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NON-DESTRUCTIVE TESTING TECHNIQUES

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Abstract

Non-destructive testing (NDT) has been developed over generations and is of the utmost importance. It has been implemented in a wide range of industries for identifying flaws, analysing material characteristics and quality control. This report discusses the fundamentals of NDT and its relationship with destructive testing and investigates three NDT techniques. It discusses their scientific principles, advantages/disadvantages and any potential errors. Finally, it demonstrates applications of each NDT's techniques use within different industries and discusses NDT's benefits within stress analysis.

Abbreviations

ET	Eddy Current Testing
MT	Magnetic Particle Testing
PT	Penetrant Testing
UT	Ultrasonic Testing
VT	Visual Testing
PAUT	Phased Array Ultrasonic Testing
DR	Digital Radiography
NDT	Non-Destructive Testing
DT	Destructive Testing

Introduction

Non-destructive testing (NDT) and destructive testing (DT) are synonymous in importance when assessing the condition, suitability or performance of a product. Conventional NDT techniques have developed over the course decades, resulting in well-established codes and related standards (Blndt, 2015). A fundamental understanding of how an object or product will withstand a load is vital to its performance. These can be static/dynamic loads and characteristically multiple loads act in unison. There are an unlimited number of loading combinations, these include tension, compression, shearing, torsion, bending and buckling, see Figure 1.

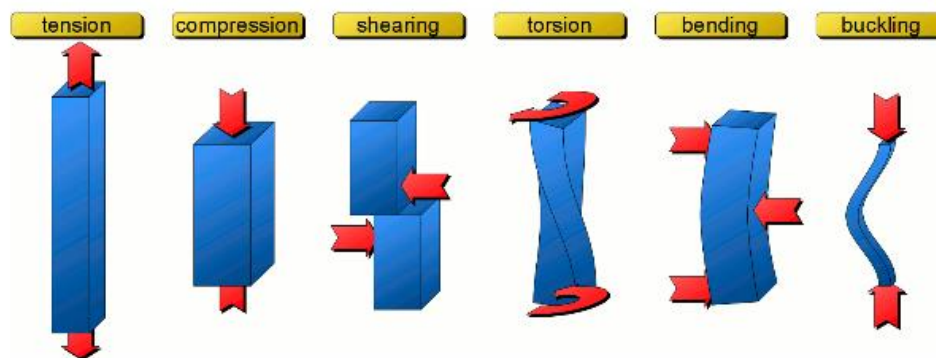


Figure 1 - Types of Load (Tec-Science, 2019)

Non-destructive testing (DT) has fundamental differences from DT as a form of object analysis. According to (Ishaya, et al., 2013). DT processes involve testing objects to failure and as a result determining its physical or mechanical properties. These DT tests are designed to replicate severe operational conditions and determine the point of failure in relation to strength, yield strength, hardness, impact toughness, elongation, etc (Tec-Science, 2019). The destructive tests listed in Table 1 are example of Destructive tests and the properties measured.

Table 1 -Destructive Testing

Destructive Test	Properties Measured
Tensile	Yield Strength Tensile Strength
Bend	Ductility of material
Impact	Ductility of material when subjected to temperature change
Elongation	Reduction of Area

In comparison the importance of NDT is to test, inspect, evaluate a product and characterise its anomalies (ASM International, 2018). But according to (Boopathy, et al., 2017) NDT methods must accomplish this by generating physical measurements that do not affect a product's current, future integrity or performance. Table 2 below compares the benefits and limitations of DT and NDT.

Table 2 - NDT/DT Benefits and Limitations

Destructive testing		Non-Destructive Testing	
Benefit	Limitation	Benefit	Limitation
Reliable and accurate data from sample	Data applies only examined sample	Part is not structurally altered	Operator skills dependent
Excellent for design purpose	Sample is useless after test procedure	No adverse consequence after test	Orientation of flaws need careful consideration
Excellent quantitative data	Often expensive laboratory equipment	Material can be examined internally and externally	Data can be subjective to the operator
Service conditions are measurable		Parts can be tested in service	Some techniques are expensive i.e. radiography
Data critical to establishing standards.		Generally, cost effective	

(Aire & Chimezie, 2016) describe NDT as an essential inspection and maintenance tool for modern engineering environments. The common objective of NDT techniques is to detect the presence of anomalies or discontinuities. These can take many forms but include, cracks, slag, porosity and delamination's (Wilcox & Downes, 2003). In Table 3 lists NDT techniques and benefits/limitations of each. (Dwivedia, et al., 2018) conclude that the most appropriate testing strategy often requires a combination of techniques.

The ability for NDT to be performed either during or after manufacture, or whilst in service is hugely beneficial (Wilcox & Downes, 2003). (ASM International, 2018) summaries NDT's ability to determine part function and expected life cycle of parts in service.

NDT has a vital role within the quality control of industrial products in increasingly competitive markets. It has the dual ability to identify substandard features whilst also quantify the quality assurance of satisfactory features (Wilcox & Downes, 2003). A company's ability to gain advantage in these global markets requires increasing investment in quality control, quality assurance and as a result NDT (IAEA, 2003). By comparison, destructive testing has advantages when the cost of a mass-produced item is economical enough to warrant a physical destructive test. Or in safety testing, such automotive crash tests where the physical data is regarded as more reliable (Ishaya, et al., 2013).

Table 3 – NDT capabilities and limitations (Dwivedia, et al., 2018)

Technique	Capabilities	Limitation
Visual inspection (VI)	Macroscopic surface flaws	Small flaws are difficult to detect, no subsurface flaws.
Microscopy	Small surface flaws	Not applicable to largest structures: no subsurface flaws
Radiography (RT)	Subsurface flaws	Smallest defect detectable is 2% of the thickness: radiation protection. No subsurface flaws for porous materials.
Die Penetrate (DP)	Surface flaws	No subsurface floors not for porous material
Ultrasonic (UT)	Subsurface flaws	Material must be good conductor of sound
Magnetic particle (MT)	Surface / near surface and layer flaw	Limited subsurface capability, only for ferromagnetic materials
Eddy current (ET)	Surface and near surface flaw	Difficult to interpret in some applications: only for metals
Acoustic emission (AE)	Can analyse entire structure	Difficult to interpret, expensive equipment's

Radiography Testing

Radiography testing (RT) is used within a wide range of industries including medicine, engineering and forensics. RT is well established within NDT practise, its ability to produce recordable data and its suitability for use with ferrous or non-ferrous materials make it an indispensable form of inspection (Blndt, 2015). Whilst it has many advantages its potentially dangerous health risks must be carefully considered.

Scientific Principles

Industrial radiography testing (RT) is a form of NDT which involves the use of radiation to examine a material or components internal configuration. The high energy, shorter wavelength, electromagnetic radiation waves, produced from X-ray or gamma ray radiation are appropriate for inspection of solid material. The target material has specific characteristics in density and thickness which attenuate the input radiation. The penetration of the radiation into a component is either absorbed or scattered depending on its internal structure. The remaining radiation is captured electronically or on film (Wilcox & Downes, 2003) (ASNT, 2019). Figure 2 below clearly illustrates the process involved in RT NDT testing. When the radiation passes through the target, the defect yields a dark area of elevated exposure to radiation absorption on a recording medium.

