frequency amplitude, harmonic spectrum and analysis, sonic and ultrasonic emissions
Radioactive signature	distribution and diffusion of isotopes and tracers
Signal or image analysis	image enhancement and quantization, pattern recognition, densitometry, signal classification, separation and correlation, discontinuity identification, definition (size and shape) and distribution analysis, discontinuity mapping and display

Each of the nondestructive testing methods has advantages and disadvantages when compared to other methods what can be concluded by evaluating information given in Tab.1 and Tab.2. This paper does not deal with nondestructive testing technique and testing technique shown here are just for very quick reference. All non destructive testing methods and procedures shown, as illustrations, in this paper were carried out in Laboratory for integrity assessment at Forli airport, University of Bologna - DIEM - Department of Mechanical Engineering.

3.1. Penetrant Testing

Penetrant solution is applied to the surface of examined object. The liquid is pulled into surface breaking defects by capillary action. This method is used to trace cracks, porosity, and other defects that break the surface of a material and have enough volume to trap and hold the penetrant liquid. Main advantages of penetrate nondestructive testing can be recognized as large surface or large volumes of examined parts can be tested fast and with low cost, parts with complex geometry are easily tested, indications are produced directly on surface of the part providing a visualisation of the discontinuity. Main disadvantages can be recognized as this method detects only surface breaking defects and this method is sensitive to surface preparation because contaminants of surface can mask defects, requires a relatively smooth and nonporous surface, cleaning after procedure is necessary to remove chemicals, requires multiple operations under controlled conditions with chemical handling precautions. In the Fig.1. example of penetrant nondestructive testing method on cover of shift plane propeller is shown.

Figure 1: Example of penetrant nondestructive testing method [3]

3.2. Magnetic Particle Testing

Magnetic particle testing (illustrative example shown in Fig.2.) is used for the detection of surface and near surface defects in ferromagnetic materials by that result in a transition in the magnetic permeability of a material. Advantages of this nondestructive testing technique can be recognized as large surface of complex geometry parts can be examined fast with detecting surface and subsurface defects, surface preparation is less critical than it is in penetrant testing. Disadvantages of magnetic particle testing can be recognized as only ferromagnetic materials can be examined, proper alignment of magnetic field and defect is critical, large homogeneous magnetic fields are needed for large parts, requires relatively smooth surface while paint or other nonmagnetic coverings badly affect sensitivity and also cleaning after testing procedure is necessary.

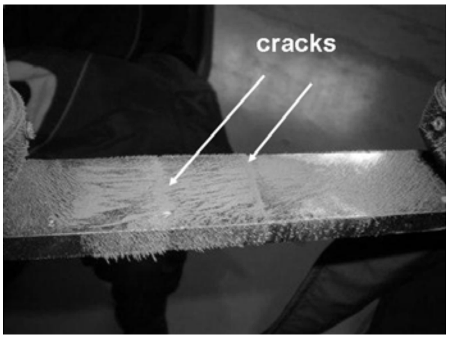

Figure 2: Illustrative example of magnetic particle nondestructive testing method [3]

3.3. Ultrasonic nondestructive Testing

Ultrasonic nondestructive testing method uses high frequency sound wave beams introduced into materials for the detection of subsurface discontinuities in examined object. This non destructive testing method can be used to locate surface and subsurface defects in many materials including metals, plastics, and wood. Ultrasonic testing is also used to measure the thickness of materials and otherwise characterize properties of material based on sound velocity and reduction measurements.
Advantages of this method are very significant such as depth of penetration for discontinuities detection or measurement is superior to other methods, only single sided access is required, provides distance information, minimum part preparation is required, method can be used for providing much more information and data than just defect detection of defects.
Ultrasonic nondestructive testing method disadvantages are: surface must be accessible to probe (Fig.3.) and compliant, skill and training required is more general than other technique, surface finish and roughness can interfere with inspection, thin parts may be difficult to inspect, linear defects oriented parallel to the sound beam can be undetected, reference standards are often needed.

Figure 3: Ultrasonic probe for nondestructive testing [3]

3.4. Eddy Current Testing

Eddy currents provoked their own magnetic field that can be measured and used to find defects and characterize conductivity, permeability, and dimensional characteristics. Eddy current testing apparatus is shown in the Fig.4. This method is used to detect surface and near - surface defects in conductive materials, such as the metals. Eddy current non - destructive testing is also used to sort materials based on electrical conductivity and magnetic permeability. This method is also used for measuring the thickness of thin sheets of metal and nonconductive coatings such as paints. Advantages of this method can be recognized as it detects surface and near surface defects, test probe does not need to contact the part, method can be used for more than defect detection, minimum sample preparation is required.

Disadvantages of this examination technique are: only conductive materials can be inspected, ferromagnetic materials require special treatment to address magnetic permeability, depth of penetration is limited, defects that is parallel to the testing probe coil winding direction can be undetected, skill and training required, surface finish and roughness may interfere, reference standards are needed for setup procedure.

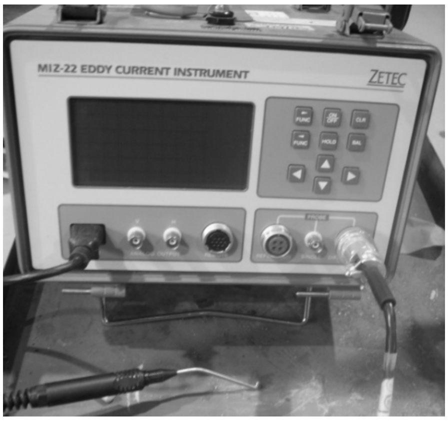

Figure 4: Equipment for Eddy current nondestructive testing method [3]

3.5. Picture Correlation Testing

Picture correlation is one of the advanced non destructive testing techniques. Example of testing set up for picture correlations shown in the Fig.5. Main characteristics of these measurements are: application on almost any components and shapes**,** full field information available in seconds**,** shows strain gradients, detailed load analysis of components. Main disadvantage of this technique is high cost of testing equipment. This technique open possibility of hybrid approach to the problem of testing both experimental and numerical.

