

Tomographic Methods for Non-Destructive Testing of Material Properties

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Abstract: *The non-destructive testing is an important task in almost every area of human activity, from ensuring the integrity of aircraft to assessing infrastructure degradation caused by deterioration or damage. The development of non-destructive methods of quality management results in economic and environmental benefits, results in increased product coverage and improved public safety and security. This dissertation presents an overview of the existing traditional methods and innovative developments and new applications in the area. It includes the most advanced non-destructive testing methods including optical, acoustic, ultrasonic and electromagnetic techniques, tomography, radiography and thermography. The results are intended for researchers and practitioners related to research, testing and maintenance of machines, products and components in laboratory and industrial environments.*

Keywords: *computer tomography, non-destructive testing, non-destructive methods, non-destructive testing of composite materials*

1. Non-Destructive Testing

The use of defective components in manufacturing processes where their braking due to failure is critical is traditionally regulated by removing these components from service before the expiry of their estimated lifetime. Such an early "retirement" of materials does not guarantee that a part will not be damaged in use. The rising cost of such a life expectancy increases the demand for improved coverage of quality control in industry and imposes alternative forms of quality control. Modern applications include non-destructive evaluation (NDE), also called NDT, as a means of monitoring levels and developing defects in materials during their lifetime.

We offer the following common definition, unifying the main features of ND methods:

Non-destructive methods are related to the process of assessing and verifying materials or components to characterize or find defects and deficiencies in comparison with some standards without altering the original properties or causing damage to the object to be tested, the methods being cost-effective and can be applied to both testing of a sample for an individual investigation or the entire material to verify a quality system for quality control.

There are a number of methods for assessing materials or components and non-destructive testing is an important category of them with many applications. Non-destructive evaluation (NDE) or non-destructive testing (NDT) includes identification and characterization of damage to the surface and inside of materials without cutting, separation or other material changes (Lockard, 2015). In other words, non-destructive testing refers to the process of assessing and verifying materials or components to characterize or find defects and deficiencies compared to some standards without altering the original properties or causing damage to the object to be tested. ND techniques offer cost-effective means of testing a sample for an individual investigation or can be applied across the entire material to check a production quality control system (Newswire, 2013).

In the case of composite materials during their processing, component manufacturing or in operation, a number of injuries may occur, most often due to the occurrence of cracks and porosity. A number of non-destructive control methods are effective in testing components for defects without damaging the component. Ultrasonic testing, X-Ray, radiography, thermography, vortexing and acoustic emissions are topical techniques for a variety of non-destructive testing applications. Each of these techniques uses different principles for detecting defects in the material. However, the geometry, physical and material properties of the component to be tested are important factors for the applicability of the technique. This chapter discusses these BC techniques and compares them in terms of characteristics and applicability in composite parts.

The main types of non-destructive testing methods include contact and non-contact methods, both of which have their specific applications in testing and evaluation of

composite materials. Most ND techniques require good contact between the sensor and the tested composite surface in order to obtain reliable data. Methods for establishing such contact are traditional ultrasonic tests, Foucault currents, magnetic testing, electromagnetic testing, and penetration testing. Another approach to speeding up the data collection process is to eliminate the need for physical contact between the sensor and the test structures. Contactless methods here are using ultrasonic waves, radiography, thermography, sharography and visual inspection (Newswire, 2013). Optical methods (such as thermography, holography or sharography) are mostly non-contact. Table 1 provides categorized contact and non-contact methods for non-destructive testing. Various non-destructive techniques are used in the industry as defect detection applications. Every technique used has its disadvantages and advantages.

Table 1: Contact and non-contact methods for non-destructive testing

Contact methods for examination	Non-contact methods of investigation
Traditional ultrasound tests	By ultrasonic transmission
Foucault Radiography Testing	Radiography
Magnetic testing	Thermography
Eletromagnetic	With infrared waves
With penetrating liquids	Holography
With penetrating liquids	Sharrography
-	Visual inspection

2. Non-Destructive Methods For Composites

There are different test methods for composites. It is important to pay sufficient attention to factors such as effectiveness and safety in analyzing what is the best method of implementation in a given situation. In addition, the chosen method must minimize the cost of performing the tests. Material defects are the major sources of damage to composite materials. These damages may take the form of cracks, layer separation, structure fractures and stretching (Mckuur, 2006). Structural integrity is a formalized process that uses state-of-the-art nondestructive methods to detect, locate, and determine the extent of damage (Andrzej Katunin et al., 2015). Non-destructive testing methods can be categorized according to the factors they evaluate. Such a division is shown in Table 2.