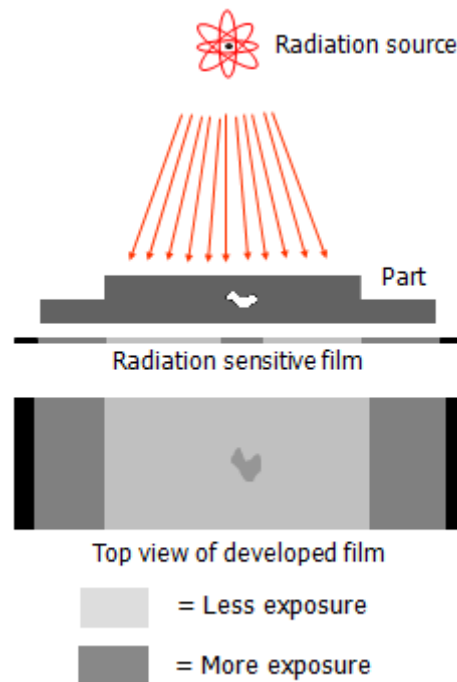


Figure 2 - RT process of defect detection (Wilcox & Downes, 2003)

The radiation type is selected as a result of material properties such as density or part thickness. X-rays are utilised for thinner, less dense objects and produced using an X-Ray head, high voltage generator and control console. X-ray penetration is determined by increasing the voltage, typically Steel requires 1000 volts/inch. Gamma Rays are radio-active isotopes and are used for thicker more dense objects (ASNT, 2019). Gamma radiation is produced as a result of decaying radioactive material, IR-192 is commonly used for ferrous steel up to 75mm thick and Co-60 for deeper penetration in thicker materials (Wilcox & Downes, 2003).

The radiation created by X-rays and gamma-rays is dangerous and as a result protective equipment and specialist training are a necessity. Safe exposure to gamma ray radiation is predominantly longer than x-ray, consequently, gamma ray is more commonly used out on location (Bindt, 2015).

Potential Errors and Assumptions

RT techniques have been refined by generations of use within different NDT applications. However, there are still potential areas for error that need addressing. According to (HSE, 2000) the type of defect and its orientation are of vital importance. Whilst RT has benefits in detection of volumetric defects it can have difficulty with planar defects such as delamination's and planar cracks. RT inspection can be hindered by an operator's ability to direct the beam at a defect in the correct plane, as a result multiple shots of varying angles can be required. While RT has clear benefits for checking porosity, (Vaughan, 2016) states that large fillet weld inspection, needs careful consideration as they can cause major problems for RT inspection. A materials attenuation must be considered as it can vary significantly in metal alloys and effect significance of results. Finally human or interpretation error are critical to RTs inspection value, the test conditions and operator skill/experience can result in variation in detection (Hellier & Petrie, 2016).

Summary of Advantages and Disadvantages

Advantages	Disadvantages
Information is presented pictorially (Wilcox & Downes, 2003).	Generally, an inability to cope with thick sections (NDT Resource Center, 2019)
A permanent record is provided which may be viewed at a time and place distant from the test (Wilcox & Downes, 2003)	Highly hazardous to operators (ASM International, 2018)
Useful for thin sections (Wilcox & Downes, 2003)	Sensitive to defect direction, requires correct orientation (NDT Resource Center, 2019)
Sensitivity declared on each film	Film processing and viewing facilities are necessary, as is an exposure compound.
Very few material limitations (INTERNATIONAL ATOMIC ENERGY AGENCY - IAEA, 2003)	Not suitable for automation, unless the system incorporates fluoroscopy with an image intensifier or other electronic aids (Wilcox & Downes, 2003)
Direct access to part is not required (NDT Resource Center, 2019)	Two-sided access needed (Bindt, 2015)
Minimal part preparation required (Bindt, 2015)	No indication of depth of a defect below the surface (ASM International, 2018)
Gamma ray inspection has excellent portability (ASNT, 2019)	Relatively expensive, especially X-ray (Bindt, 2015)

Magnetic Particle Testing

Magnetic Particle Testing (MT) abilities within NDT have seen it become one of the most widely used testing methods (NDT Resource Center, 2019). MT utilizes the fundamentals of magnetic fields to identify flaws within a component. The only requirement being that the component is made of a ferromagnetic material. It is typically used within industry to check castings, forgings or weldments (Blndt, 2015).

Scientific Principles

MT utilizes magnetic fields to identify flaws at/near the surface within ferromagnetic materials. Ferromagnetic metals are alloys containing iron, nickel and cobalt. A magnetic force is applied to a component via a permanent or electro-magnet. This creates magnetic flux lines through the object, entering and exiting through the object's magnetic poles (Wilcox & Downes, 2003). A discontinuity cannot support a magnetic field/flux, (NDT Resource Center, 2019) states this is due to air's substandard ability to support the same magnetic field per unit volume as a magnet. The result is a deflection of the magnetic field/flux line. This is often referred to the flux leakage field from a component defect. Figure 3 demonstrates when ferromagnetic particles are applied to the components surface and the subsequent attraction towards any defects at/near the surface (ASNT, 2019).

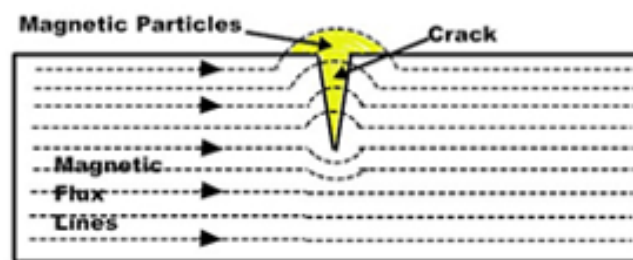


Figure 3 - Graphic of MPI ability to attract particles to a defect (Tec-Science, 2019).

Typically, the magnetic flux lines must be applied at 90 degrees to any suspected discontinuity (NDT Resource Center, 2019). This is substantiated by (Wilcox & Downes, 2003) who state that a flux line will approach a defect at 90 degrees, creating attraction of opposing magnetic poles at the defect edge.

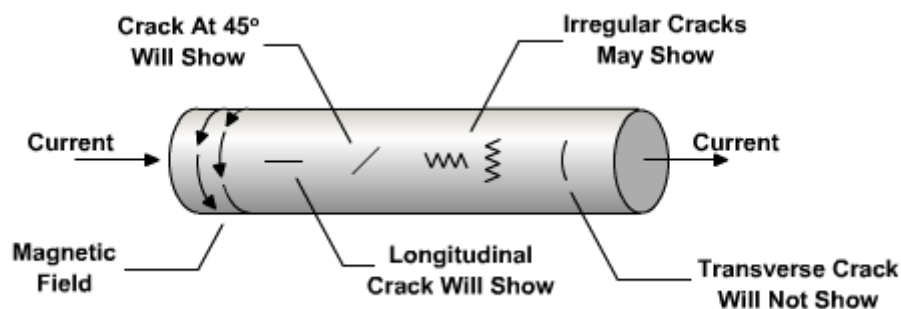


Figure 4 - Type of defect detectable with a magnetic field (NDT Resource Center, 2019).

Figure 4 clearly demonstrates how the direction of magnetic field has an overwhelming effect on defect detection. Therefore (NDT Resource Center, 2019) states that a thorough inspection of a component's performance, requires generating a magnetic field in at least two directions.

MPI techniques vary depending on their method of induction and the equipment used. Common portable methods utilise yokes, prods or coils see Figure 5. This differs to automated systems; these typically use heads or a central conductor coil for the control of the magnetic field within a test component.

