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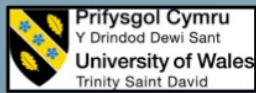
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BENG MANUFACTURING SYSTEMS

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Advanced Stress Analysis & FEA: Non-Destructive Testing (NDT)

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Executive Summary

In the interest of quality, safety and reliability remaining paramount within the manufacturing industry, it is part of everyday procedures that materials, components and infrastructure be subjected to non-destructive testing (NDT) and inspection (NDI) to prevent failures and reduce associated costs. Periodic testing is typically used to ensure regular feedback is obtained and corrective work actioned at the earliest possible stage. Knowledge of the minimum crack size, structural loads, critical defect size and crack growth rates can be determined with testing and the appropriate actions taken. This report uses literature reviews and previous studies to examine the uses, advantages and drawbacks and overall principles behind three widely recognised methods of NDT and their recommended applications within industry. Some NDT methods precede more modern-day alternatives therefore literature available for research on this report ranges from 1994-2019 and therefore may conflict due to modern day advances in technology and studies. Research was obtained with a balance of academic and online resources.

The report doesn't draw any findings related to data comparison in order to establish which NDT method is superior, but rather compare and contrast multiple methods and their suitable application dependant on where their individual strengths and weaknesses lie resulting in a conclusion of how they can implemented into stress analysis.

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1. Introduction

It is estimated that manufacturing contributes £6.7 trillion to the global economy with the UK manufacturing thriving in that with the eighth largest industrial nation in the world, it is also on target to break into the top five by the year 2021 (The Manufacturer, 2019). Manufacturers within the UK and other developed countries have responded to a rise in globalisation and increased competition from abroad by outsourcing work to emerging countries within their production activities. The Department for Business Innovation and Skills (BIS) state that this allows manufacturers to enhance productivity, reduce costs while gaining access to a fast developing market (2010). BIS highlight however that one in seven UK manufacturing companies are beginning to bring their production closer to home according to a 2009 survey by EEF/BDO with the quality of goods produced in emerging countries highlighted as one factor due to it not being of a sufficiently high standard offsetting the cost savings made from production abroad.

The use of Non-Destructive Testing (NDT) to provide quality control and assurance in the industrial domain cannot be over-emphasised according to Krishnamoorthy (2009). Using NDT to maintain high quality standards also plays a vital role in the reliability of products where their integrity is of paramount importance from a safety aspect. Krishnamoorthy explains further in highlighting that billions of parts in manufacturing, power generation and transportation industries are inspected daily using NDT methods resulting in a direct impact on reducing potential accidents, equipment failures and doing so in a timely manner through careful application.

This report focuses on current NDT methods and compares them to commonly used destructive alternatives, and homes in on three NDT methods and their purpose, benefits, drawbacks and application within manufacturing and industry further afield. An application considered in the report are the benefits NDT provide to stress analysis. Stress analysis is an important part of engineering as most components that fail have usually come under either a sudden large or consistent loading force which eventually places the component under damaging forces. The nature of NDT is to identify material limits, operational conditions and how to minimise to near elimination so that potential problems are eradicated.



2. Non-Destructive Testing (NDT)

2.1 What is Non-Destructive Testing

Non-destructive testing incorporates methods used to evaluate a materials integrity for surface, internal flaws or metallurgical condition without the risk of interfering at all with the destruction of the tested material or its suitability for future use (Kumar & Mahto, 2013). In order to thoroughly identify and understand defects within materials Gholizadeth (2016) states that more than one method NDT may be required along with invasive openings in the material to assess the results. If done well, NDT can provide useful information to assist in the management of plant safety (HSE, 2019). Due to the variety of materials and their associated characteristics, it is essential that an understanding of the advantages and limitations of each NDT method be established to increase the success of any testing, discussed further in this report.

NDT methods fall into two categories;

- i. Those which only detect size of defects/damage present on the surface
- ii. Those which can detect size of defects/damage embodied within a component

According to The American Society for Non-Destructive Testing (2019) the 6 most common NDT methods are;

1. Magnetic Particle Testing (MT)
2. Liquid Penetrant Testing (PT)
3. Radiographic Testing (RT)
4. Ultrasonic Testing (UT)
5. Electromagnetic Testing (ET)
6. Visual Testing (VT)

Further methods include Acoustic Emission Testing (AE), Ground Penetrating Radar (GPR), Laser Testing Methods (LM), Leak Testing (LT), Microwave Testing, Neutron Radiographic Testing (NR), Thermal/Infrared Testing (IRT), Vibration Analysis (VA).