Table. 2: Categorization of non-destructive testing methods

Category	Applications
Assessment of physico-mechanical properties, and detection of significant deficiencies in composites	Measurement of Dynamic Mechanical Analysis (DMA) (Sturm et al., 2015), phase quantity (El-Sabah et al., 2013), mechanical strength and hardness (Ray, 2006), elastic constants (Rojek et al., 2015), material content (El-Sabah et al., 2013), appearance of defects and subsequent developments (Talreja, 2008), lamination (Ghadermazi et al., 2015), laminate construction (Scarselli et al., 2005), resilient hardening (Aggelis & Paipetis, 2012), phase / matrix interface condition (Kersemans et al., 2014).
Determination of the integrity of structural components made of composite materials	Detection of cracks and delamination (Giurgiutiu, 2016), mechanical friction (Gostautas et al., 2005), fibrous detachment (Short and al., 2002), phase fracture (Narita et al., 2014).

Computed Tomography

Computed tomography is an innovative method for visualizing of images obtained from non-destructive material research. Radiographic research relies on the use of X-rays to penetrate into matter and create the image of the inner structure of the object. The distribution of densities in the structure will result in a different input value of the x-ray image. Computer tomography (CT) scan is an X-ray device that produces a three-dimensional image. For industrial CT scans, this image is created by placing an object on a rotating table and creating a series of two-dimensional x-ray images representing a view from different angles of the material. These slices can be combined to form a three-dimensional representation of the object. Depending on the density of the material, X-ray photons will either be absorbed, scattered, or will pass unhindered. The photons are collected by a detector; the areas through which more photons have gone unhindered will have a higher output density of the collected photons. This means that the material has air gaps or pockets. The appearance of a darker image area occurs with a larger number of photons passed, the darker pixel is represented by a lower gray scale, meaning delamination areas are expected to have lower values than the surrounding areas of the image.

X-ray radiation is widely used for imaging, its large depth of penetration makes the method ideal for non-destructive visualization of the internal structure and / or material deficiencies that can not otherwise be achieved. Currently, non-destructive evaluation tools - X-ray and tomography - are based on absorption and work well for heavy elements where the density or composition variations due to the internal structure or defects are high enough to result in significant absorption contrast. However, in many cases, when materials are light and / or composite having similar mass absorption coefficients, conventional X-ray methods based on absorption become less useful. In fact, the lightweight and ultra-high strength requirements for

the most advanced materials pose a great challenge to standard NDE tools as the absorption contrast resulting from the internal structure of these materials is often too weak to be used. There are methods of imaging based on absorption and phase contrast image.

Composites are materials that consist of more than one base material, the individual materials retaining their own structure and properties instead of forming a combined alloy. This allows the combination of the advantages of the component materials. Different types of materials show significantly different properties in CT imaging. Some non-composite materials such as stainless steel are relatively uniform in the texture, with anomalies that are represented by distinctly different areas in different values in the gray scale of the base material. For example, a common problem that arises with stainless steel is the formation of air bubbles during the welding process, which results in spherical porosity in the material. On computer scan, these cavities appear as very dark circles with well-defined boundaries wrapped in much lighter surrounding material.

X-ray computed tomography, sometimes abbreviated to XCT or iCT (i for industrial), is a method of using X-ray radiation to construct 2D images of an object at many positions around the axis of rotation. From these images using software, a three-dimensional (3D) model of the object's external object can be built, reconstructed and the internal structure analyzed. CT is similar to magnetic resonance imaging (MRI), but where MRI uses non-ionizing radiofrequency to determine the magnetic resonance of hydrogen molecules, CT uses ionizing radiation and measures X-ray absorption. Therefore, the two techniques have different application areas. CT is a useful tool for exploring high atomic number materials, while MRI is an extremely useful method in the study of soft biological tissues. Other 3D imaging techniques using neutron sources are currently being developed for soft materials and some overlapping in methodology and applications. Typical areas of CT use in industry are to detect deficiencies such as cracks and cracks and particle analysis in materials. In metrology, CT allows measurement of both external and internal geometry of complex parts. Until now, CT has been the only technology capable of measuring both internal and external geometry of a component without the need for its destruction or fragmentation.