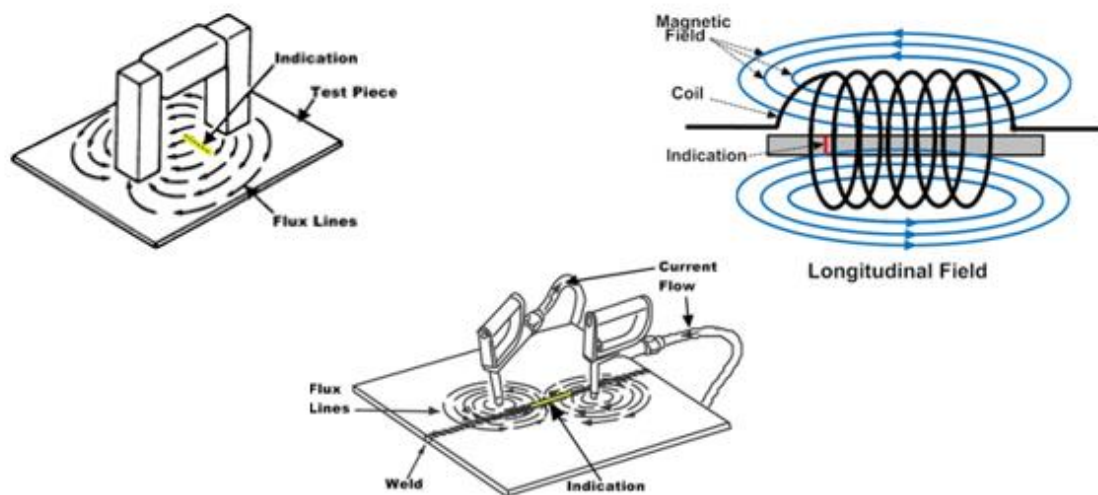


Figure 5 - Examples of yoke, prod and coil used in MPI (ASNT, 2019)

The magnetic particles used within MPI techniques range between dry powder to liquid solution. The size of particle used will vary to suit different applications. Particles are typically coloured or even ultraviolet to increase visibility (ASNT, 2019) see Figure 6. Table 4 below discusses the advantage and disadvantages of wet verses dry particle selection.

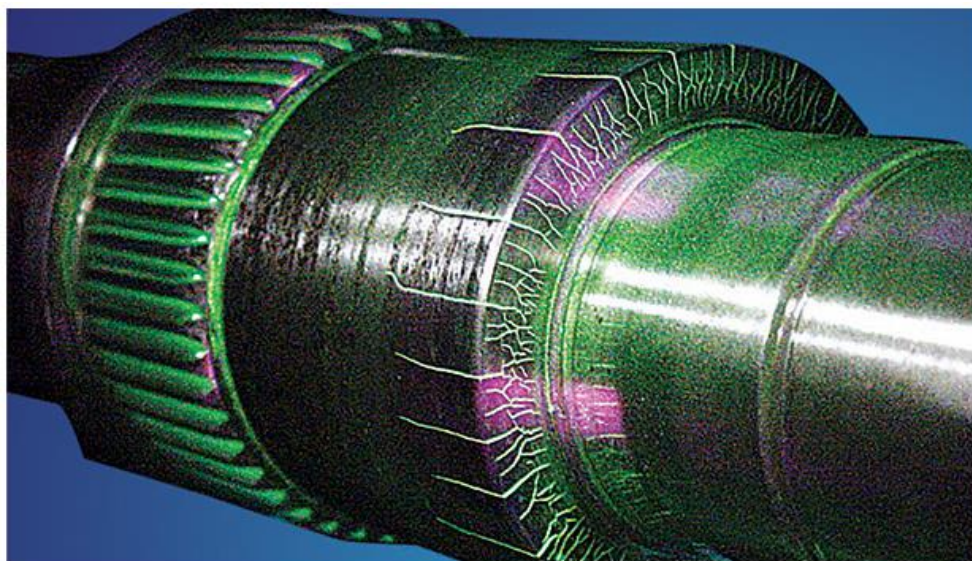


Figure 6 - Defects identified in ultraviolet light using MPI (NDT Resource Center, 2019)

Table 4 - Wet and Dry particle advantages and disadvantages

Advantages	Disadvantages
Wet Particle	
Excellent for shallow and fine surface cracks	Not usually capable of finding below surface defects
Easily covers irregular shaped parts, large or small	"Messy" to work with
Easy to measure and control concentration of bath, which makes for uniform and accurate reproducibility of results	When oil is used can present potential fire hazard
Can be used in automatic system	Recirculating system is required to keep the particles in suspension
Excellent mobility in liquid suspension	Post cleaning may be required in some applications, which adds a process step
Dry Particle	
Excellent for locating surface and subsurface discontinuities	Not as sensitive as wet particle method for fine shallow cracks
Easy to use and large objects with portable equipment	Not easy to cover large surfaces properly, especially irregular shaped parts
Easy to use for field inspection	Poor for large volume inspection
Good mobility when used with AC or half wave DC	Poor mobility when not used with AC or half wave DC
Cleaner method than wet particle	Difficult to adapt to mechanise test system
Preferred for use on rough surfaces (HSE, 2000)	

Potential Errors and Assumptions

MPI has been used since the early 1930's and it is considered a principal technique of NDT within industry. However, there are still areas of misperception that need identification. According to (Blndt, 2015) MPI operators require information regarding defect orientation for a precise testing procedure. In addition, test parts require the operator ability to induce a satisfactory flux density, typically readings above 0.72 Telsa are required, with 1.1T the optimal figure (HSE, 2000). Complex parts cause further issues regarding correct amperage selection and magnetic field intensity.

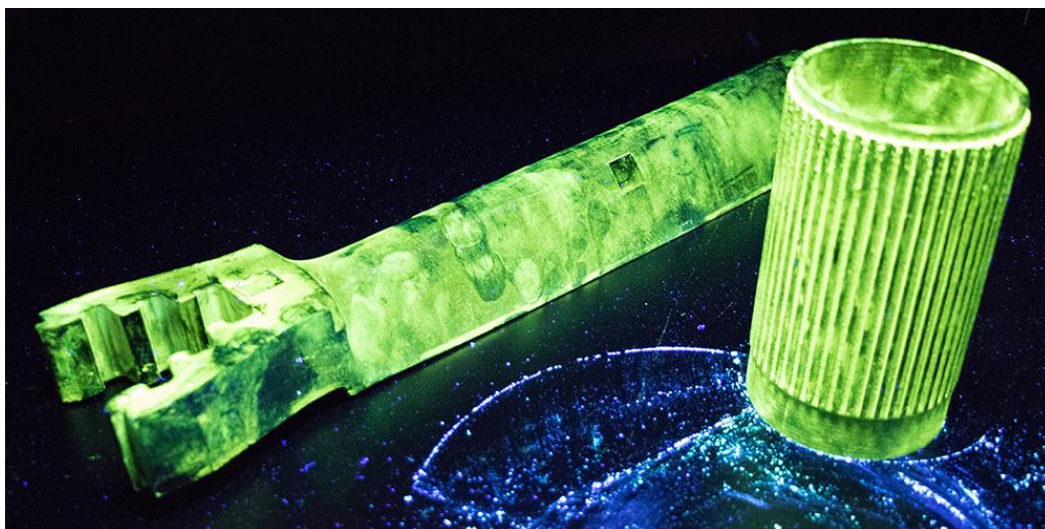


Figure 7 – Excessive amperage reduces defect visibility (Magnaflux, 2019)

Figure 7 demonstrates how defect visibility is reduced when the incorrect amperage values cause excessive magnetism (Magnaflux, 2019). Although one requirement of MPI, is that the test component be made of ferromagnetic material. There are certain ferromagnetic materials that do not conform, Monel® is one (Magnaflux, 2019).

There are other factors that must be considered for successful MPI results. Parts must be relieved of any residual magnetism before testing as it can have adverse effects on sensitivity of results (HSE, 2000). This process is then repeated after inspection. One of the benefits of MPI according to (Aire & Chimezie, 2016) is its ability to generate accurate results on coated components. Whilst (HSE, 2000) advises that a coating thicker than 50um will greatly reduce the sensitivity of the test and all areas of electrical contact must be exposed.