NDT provides an economical and very-accurate method of inspection since the results are repeatable as the piece itself is not destroyed and multiple tests can be performed on the same item to identify discontinuities. (TWI, 2019). With the main objective of NDT to identify the presence of discontinuities, it is important to note that a discontinuity is not always a defect. Two discontinuities, such as cracks of the same size and depth, may be acceptable when present on one item but not on another, the failed tolerances on the second item could therefore be considered a defect.

2.2 Material Choice and NDT

When considering NDT with metals, which account for about two thirds of all the elements (NDT Resource Center, 2019), discontinuities in metals can be in the form of cracks, slag, porosity and stringers (Smith, 2015). Therefore, if inappropriate NDT is applied or NDT is not applied correctly, then the results are likely to give a false impression of the integrity and safety of the plant (HSE, 2019).

When NDT composites however, it has been noted by Lim and Cao (2013) that NDT plays a vital role in the testing but also production of composite materials and a variety of testing methods are possible. In Dr. Bafekrpour's book '*Advanced Composite Materials: Properties and Applications*' he states:

"Composite materials are a major growth area within advanced materials and the range of applications for such products continues to grow and increase in diversity with every new development. Composite products are highly in demand and reached sales of \$21.2 billion globally in 2014. The top three market segments in 2014 were transportation, construction, pipes, and tanks. Other segments include energy, automotive, and aerospace."

(Bafekrpour, 2017)

Therefore, due to its increasing presence and safety uses within engineering and manufacturing, NDT data on composites is likely to grow further as they become more prominent in their use due to being on the cutting edge of active material research. Material composition and advancement has prompted development and adaptation of a number of NDT methods to detect flaws and it requires skilled work as often the materials are non-homogeneous and anisotropic. When comparing composites to pure metals, the damage and variability of mechanical properties due to anisotropy, heterogeneity and defects from material selection and processing techniques, become more important to understand (Jollivet, et al., 2013). Damages within composites commonly arising during

material processing are cracks, delamination and porosity. Therefore, it is justified that advanced NDT is performed in order to ensure the production and condition of composites when being used is adequate and safe to do so. The more preferred methods of NDT on composites consists of Ultrasonic Testing, Acoustic Emission Testing and Infrared/Thermographic Testing with Ultrasonic providing more accurate and reliable results in a non-hazardous environment (Dwivedi, et al., 2017).

Composites have better stiffness and their anisotropic properties are customisable providing advancements in areas such as transportation in the aerospace industry. A full list of potential defects with composites are listed in *Table 1*.

Potential Composite Defects	
Wavy Fibres	Thermal Damage
Cracks	Delamination
Contamination	Voids
Resin Issues	Improper Care/Treatment
Thickness Variations	Dimensional Discrepancies
Misaligned Fibres	Missing Adhesive
Impact Damage	Thermal Damage

Table 1 - Defects in Composites

2.3 NDT vs Traditional Destructive Techniques

NDT provides manufacturers with many benefits without comprising the integrity of the components being tested. There are circumstances where material tensile limits require being pushed to failure in order to gain a wider amount of data providing evidence on the performance of the component under stress. Destructive testing becomes redundant when a component that is in situ requires testing which cannot be removed or destroyed. For example, pipework, infrastructure and critical costly components will deteriorate and safety inspections will be required as normal.

An example of a materials properties that destructive testing will establish is fatigue. Testing for fatigue will indicate maximum stress, stress amplitude and a stress range for infinite life of the component at a specific loading in desired conditions (IDC Technologies, 2008). An S/N curve graph is developed in order to portray the fatigue rates a component experiences in uniformed conditions with a higher peak stress application. Roylance (2001) explains that an S/N curve quantifies the fatigue process when a constant cyclic stress is applied to a component or material and continuously cycled through stresses in a specific application until failure occurs i.e. a part may fail after ten thousand cycles at 5 M/N m² however after twenty thousand cycles if the stress is reduced to 3 M/N m². A typical S/n curve graph is shown in *Figure 1*.