As such, it is the only technology for industrial quality control of machined parts that have inaccessible internal characteristics (for example components produced by the manufacture of additives) or multi-component components (for example, two-component injection molded plastic parts or plastic parts with metal inserts). CT may be considered as the third revolutionary development in coordinate metrology following the introduction of tactile 3D CMMs in the seventies, and that of optical three-dimensional scanners in the eighties. The number of industrial applications of CT is large and fast growing. Nowadays, CT application in the industry involves quality control, with the main purpose of measuring size and detecting defects.

For new materials such as metal foam and CFRP (carbon fiber reinforced plastic) and other composite materials, CT will allow new technical solutions. Procedures for

testing these materials as well as component testing should follow the technology, resulting in a significant market share of industrial CT systems.

CT imaging systems and other industrial applications without the need to break the object of investigation are fundamentally different from clinical scanners. In these systems, the subject rotates under the X-ray beam while the X-ray source and the detector remain stationary. There is no such restriction on radiation intensity here and it is greater than that applied to clinical CT. Moreover, because the resolution and accuracy requirements are different, the scanning parameters usually differ significantly from those in clinical CT (Kalender, 2011; Kastner, 2012). Resolution and accuracy can be adjusted by moving the axis of rotation that supports the subject or closer to the source (greater pixel zoom and pixel resolution but more blur) or closer to the detector (clearer images, but smaller resolution) (Kruth, 2011). This is usually not possible with clinical scanners where the axis of rotation is centered between a source and a detector. In contrast to clinical scanners, most CT imaging systems for industrial analysis use cone beam geometry and flat panel detectors, resulting in a hundred-fold reduction in scanning time (multiple visual incisions measured with one turn) and good image quality (Goebbels & Zscherpel, 2011). Radiation fan geometry systems and linear detectors are also used, especially to reduce scattering effects when it is to be deeply penetrated using high-voltage pipes.

Scan Parameters

→ Resolution

Many factors influence the spatial resolution of reconstructions, including: x-ray focal spot size, detector efficiency, magnification, number of projections, reconstruction algorithms, and data processing. Focusing size is particularly important when determining image quality. Systems with a focal spot size greater than 0.1 mm are commonly referred to as conventional CT or macro CT. Microfocus systems (mCTs) have a focal length of up to one micrometer or several micrometers. Nano-focal systems (nanoCT) can reach a size below the micrometer, which is currently up to 0.4 mm. Synchronous CT (sCT) systems can reach 0.2 mm resolution, and a 0.04 mm resolution (Requena et al., 2009) can now be reached with Kirkpatrick-Baez optics (sCT + KB). Figure 1 shows typical spatial resolution ranges for the tomography systems under consideration above.

→ Scan Speed

Unlike the coordinate measuring machines, CT scanning time is independent of the number of object characteristics. On the other hand, scanning time depends on a number of parameters, including exposure time, number of projections, and data processing efficiency (Kruth et al., 2011). A typical scanning time for industrial CT beams currently varies from a few minutes to one or several hours (Christoph et al., 2011).

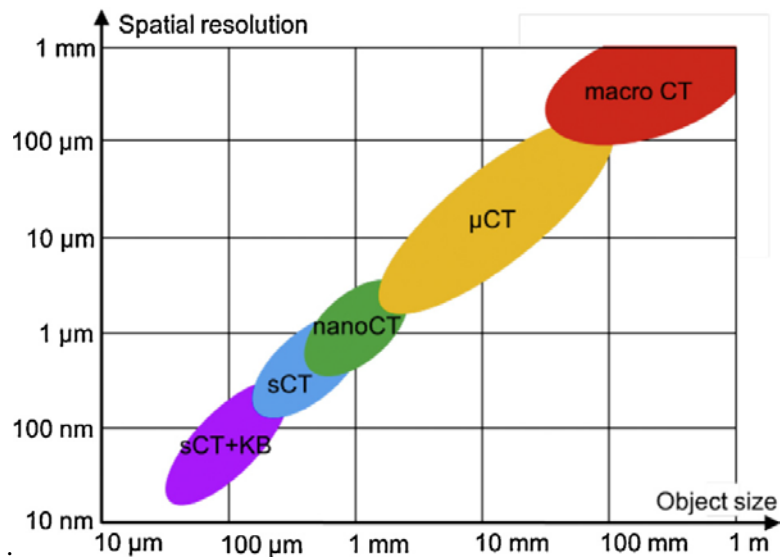


Figure 1. Typical spatial resolution and object dimensions (diameter) for macro CT, micro CT, nano CT, synchrotron CT (sCT) and synchrotron CT with KB mirrors (sCT + KB) (De Chiffre et al., 2014)