Summary of Advantages and Disadvantages

Advantages	Disadvantages
Large surface areas of complex parts can be inspected rapidly (ASNT, 2019).	Only ferromagnetic materials can be inspected (Wilcox & Downes, 2003).
Can detect surface and subsurface flaws (NDT Resource Center, 2019).	Proper alignment of magnetic field and defect is critical (Aire & Chimezie, 2016).
Surface preparation is less critical than it is in penetrant inspection (ASM International, 2018).	Large currents are needed for very large parts (Schmidt, et al., 2008).
Magnetic particle indications are produced directly on the surface of the part and form an image of the discontinuity (Blndt, 2015).	Requires relatively smooth surface (ASM International, 2018).
Equipment costs are relatively low (Schmidt, et al., 2008).	Paint or other nonmagnetic coverings adversely affect sensitivity (ASNT, 2019).
The method has high sensitivity to small surface discontinuities (NDT Resource Center, 2019)	Demagnetization and post cleaning are usually necessary (Blndt, 2015).
Simplicity of Operation an application (Wilcox & Downes, 2003)	
Quantitative data (Wilcox & Downes, 2003)	
Automated application (Wilcox & Downes, 2003)	

Ultrasonic Testing

Ultrasonic testing is regarded as one the most versatile non-destructive testing (NDT) methods. It is commonly used to identify defects but also measure and characterize material properties. It utilises sound wave velocity and measurement to perform tests on various materials, these include non-ferrous/ferrous metals and plastics (NDT Resource Center, 2019). According to (BIndt, 2015) It is widely regarded as one of the most important NDT methods in industry within the UK.

As stated by (NDT Resource Center, 2019) “Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and formulate measurements. Ultrasonic inspection is commonly used for flaw detection/evaluation, dimensional measurements and material classification”. Typically ultrasonic testing utilises the pulse-echo technique. Pulse-echo acoustic waves are applied to a part at a ultra high frequency, the waves are then measured to determine any flaws or discontinuities in a material as displayed in Figure 8 . This requires the formation of acoustic waves at a predetermined frequency, the frequency considers a materials acoustic impedance characteristics - density and acoustic velocity (ASNT, 2019).

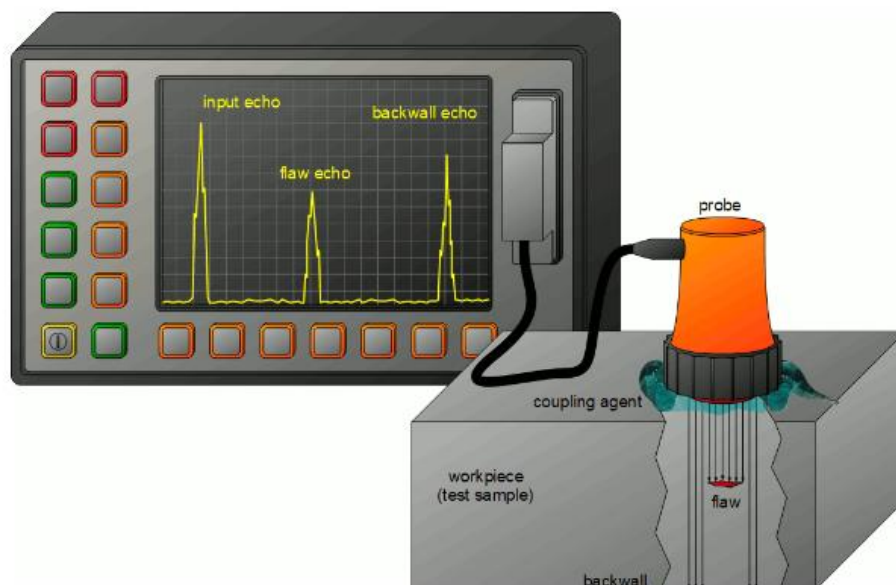


Figure 8 - Typical pulse-echo measurement system (Tec-Science, 2019)

Scientific Principles

To fully understand ultrasonic testing, a basic knowledge of sound waves formation and the piezo-electric effect is vital (Tec-Science, 2019). Ultrasonic testing principles are dependent on the fundamentals of the piezoelectric effect for sound generation. The piezo-electric effect utilises mechanical deformation or stress, i.e. record compressive or tensile stress as electrical voltage measurements (Tec-Science, 2019).

Figure 9 demonstrates the conversion of energy into sound waves and back to electrical energy. The result of this piezoelectric effect in UT is the transmission of ultrasonic waves from the transducer/probe (Wilcox & Downes, 2003).

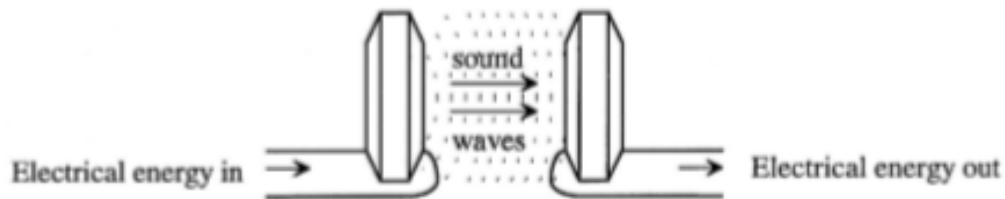


Figure 9 - Diagram of conversion of electrical energy to sound energy and sound energy to electrical energy (Wilcox & Downes, 2003)

The ultrasonic wave created in an UT technique is typically a short-duration high-frequency wave. The result of this wave formation is the mechanical vibration of the atoms within the target material. This mechanical vibration is only possible in a suitable medium such as a solid, liquid or gas (Blndt, 2015). The form of ultrasonic wave generated varies specifically for the material being tested. For gaseous, liquid or solid materials, acoustic sound waves transmit in the form of pressure oscillations. Figure 10 displays the different wave forms used in UT, these include compression and shear (ASNT, 2019).

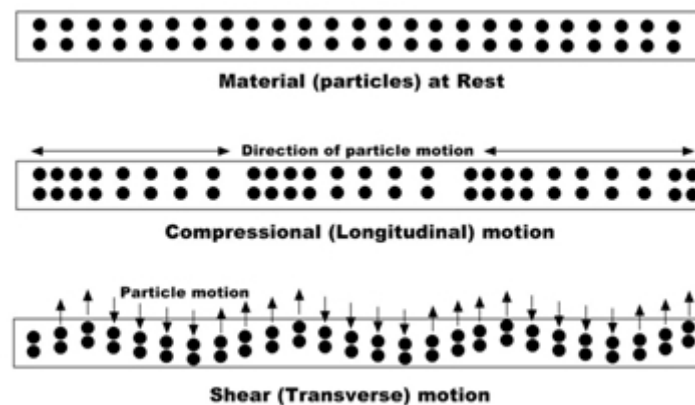


Figure 10 - Pressure wave forms (ASNT, 2019)

The acoustic wave or pulse is introduced into a chosen part at a frequency between 0.2mhz and 100mhz. The chosen frequency is of the utmost importance within UT, the correct frequency is vital to correctly identify any flaw or discontinuity in a component. A combination of sensitivity and resolution must be correctly balanced. Sensitivity refers to the waves ability to identifying the smallest of imperfections whereas, resolution refers to the UT systems ability to display any imperfections distinctly on its instrumentation (Blndt, 2015).

The acoustic wave propagates at the acoustic impedance of the component's characteristics. The wave will change speed and direction dependant of the features within the component being tested, this is commonly referred to as the echo (ASNT, 2019). The systems instrumentation will record the values of energy transmitted and received. This information must then be analysed by an experienced operator. Their experience will enable them to determine if the component has any discontinuities, and of equal importance their size, position and orientation (NDT Resource Centre, 2019).

The acoustic sound waves are created in UT techniques by use of the transducer (NDT Resource Center, 2019). A “couplant” is a liquid or gel used between transducer and component, it is vital to ultrasonic testing as the transducer must be in full contact with the component. Ultrasonic waves cannot travel through air due to its atom arrangement (ASNT, 2019).