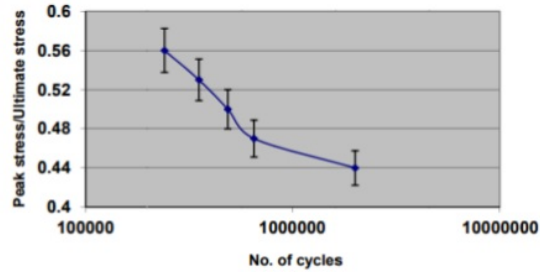


Figure 1 - S/N Curve example (Peak stress vs. Number of cycles) (IDC Technologies, 2008)

2.3.1 Non-Destructive Modern Alternatives of Radiography Testing

This report discusses radiography and its dated history within industry further in the report.

However modern methods of this technique have been developed over the years which bring one of the oldest methods of NDT into the modern testing environment. Modern developments of this technology are discussed in *Table 2*.



Modern Radiography Alternatives	Process Description
Digital Radiography	Vastly more sensitive with flaw detection possible with small amounts of x-ray exposure (Achterkirchen, 2014). Advanced when the speed and memory of computers developed,  enabled production of digital images using inexpensive equipment that can be portable (Vidisco, 2019)

Real-Time Radiography	Captures radiographic imagery and displays it in real-time on a computer screen. Converts radiation into light using fluorescent screens. Real-time systems are used in airports
Computerised Tomography	Around since the 1940s, modern developments in technology have dramatically improved this process. It shows a slice through an image rather than the traditional two-dimensional images with no interference
Neutron Radiography	Uses neutrons instead of traditional x-ray/gamma rays to travel through an object. Passes through dense materials with ease but absorbed by light materials, opposite to x- and gamma rays. Expensive and large equipment required with possible safety issues where over firing neutrons at a material can make certain materials radioactive

Table 2 - Modern Developments of Radiography Testing

3. Applications of NDT

3.1 Ultrasonic Testing (UT)

3.1.1 Scientific principles behind Ultrasonic Testing

Ultrasonic Testing (UT) is an instant result, easily portable and adaptable system for a variety of different sized components (Aspect 3Sixty, 2019). According to Dr. Hijazi (2019) UT utilises high frequency sound waves to conduct examinations and allow measurements to be taken, furthermore, The American Society for Non-Destructive Testing (ASNT) (2019) states this is above human audible range, between 16 Hz and 20,000 Hz, explaining that the ultrasonic testing range is typically between 500 kHz and 25 MHz. The large frequency range is pivotal to the object being tested i.e ASNT elaborate that a high frequency sound of around 5 MHz for contact testing would provide good sensitivity, a term referring to the ability of detecting small imperfections without the component's material, referred to as discontinuities. However, when considering cast items, which

commonly have a large grain structure, a high frequency sound loses its dominance to a lower range, typically around 1 MHz which provides good penetration but poor sensitivity and resolution.

A commonly used UT Inspection system consists of the following components;

Component	Purpose
Pulser/Receiver (Probe)	Must be in contact with the component, fires and receives feedback of sound waves at several hundred pulses every second. Generates short, large amplitude electric pulses of controlled energy which are converted into short ultrasonic pulses when applied to an ultrasonic transducer. Converts sound waves on the way back to an electrical signal.
Contact Transducer	Converts the high voltage pulses from the probe to generate high frequency ultrasonic energy. Ergonomic design to allow easy grip and movement along surface with a rugged replaceable casing to withstand sliding contact with harder materials.
Display Device (Flaw Detector)	Sends the initial voltage pulse to the probe and converts the received electrical signal feedback onto the display monitor to provide results.

Table 3 - UT Components

As the sound energy propagates through the component under testing, if there is a discontinuity within the part the waves will reflect back, however, if the component is clear of all discontinuities then the sound wave will hit the back wall of the component and reflect back still but in at a slightly more extended time period as shown in *Figure 2*. This continuous feedback and time period will help to identify whether or not the component has failed or passed the testing.