3.5. Strain Gauges Testing

Strain gauge was used to measure the strain on an object. If strain gage is properly attached onto the surface of a structure which strain is to be measured, the strain gage will also elongate or contract with the structure, and due to change in length and cross section, the resistance of the strain gage changes accordingly. Main disadvantage of this method is that full field testing cannot be done. This method is low cost and very easy to use and it can be used for continual monitoring of working characteristic of the construction with remote measuring as shown, for example, in the Fig.6.

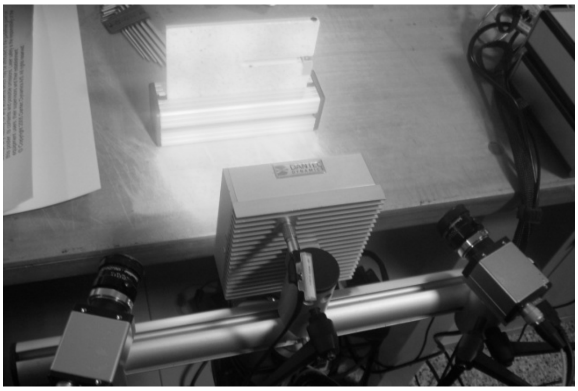

Figure 5: Testing set up for picture correlation nondestructive testing method [3]

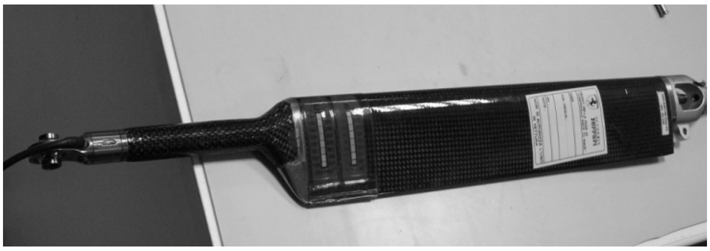

Figure 6: Strain gauges for continual monitoring of working characteristic with telemetry [3]

3.6. Photoelasticity Testing

Photoelasticity is a testing technique for the measurement of stresses and strains in material objects by means of the phenomenon of mechanical birefringence. Photoelasticity is a method of analyzing stresses which is based on the characteristic of photoelastic materials to become optically anisotropic in a loaded condition. Optical anisotropy of these materials can be measured with polarized light in a polariscope and depends on the value and the distribution of the stresses in them. Photoelasticity is especially useful for the study of objects with irregular boundaries and stress concentrations, such as pieces of machinery with notches or curves, structural components with slits or holes, and materials with cracks (example shown in the Fig.7.). The method provides a visual means of observing overall stress characteristics of an object by means of the light patterns. This method can be very useful to establish boundary conditions, and conditions around singularities for further using in FEM evaluation.

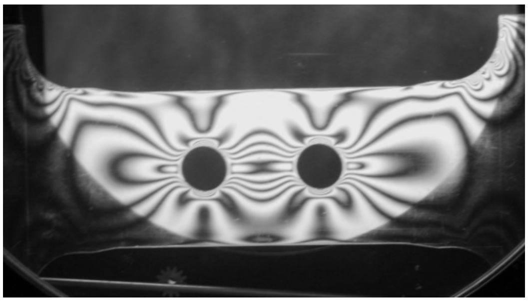

Figure 7: Example of photoelasticity examination[3]

4. CONCLUSIONS

As concerns about population growth, global warming, resources lack, globalization, and environmental degradation have increased, it has become apparent that engineering must be engaged more effectively to advance the goal of sustainability. This will require a new framework that incorporates sustainability factors as explicit performance criteria. Sustainability has been defined as "meeting the needs of the current generation without impacting the needs of future generations to meet their own needs" and is often interpreted as the simultaneous advancement of prosperity, environment and society.
The practice of engineering is continually changing so as nondestructive testing as one of the main testing method. Engineers today must be able not only to succeed in an environment of rapid technological change and globalization, but also to work on interdisciplinary teams to evaluate and improve own engineering solutions.

Cutting edge research is being done at the intersections of engineering disciplines as area of nondestructive testing and successful researchers and practitioners must be aware of developments and challenges in areas other than their own.
Growth of finite element methods (FEM), because of the quality and versatility of the commercial packages, it seems as though all analyses are now done with FEM. But, also, in worldwide industry there has been a corresponding moving back to experimental methods such as nondestructive testing and experimental stress analysis in particular. On the other hand, the nature of the problems has been changed. In product development, there was a time when provided the solution directly, for example, the stress at a point or the failure load is essential. In research, there was a time when experimental stress analysis gave insight into the phenomenon, for example, dynamic crack initiation and arrest. What they both had in common is that they attempted to give "the answer". In short, we identified an unknown and designed experiment to measure it. Modern problems are far more complex, and the solutions required are not open to simple or discrete answers. The engineering point to be made is that every experiment or every nondestructive testing method is ultimately incomplete; there will always be some unknowns, and at some stage. So nondestructive testing become at the present time main factor in evaluating and improving engineering solution and design of mechanical construction.

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