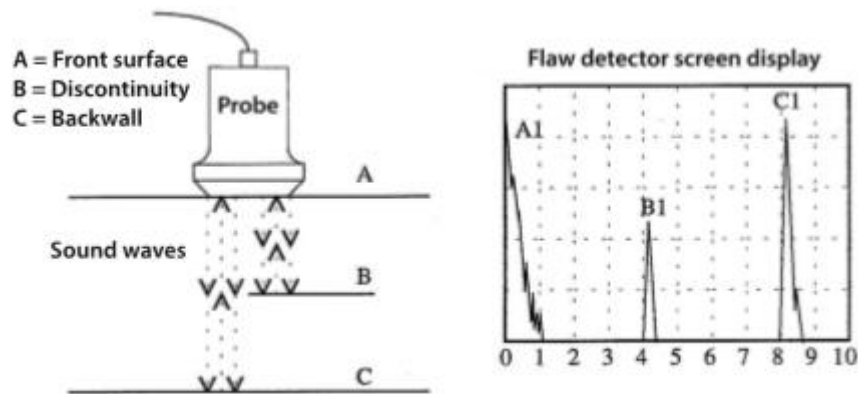


Figure 11 – Diagram of pulse echo ultrasonic testing system (Blndt, 2015)

Figure 11 clearly demonstrates how a pulse echo UT system could identify a flaw within a component. “The echo at A1 is the result of sound energy reflecting back off the front surface of the specimen. B1 is the discontinuity echo and C1 is the backwall echo” (Blndt, 2015).

Potential Errors and Assumptions

It is widely recognised that NDT can be less effective than anticipated when implemented in unsatisfactory conditions (Buirks, et al., 2007). To obtain satisfactory results from UT, reference standards must be established. Reference standards are generated by testing parts with known discontinuities, this enables consistency within UT methods. Figure 12 below contains essential requirements to establish a UT measurement system.

Performance of Beam	Sensitivity, resolution and beam spread
Sound beam path	Point of exit
Sound beam refraction angle	
Sound path Distance	
System evaluation	time base, linearity

Figure 12 - Table of UT system calibration (Buirks, et al., 2007)

Where UT is used to detect discontinuities with no known defect / material characteristics, results must be considered with limited confidence (HSE, 2000) (IAEA, 2003).

UT effectiveness can be hindered by an objects surface finish and coating, both can have a negative effect on system accuracy (NASA, 1995). In addition, certain materials such as austenitic steels and Inconel need careful consideration. This is due to results distortion resulting from wave scatter and high background noise exhibited due to low ultrasonic attenuation (HSE, 2000).

Summary of Advantages and Disadvantages

Advantages	Disadvantages
Depth of penetration for flaw detection or measurement is superior to other methods (ASM International, 2018).	Surface must be accessible to probe and couplant (ASNT, 2019)
Only single sided access is required (Buirks, et al., 2007)	Skill and training required is more extensive than other technique (Buirks, et al., 2007)
Test depths of several meters are theoretically possible (Tec-Science, 2019)	Only flaws that are larger than half the wavelength of the ultrasonic waves can be physically resolved (NDT Resource Center, 2019)
Provides wall thickness measurement measuring the layer thickness of components subject to wear (Tec-Science, 2019)	Surface finish and roughness can interfere with inspection (Blndt, 2015)
Minimum part preparation is required (NDT Resource Center, 2019).	Thin parts may be difficult to inspect (Buirks, et al., 2007)
Can be easily automated (Tec-Science, 2019)	Linear defects oriented parallel to the sound beam can go undetected (NASA, 1995)
No protective equipment required (ASNT, 2019)	Reference standards are often needed (HSE, 2000)
Portable with instant test results (Wilcox & Downes, 2003)	flaw size cannot be determined easily (Tec-Science, 2019)
	Depending on the spatial orientation of the flaws, they are difficult to detect. Likewise, the flaw size is usually not clearly determinable! (Tec-Science, 2019)

Industry Applications of NDT

NDT inspection techniques are an integral part of quality within a wide range of industries. These include oil, gas and petrochemical industries, chemical, aerospace, automotive, and defence. These techniques are of paramount importance to increased quality, reliability and of minimising failure (Aire & Chimezie, 2016).

Manufacturing	In-Service
▪ Delamination ▪ Fiber misalignment ▪ Resin starved or rich areas ▪ Blisters, air bubbles ▪ Wrinkles ▪ Voids or porosity ▪ Thermal decomposition ▪ Uneven, insufficient or over curing ▪ Insufficient fiber volume ▪ Inclusions	▪ Environmental degradation ▪ Impact damage ▪ Moisture ingress ▪ Fatigue ▪ Cracks from (local) overload 🟡 ▪ Debonding, Delamination ▪ Fiber fracturing ▪ Erosion or abrasion ▪ UV damage, weathering ▪ Chemical attack

Figure 13 – NDT discontinuities detection abilities (Troost, 2014)

Evidence of NDT application goes back decades, with real advancements in techniques occurring after World War 1. Figure 13 lists the categories of discontinuities now able to be identified with modern NDT techniques.

Pipe and tube manufacturing	Roll, plate strip testing. Offline pipe spiral weld testing
Steel industry	Testing rolled and re-rolled products including billets, plates, sheet and structural sections
Aerospace industry	Testing components for aeroengine, landing gear and airframe production
Aircraft industry	Testing components during overhaul included aero-engine landing gear components
Shipbuilding industry	Structural welding testing. Hull and bulk thickness measurement. Engine components testing.
Iron foundry	Testing ductile iron castings for metal strength on 100% quality-controlled basis
Power generation	Pressure vessel testing of weld defects during manufacturing and in service.
Agricultural engineering	Testing of all fabricated, forged and cast components
Mining industry	Testing of pit equipment and underground safety critical components
Rail industry	Testing locomotive rolling stock for fatigue cracks. Testing rails for heat induced cracking
Petrochemical and oil industry	Pipeline and tank corrosion testing

Table 5 - Typical applications of NDT within Industry

NDT is a cradle-to-grave requirement for asset integrity. Its ability to produce quantified historical data is vital in modern industry quality control. NDT has a vast array of applications which chart the inspection data through the life cycle of many components. Table 5 lists typical industries adopting NDT techniques and their applications within those industries.

Ultrasonic Testing

UT has wide ranging applications within NDT, these include use within civil engineering, automotive, aerospace, oil/gas and foundry. The evidence of UT's merits within the Automobile industry were discussed by (Brown, 1973) as early as 1973, where he described an important place for UT within the future of quality control in the automobile industry. Further to this (Alobaidi, et al., 2015) describes the wealth of data collected as a result of the diverse abilities of UT within the Oil and Gas industry.