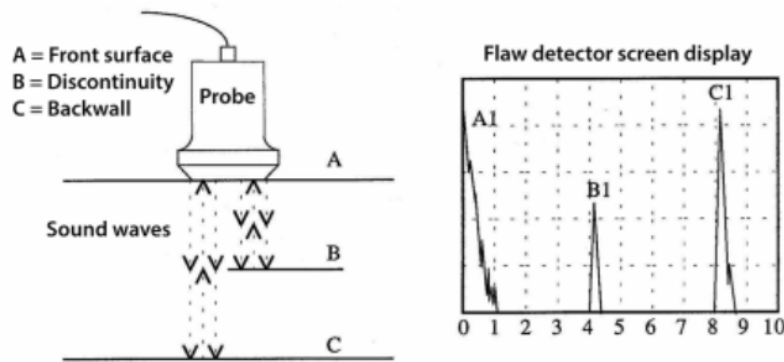


Figure 2 - UT Result Display (The British Institute of Non-Destructive Testing, 2015)

5. Resolution(-)

According to Dr. Hijazi (2019) the wavelength of the sound waves propagating in isotropic solid materials can be calculated with the following equation:

$$\lambda = \frac{V}{f}$$

Where;

λ = Wavelength (m)

V = Velocity (m/s)

f = Frequency (Hz)

Furthermore, it is stated that an increase in the frequency will result in a decrease in the wavelength, thus having implications on the testing boundaries. For example;

“When testing steel where the velocity of longitudinal waves is 5850 m/s and the frequency is 1 MHz, the resulting wavelength is that of 5.85 mm.”

(Hijazi, 2019)

In solid materials sound waves can propagate in four ways, referred to as the four principle modes that base themselves on how the particles oscillate (Hijazi, 2019). The four principles are;

1. **Longitudinal waves** – Consist of alternate compression of pressure waves similar to speech, these vibrations move in the same direction as the propagational energy.

2. **Shear waves** – Unlike longitudinal waves, shear waves are at 90° to the propagating energy source, shear waves can only occur in materials that possess shear elasticity (HSE, 1994). Shear elasticity/modulus is stated by Helmenstine (Helmenstine, 2019) as the ratio of shear stress to shear strain. In metals, a materials shear elasticity decreases as its temperature increases (March, 1996).

Longitudinal Vs. Shear Waves

Comparison of Longitudinal and Shear Waves

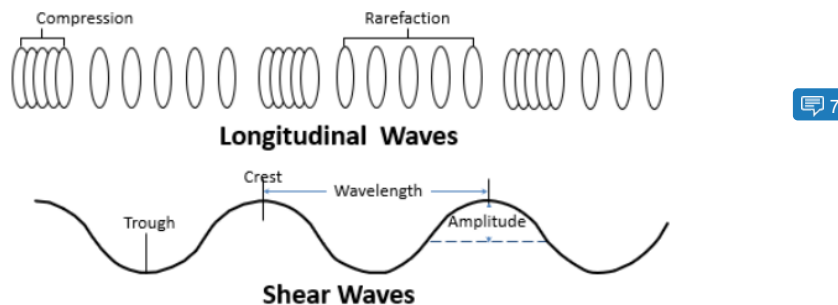


Figure 3 - Wave Comparison of Longitudinal and Shear Waves (Skills Commons, 2016)

3. **Surface waves** – Similar to shear waves however penetration of surface waves is only one wavelength deep, their velocity is also 2% less than that of shear waves. Surface waves behave with a combination of Longitudinal and Shear waves therefore they follow a rolling or orbital particle motion (HSE, 1994).
4. **Plate waves** – Plates waves, or Lamb waves as they're also referred to which are the most commonly used plate waves in NDT, are similar to surface waves. They are used to inspect thin plates of only a few wavelengths in thickness (Skills Commons, 2016). Lamb waves are complex vibrations that propagate parallel to the material being tested and must travel throughout the entire thickness (NDT Resource Center, 2019). Propagation of Lamb waves is dependent on the density and elasticity of the material being tested. They can move symmetrically and Symmetrically. Asymmetric waves move in uniform motion where Symmetrical waves move in a compression and extension motion as shown in Figure 4.

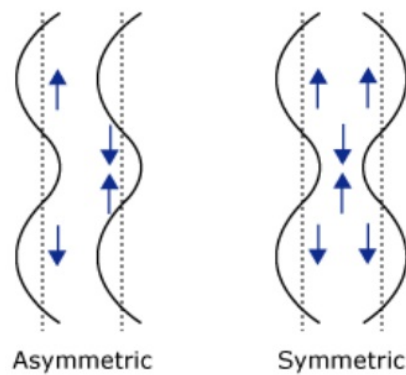


Figure 4 - Asymmetric and Symmetric Lamb wave motions (NDT Resource Center, 2019)

Velocity is described in the Oxford Dictionary (2001) as ‘the speed of something in a given direction’. When considering specific material choices, this is a value that can alter dependant on the sound waves present. i.e. the velocity of sound in longitudinal waves is approximately half the velocity of sound witnessed in that of shear waves when in the same material. This velocity in a variety of material compositions is highlighted in Figure 5.