→ **Measuring Diaphase**

There are many different types of CT systems: desktop CT with reduced measurement to CT large scale. The dimensions of the object that can be scanned in these systems is limited by the measured volume between the source and the detector and also depends on: the applied magnification due to the cone beam geometry, the maximum thickness of the penetrating material, and the CT system's capability for expanded scanning procedures such as scanning a region of interest, advanced field scanning, and spiral scanning.

→ **Maximum Depth Of Injection**

The maximum depth of the material in which X-rays can penetrate depends on the attenuation coefficient (wave absorption and sputtering) of the material and the X-ray energy photon. Typical values for ordinary materials are given in Table 3; full charts and graphs are available in the literature (Chantler, 2000; NIST) Before scanning, the object should be oriented in order to minimize the thickness of the material as much as possible. Optimal parts orientation should also minimize the penetration depth variation during rotation of the object in order to avoid saturation or extinction of pixels in X-ray projections (Weckenmann & Kraemer, 2009).

Table 3. Maximum depth of penetration in traditional materials (Christoph & Neumann, 2011)

Intensity of rays	130kV	150kV	190kV	225kV	450kV
Steel / ceramics	5mm	<8mm	<25mm	<40mm	<70mm
Aluminium	<30mm	<50mm	<90mm	<150mm	<250mm
Plastic	<90mm	<130mm	<200mm	<250mm	<450mm

→ **Rength Dose**

While the scan radiation dose is particularly important in clinical and biological CT, the effects of X-ray exposure on the scanned object are often negligible in industrial CT assay methods. However, in some cases the X-ray dose should be limited to avoid degradation of the materials studied, for example in the case of polymers (Cardoso & Kawano, 1994) and to prevent specific effects, such as color modifications in precious stones (Pough & Rogers , 1947).

→ **Multifunctional Scan Options**

The ability to analyze objects made up of multiple materials is a common requirement in some industrial applications. CT scanning of such objects is associated with difficulties due to different X-ray attenuation in different materials and specific images of artifacts (Verburg & Seco, 2012). CT manufacturers offer different solutions to facilitate measurements of objects containing different materials through multi-spectral scanning, including: multi-material targets (for example, different indexable head materials), dual source CT and energy-sensitive sandwich detectors (Fornaro & Leschka, 2011). Another problem that requires particular attention in performing CT measurements of details with different materials is the identification of adequate thresholds for proper surface determination. When compiling statistical hypotheses, the results are statistically significant when they are very unlikely to occur under a zero hypothesis. More precisely, the level of significance defined for one study, α , is the probability of the study to reject the null hypothesis, given that the p-value of the result was true, p is the probability of obtaining a result in the end values, when the zero hypothesis was true. The result is statistically significant, according to study standards, when $p < \alpha$. The signaling level for one study is selected prior to data collection and is usually set at 5% or much lower, depending on the area of study. The level of significance α is the threshold for p , under which the conducting test assumes that the null hypothesis is false and something else is happening. This means that α is the probability of wrong hypothesis rejection if the null hypothesis is true.

→ **Accuracy**

As with other measurement systems (Carmignato et al., 2010; Wilhelm et al., 2001), the uncertainty of CT measurement depends on the specific object and the specific parameters selected for the measurement process. Factors influencing precision measurement are listed and discussed by Kruth et al., 2011. The results of the first international interlaboratory comparison of the CT systems used to measure the dimensions in 2011 (Carmignato, 2012) show that the accuracy of sub-level level is possible for dimensional measurements with artefacts CT systems. In particular, the comparison showed that measurement errors of the order of 1/10 of the voxel size were available for dimensional measurements, while form measurements were more affected by the noise impact of CT data (Carmignato et al., 2012).

Smoothing Of The Image

Images obtained by CT scanning of composite materials often contain high noise. The adjacent pixels may have significant differences in values, although the material should have relatively homogeneous characteristics. Smoothing or blurring of the image reduces these local variations and allows a better understanding of the actual localized trend in an image.