The aerospace industry has fully embraced NDT's abilities to detect delamination's, de-bond's and other inconsistencies within composite components (Troost, 2014). This is confirmed by (Schnars & Heinrich, 2006) who describe the delamination and debonding that is detectable using the D scan UT technique used by Airbus seen in Figure 14

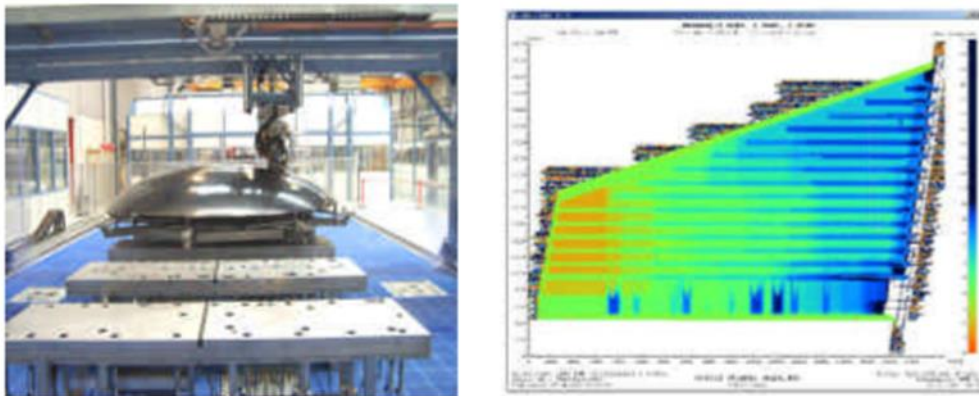


Figure 14 - Airbus Multi channel D scan Ultrasonic Testing (Schnars & Heinrich, 2006)

Further to this (Malek & Kaouther, 2014) explores the merits of UT within testing of concrete structures. Evidence of this in relation to concrete bridge delamination can be seen in Figure 15

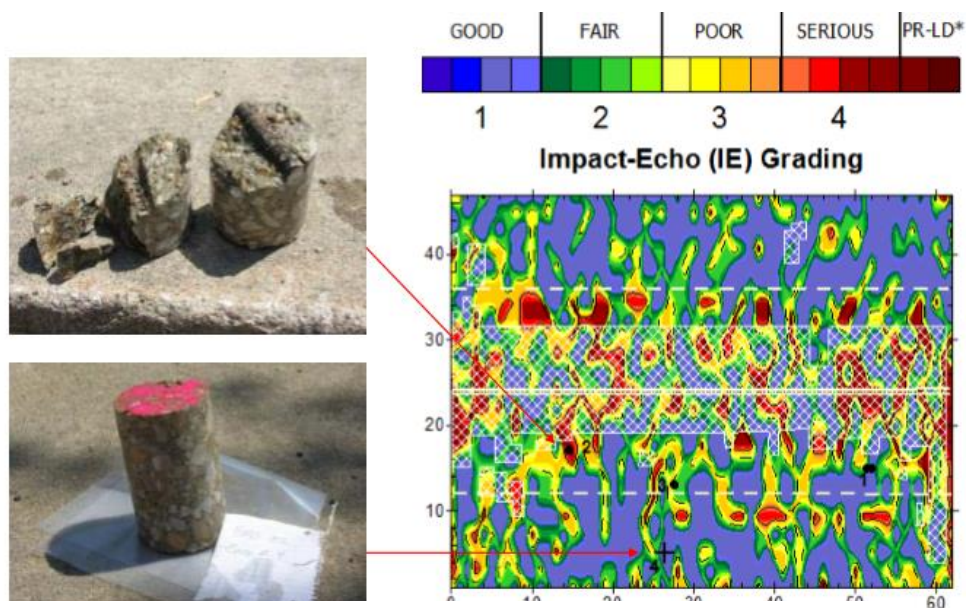


Figure 15 - Impact Echo Delamination Assessment (Gucunski, et al., 2010)

Magnetic Particle Testing

MT is extensively used within aerospace, automotive, petrochemical, structural steel and power generation due to its ability to provide accurate results promptly and with relative ease (Eisenmann , et al., 2014). (Schnars & Heinrich, 2006) state that 90% of the steel parts within the aerospace industry are tested with MT during their lifecycle. According to (Vetterlein & Georgi, 2006) it is well established for the use in testing engine, suspension, braking components, castings, forgings and weldments within the automotive industry and has been utilised for in excess of 80 yrs. In Germany alone in 2006 over 1 billion parts were tested using MT within the automotive industry (Vetterlein & Georgi, 2006). Figure 16 below is an example of MPI use within the automotive industry. A crankshaft has been subject to an automated process to check for suspect defects using MT.

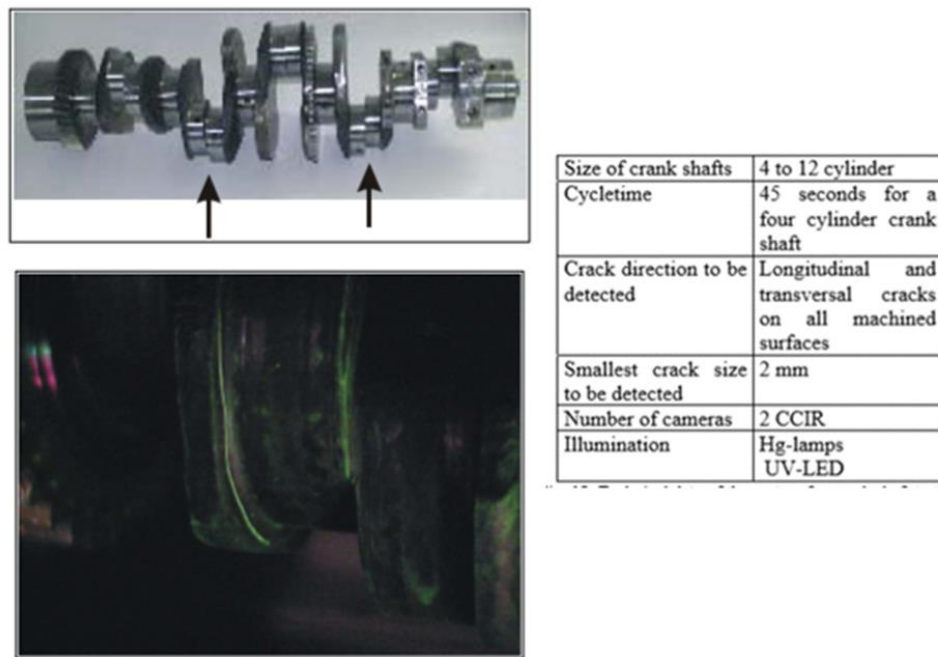


Figure 16 – MP test of engine crankshaft and test specification (Vetterlein & Georgi, 2006)

MT is widely utilised for testing ferromagnetic pipelines, storage tanks and pressure vessels (Shi, et al., 2015). Figure 17 shows an example of an MP examination and the identified longitudinal crack along the pipeline weld (TWI Global, 2019).



Figure 17 -MPI pipe testing and crack detection (TWI Global, 2019)

Figure 18 below is the Starman crack identification system designed for railway wheel NDT inspection. The system magnetises the wheel and uses high speed digital cameras to identify magnetic flux leakage and automatically identifying defective parts (Starmans, 2019).

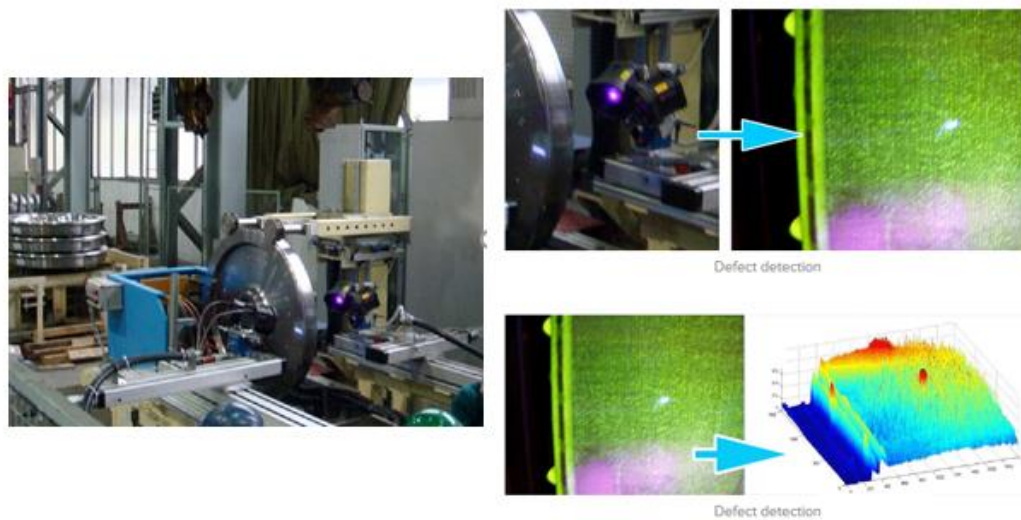


Figure 18 – Starmans MP system for identifying cracks in railway train wheels (Starmans, 2019)

Radiography Testing

After more than a century of use this method of inspection has developed into one of the fundamental choices within NDT where portability is paramount. It has a wide range of use within many industries but primarily for detecting discontinuities in welds, castings, valves and pressure vessels. In addition, it has excellent abilities to evaluate corrosion and debris accumulation within pipeline and pressure vessels (ASM International, 2018).