Material	Compression Velocity	Shear Velocity
	Mm/s	
Air	332	-
Aluminium	6,400	3,130
Brass (70-30)	4,372	2,100
Cast Iron	3,500	2,200
Copper	4,769	2,325
Gold	3,240	1,200
Iron	5,957	3,224
Lead	2,400	790
Oil	1,440	-
Perspex	2,740	1,320
Steel-mild	5,960	3,240
Steel- stainless	5,740	3,130
Water	1,480	-
Tungsten	5,174	2,880
Zinc	4,170	2,480
Zirconium	4,650	2,300

5. Resolution(-)

Figure 5- Velocity of Sound Waves in Materials (HSE, 1994)

3.1.2 Advantages and disadvantages of UT

When compared to other NDT techniques, UT has the following:

Advantages

- Sensitive to both surface and subsurface discontinuities.
- No risk to operators or others nearby, nor does it have an effect on the tested material.
- Depth of penetration for flaw detection is far greater than other NDT techniques.
- Part preparation is minimal and only one-sided access required for the pulse method.
- Instant results given.
- Thickness of a hidden component can be obtained using the pulse/echo method.
- Highly portable and convenient, easy to use.
- Defects including internal ones can be sized and positioned accurately when discovered including the shape and orientation of the defect.
- Wide range of thicknesses can be tested, from a few millimetres up to several metres.

Disadvantages

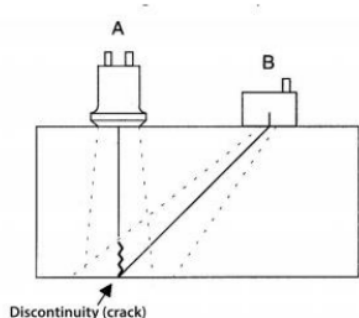
- Surface must be accessible and contact possible for ultrasound to be transmitted and accurate.
- Easy to use however extensive training compared to other NDT methods.
- Inaccurate and hard to use on materials which are rough, extremely small, exceptionally thin or irregular in shape, i.e. cast items.
- Defects running parallel to the sound waves may go undetected due to their minimal disruption to the pulse and echo.
- Results are determined by specific reference standard requirements for both equipment calibration and part tolerances with acceptable/unacceptable flaw size.
- Single crystal probes have a dead-zone in which defects will not be detected, twin crystal probes are usually focused and have a limited depth range, so extensive training and experience is required to ensure the correct probe is used.



Figure 6 - Single and Twin Crystal UT Probes (HSE, 1994)

- Couplant, a material that facilitates the transmission of ultrasonic energy from the transducer into the test piece (NDT Resource Center, 2019) can act as a contaminant and removal prior to testing, such as any surface paint or coating may be required.

3.1.3 Potential sources of error with UT and assumptions that need to be made

Potential Sources for Error	Reasoning
Defect Orientation	If the sound waves travel parallel to the discontinuity, a 0° probe (probe A) will receive very little feedback if any, therefore the only way to determine an accurate outcome is to use a 45° probe (probe B) which is a shear wave probe and will detect the discontinuity with ease.  (The British Institute of Non-Destructive Testing, 2015)

Calibration and Equipment Accuracy	Calibration of testing equipment is pivotal to gaining accurate results. Accurate results ensure the levels of safety required are obtained and risk is minimised as much as it reasonably possible. However, further inspection is needed to ensure that the equipment being used is not damaged externally or internally in order to function precisely. i.e. Shared equipment cannot always be monitored for any drops or impacts the equipment may receive.
Incorrect Equipment	Inexperienced, costs, undertrained workforce or incompetence can result in the wrong equipment being used, furthermore this will result in unreliable data, potential errors and inevitably product failures.