There is a high level of local variation in the pixel value. Even in delamination zones (centered around region 100 and region 200), many pixels fall in the same range as the surrounding areas (see image below). Calculating a regression model for this signal will result in only a few of the pixels in the delamination zone being identified as a deviation. It should be noted that it is not easy to see where the delamination occurs when visualizing the signal as only the scattered individual pixels appear as end values.

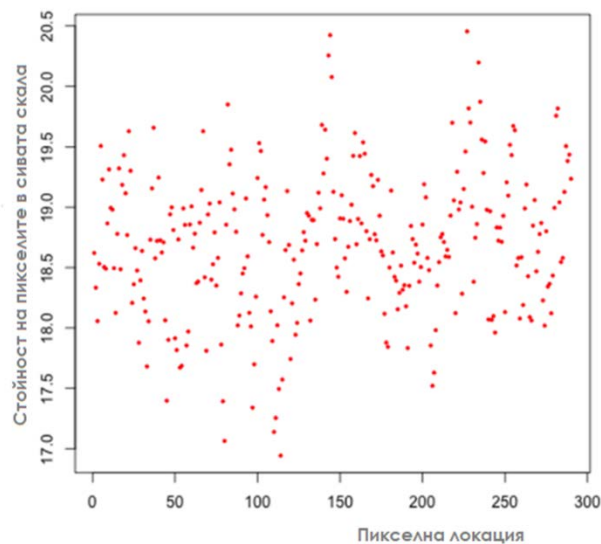


Fig.3. Smoothing involves calculating some statistics, typically some form of average value in a region of some size around each pixel in the image, and replacing the pixel value with the new one.

Several types of smoothing lines can be used to blur images with different subsequent properties. This thesis proposes the use of a filter at the average imaging value of BC of carbon fiber materials. While this filter is sometimes desirable because of its edge-retaining properties in limited circumstances (Arias-Castro and Donoho, 2009), it creates image problems where delaminations are barely visible. This is often just a cluster of very dark points that indicate the presence of a delamination, with most of the points deviating slightly from those in the surrounding region. This will remove the influence of this small region from significantly different points, leaving the delamination undetectable. On the other hand, the average filter distributes the impact of these points so as to create an area with lower than expected pixel values that we can identify. Ideally, we would like to smooth the image noise without excessive

smoothing, as smoothing will reduce the ability to distinguish the detail of the image. In order to determine the optimal size of the filter, the variance is calculated for a number of regions of different size in several sample patterns where there was no delamination. Testing shows that this is a suitable image size for those predicted for analysis in this study, so that an average filter value of 41x41 pixels was adopted for this purpose; other images from other CT machines or machines with different settings may require a different filter size. This variance analysis method can be automated to determine the appropriate size of the filter by giving a new type of sample.

References

1. Chrysochoos A., Louche H., 2000, An infrared image processing to analyse the calorific effects accompanying strain localisation, Int. J. Eng. Sci., 38,1759-1788
2. Guduru P.R., Rosakis A.J., Ravichandran G., 2001, Dynamic shear bands: an investigation using high speed optical and infrared diagnostics, Mechanics of Material, 33, 371-402
3. Hodowany J., Ravichandran G., Rosakis A.J., Rosakis P., 1999, Partition of plastic work into heat and stored energy in metals, Experimental Mechanics, 40, 113-123
4. Христов, С.Г., Испитване и дефектоскопия на металите, С., Техника, 1988.

Томографические методы неразрушающего контроля свойств материалов

Десислава Иванова

Резюме: Неразрушающий контроль является важной задачей во всех сферах человеческой деятельности: от обеспечения целостности воздушных судов до оценки деградации инфраструктуры, вызванной ухудшением или повреждением. Развитие неразрушающих методов управления качеством приводит к экономическим и экологическим выгодам, приводит к увеличению охвата продукции и повышению общественной безопасности и безопасности. В докладе представлен обзор существующих традиционных методов и инновационных разработок и новых применений в этой области. Он включает в себя самые современные методы неразрушающего контроля: оптические, акустические, ультразвуковые и электромагнитные методы, томографию, рентгенографию и термографию. Результаты предназначены для исследователей и практиков, связанных с исследованиями, тестированием и обслуживанием машин, изделий и компонентов в лабораторных и промышленных условиях.