(Pellegrino & Nugent, 2019) have examined the use of RT for detecting corrosion under Insulation (CUI). CUI is when corrosion is present as result of water becoming trapped between pipe and its insulation. They conclude RT would reduce inspection times by > 95%, which resulted in reduced radiation exposure time. Figure 19 and Figure 20 below demonstrate the application and the design of RT system used.

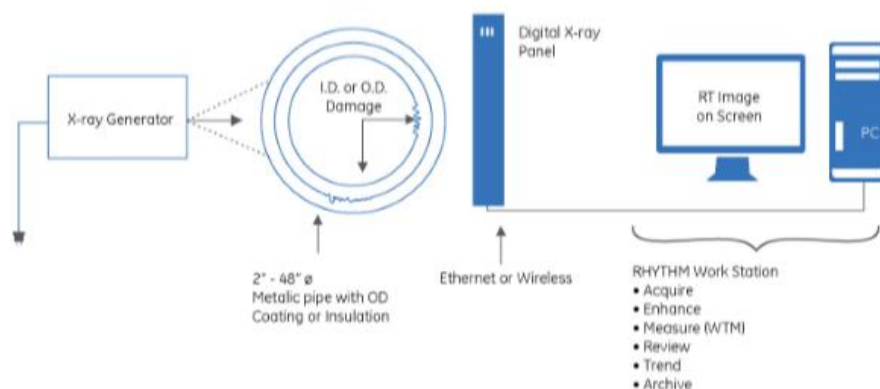
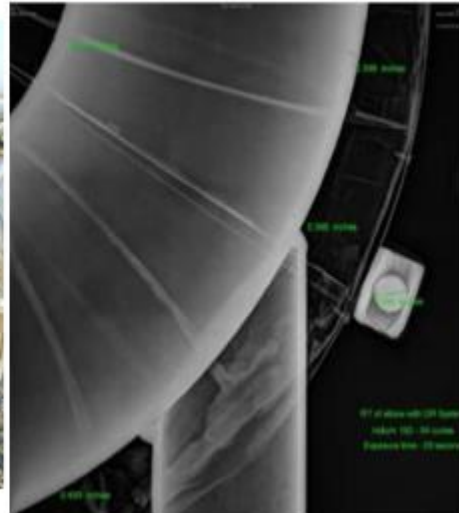


Figure 19 - Schematic of RT system



(Kah, et al., 2014) discuss the use of an automated RT system for weld inspection. The benefits are clear in respect of reduced inspection time and improved quality of captured visual data. Figure 21 below displays a diagram and picture of the system used and a demonstration of the defects detected.

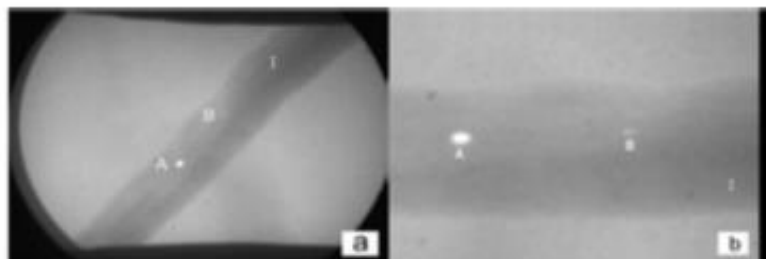


Figure 21 - Weld inspection system and defect results using RT (Kah, et al., 2014)

RT has seen recent developments which have enabled NDT to transfer into new markets. An example of this is battery testing and their failure analysis. X-ray CT scanning has demonstrated excellent results in determining battery failure due to its non-destructive nature (NTS, 2016). Figure 22 below are some of the CT scan results of defective batteries.

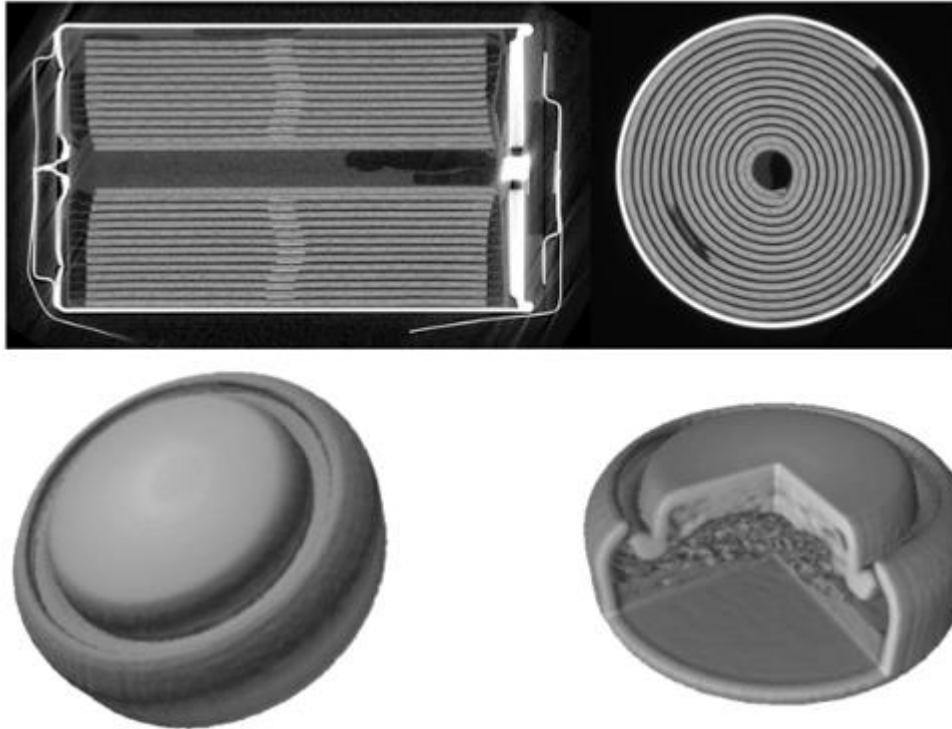


Figure 22 - Radiography CT scan results of defective batteries (NTS, 2016)

Non-Destructive Testing benefits within Stress Analysis

Stress analysis or stress-strain analysis is the study of the stresses and strains within any material or structure subjected to a force. Historically stress and strain has been calculated using mathematical techniques developed over generations. The function of stress analysis is to develop an understanding of how materials and structures perform under load and use this knowledge to drive good design. NDT analysis is particularly valuable for calculating stress and strain within components with complicated geometry, complicated loading conditions, or both. Its ability to measure and/or record data removing the need for analytical or mathematical calculations that are either unmanageable or burdensome is hugely beneficial (Goyle & Phillips, 1997). NDT inspections ability to assist stress analysis within materials is of vital importance in creating technical standards and regulatory requirements (Jang, et al., 2005). Stress analysis has an unquestionable influence in the engineering of components and structural elements (Basavaraj & Vrushabha, 2019). The ability of components and their material to remain stable and fit for purpose is critical for their service life. Materials are subject to critical variations in stress, these are the result to age, mechanical, chemical and thermal effects when in service. If unchecked these factors have detrimental effects on performance (Jang, et al., 2005).