Table 4 - Potential Sources of error with UT

3.1.4 Typical applications that use UT

Industries that utilise UT comprise of:

- **Manufacturing** – Can determine the condition of materials/components in order to improve quality, safety and reliability.
- **Medical Industry** – Used on a large range of human organs for diagnostic purposes.
- **Oil and Gas Industry** – UT can aid checks and underwater inspections of pipes and offshore structure inspections.
- **Shipping Industry** – Routine maintenance on cargo hatches, erosion to ship walls/bulkheads and inspections of pipework which supply utilities and fuelling to the ship.

Applications within manufacturing consist of;

Application	Use of Application
Through-transmission testing	Alternative method to single probe pulse/echo UT, a probe is placed either side of component and one will transmit pulses of ultrasonic energy, one will receive. The receiver signal is displayed, and when travelling through a defect, the signal level will drop due to the interruption across the wave path.
Immersion UT	An automated approach whereby the test piece is submerged into a water-filled immersion tank. The probe can be moved and angled according to the test requirements. The probe will not touch the test-piece and will typically travel at a uniformed distance from the part ensuring a uniformed focus at a specific depth is kept.
Thickness measurement and Condition Monitoring	The distance the ultrasonic waves travel can be highlighted resulting in the possibility to calculate thicknesses of materials. This is useful where only one side of the material can be accessed. In order to calculate thickness, the velocity of sound in a material is required, along with the time of the pulse being measured. This can be effective with condition monitoring applications whereby corrosion of a material whereby only one side can be accessed can be determined. If the pulse waves return quicker than the desired time, then the likelihood that the material has thinned is high, thus requiring attention and repair prior to failure occurring.

Material Condition	Can assess microstructural differences in metals. For example, as the waves travel through the metal multiple times energy is lost. Therefore, if the energy decay of the tested part is larger than that of the standardised part/master part, it can be assumed that the microstructure of the tested part is coarser and may not be fit for use if outside of the tolerance window.
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Table 5 - Applications of UT in Industry

3.1.5 How the results of UT can be used to improve stress analysis

UT provides multiple readings which can determine the condition of a material or part. Therefore, utilising these findings can determine stress management of a part which is another useful tool of UT. Using UT pulsing methods, all velocity changes within a metal part such as tensile loading of steel bolts and measuring residual stress in metal components are possible (The British Institute of Non-Destructive Testing, 2015). Any velocity changes within the part can be an outcome due to the presence of stress which may result in further testing being required or replacement of parts.

According to Jagasivamani (1992) experiments were carried out with shear, tensile and compressive loading and the acoustic properties were shown to be influenced by externally applied stresses giving information regarding bonds using the stress sensitive acoustic properties.



In order to develop data for absolute stress levels, Janssen (1992) used ultrasonic bulk waves from shear and longitudinal waves simultaneously. Janssen discovered between two comparable structural steel properties, this use of UT showed clear potential for measuring absolute stress levels on these materials.

In 1993, an experiment was carried out in order to utilise Rayleigh waves to detect the presence of residual stresses. The ability to control the penetration depth of the Rayleigh waves enabled mapping out possibilities of the residual stress gradient as they propagate along the surface of a material regardless of shape or contour. By altering the wave frequency, the waves were controllable and it was concluded that UT made it possible to determine the magnitude and depth of the residual stress in the material being tested (Lindgren, et al., 1993).

3.2 Magnetic Particle Testing (MT)

3.2.1 Scientific principles behind Magnetic Particle Testing

Magnetic particle testing is an NDT process that uses magnetic fields to discover any defects on or near the surface of ferromagnetic materials (TWI, 2019). A ferromagnetic material is stated by Chandrasekharan (2016) as a substance which when placed in a magnetic field are strongly magnetised in the direction of the magnetic field, according to Birmingham University (2018), due to the atoms having a parallel aligned magnetic moment as shown in *Figure 7*. Such materials include Nickel, Iron and Cobalt.

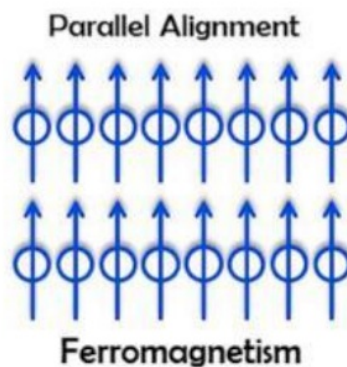


Figure 7 - Ferromagnetism Atom Alignment (Chattopadhyay, 2019)

MT is based on the magnetic mark of magnetic particle formation on a workpiece surface, created by the phenomenon magnetic leakage field (*Figure 8*) which as a result exposes the characteristics of any defects within the workpiece (Lin, et al., 2013).