Many NDT techniques have been developed with the capability to quantify residual stresses within components. The results from these techniques have guided the development of production techniques which have in turn reduced these residual stresses (Basavaraj & Vrushabha, 2019). The complementary development of technologies of NDT and manufacturing have been predominantly due to advancements in computational power. The benefits to stress analysis and NDT are real advances in stress measurement and application (Basavaraj & Vrushabha, 2019).

Ultrasonic testing's ability to identify residual stress within pressure vessels is clearly beneficial. (Javadi & Mosteshary, 2017) describe the ability to experimentally measure residual stress in pressure vessels using UT and combine with data obtained from 3D thermo mechanical finite element numerical analysis. The residual stress values for both UT and FE are evaluated for combined accuracy. This can be corroborated by (Chunguang, et al., 2016) who studied the relationship of acoustoelasticity theory and the relationship between ultrasonic testing and stress within components. (Khan & Gangel, 2016) deliberates the clear advantages of NDT's non-destructive nature and the ability to retain part functionality after UT while still obtain accurate residual stress measurement. Figure 23 shows the existing selections available to test residual stress.

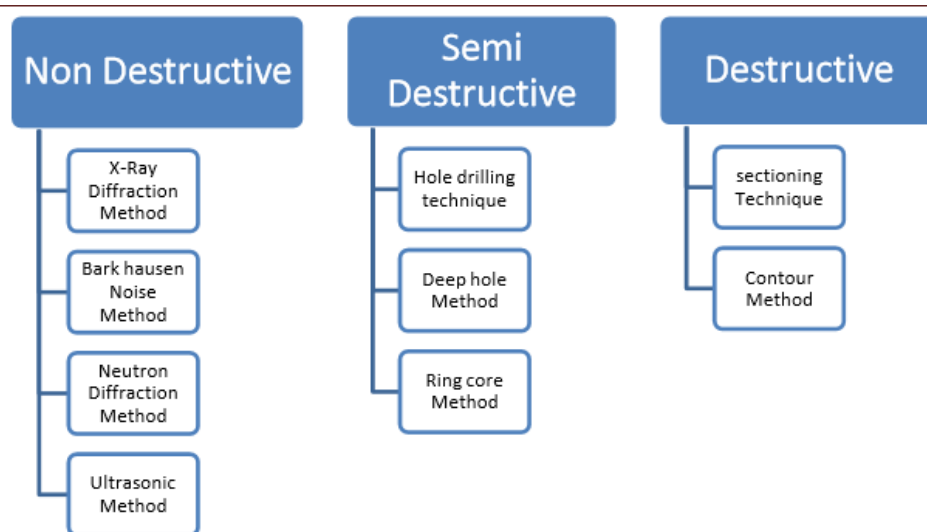
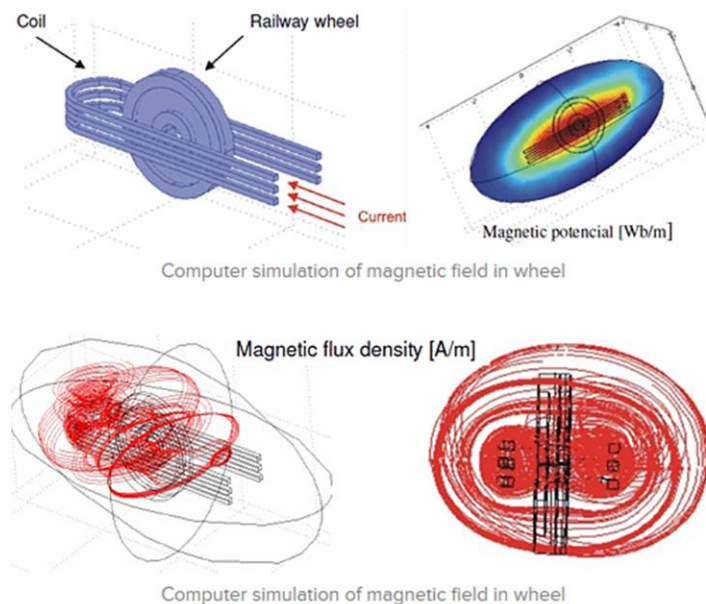


Figure 23 - Residual Stress measurement techniques (Khan & Gangel, 2016)

The understanding of fatigue and residual stress within components is vital to provide early indications of elevated stress levels and expected failure. These stresses were originally considered an ‘engineering problem’ but advancements in NDT and stress analysis have created a breakthrough in an understanding of the problem (AZEER, 2013). When ferromagnetic metals are strained, the internal structure of a component is altered. The ability of NDT and stress analysis to measure and evaluate these changes results in the creation of a material or part stress history (Wilson, et al., 2006). An example of this is Starmans development of an automatic defect system for train wheels. The system utilises data from NDT measurements combined with stress analysis to produce an algorithm to predict flaws in train wheels (Starmans, 2019).



(Ooka, et al., 2017) and (Brekow, et al., 2017) investigated the use of RT and UT for the analysis and detection of fatigue and Stress Corrosion Cracking. RT/UT results were developed alongside an algorithm titled SAFT. The combination of NDT and the SAFT algorithm have enabled the simulation of stress analysis of numerous industrial applications.

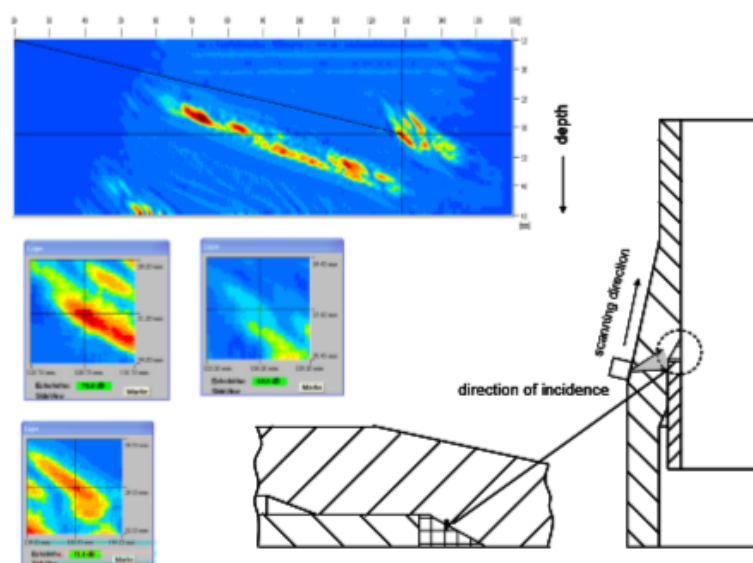


Figure 24 - Display of SAFT NDT technique (Brekow, et al., 2017)

Conclusion

This report has identified that NDT has clear benefits for use within a diverse range of industries. The most apparent is NDT's ability to test, inspect, evaluate a product and distinguish its inconsistencies but without affecting an objects current or future integrity or performance.

The discipline of NDT has been developed across generations and combined with modern advances in computational power it is becoming increasingly complex. NDT combines the fundamentals of scientific phenomena such as electromagnetism, acoustic emission, high energy radiation and introduces new competences in connectivity, data handling and assessment. combination of NDT and stress analysis provide data which is vital for validation for FEA and ACM software.

NDT's use within process control has been well documented, its typically used at the end of a process for quality control. But this is changing in modern manufacturing facilities where it is utilised from start to finish, ensuring 'right first time, every time'. In addition, it has become an essential technique within product design. NDT techniques are critical for developing an understanding of defects and how they affect product design. The data gathered from NDT assists in quantifying a products life cycle capabilities and improving future design.

Whilst NDT has many benefits and uses, but it does require investment in techniques, equipment and most importantly training. NDT techniques rely on the experience and skill of the inspector and defect identification is subjective. False or missed defect identification is predominantly down to human error. Techniques require calibration and material characterises data for accurate results. Any inspection of an unknown defect type or material can be particularly problematic.

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