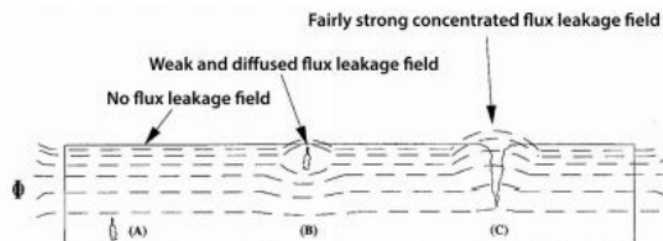


Figure 8 - MT Discontinuities Leading to Flux Leakages (The British Institute of Non-Destructive Testing, 2015)

When discontinuities are detected, such as the cracks in *Figure 8*, Professor Robert Smith of the BINDT (2015) states that it is due to them intersecting the magnetic field lines and MT can detect cracks from any intersection angle typically between 45-90° and is highlighted using detection media.

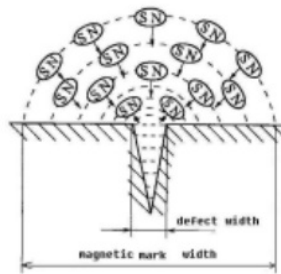


Figure 9 – MT testing powder being attracted to the magnetic flux

Highlighted in *Figure 10* are the resultant discontinuities that can be expected from an MT, where the adsorption of magnetic powder, such as iron filings, after ferromagnetism. The potential defects are clearly visible under white light or ultraviolet light, the latter being used in a minimal natural light environment (Hijazi, 2019). Once magnetised the powder will form in the shape of where the magnetic leaks occur. Magnetic mark analysis can therefore be used to identify and guarantee the performance of a workpiece (Lin, et al., 2013).

5. Spelling(-)

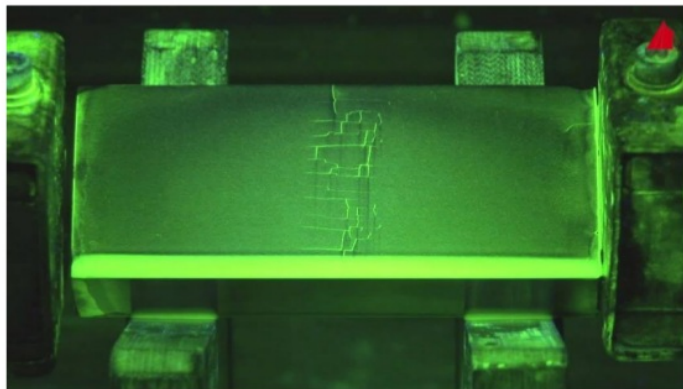


Figure 10 - Resultant MT Discontinuities (Magnetic Particle Inspection, 2014)

Once testing has concluded, often the workpiece can retain residual magnetism. This may be important in the components service life, this is explained in an extreme example by Dr. Hijazi (2019) who notes the potential problems if the magnetised part is installed near a compass in future. Therefore demagnetisation is part of the MT process and several methods can be used but the most common method highlighted in multiple reports on such analysis is to reverse the magnetising force opposite to the initial magnetised force used, this force is called the coercive force.

3.2.2 Advantages and disadvantages of MT

When compared to other NDT techniques, MT has the following:

Advantages

- Very sensitive to near surface discontinuity location in ferromagnetic materials.
- Workpieces of a large size and shape variety can be tested accurately.
- Quick testing method with instantaneous results displayed.
- Testing does not always require surface be free of paint or coatings.
- Quick method to learn and become competent in.
- Indications from testing are very precise and clear.
- Some equipment for testing can be portable so that components can be tested without full removal if situated within a larger unit.

Disadvantages

- Only applicable to ferromagnetic materials with limited subsurface capability.
- Due to potential defect orientation and sizing, complete testing requires two magnetic fields 90° apart in individual tests.
- Cleaning often required after testing to free the component of any residual powder.
- Demagnetisation required to ensure residual magnetic fields are removed to reduce further complications in components future life.
- Some testing can require high electric currents which may result in burns on the part if performed incorrectly resulting in scrappage after testing.

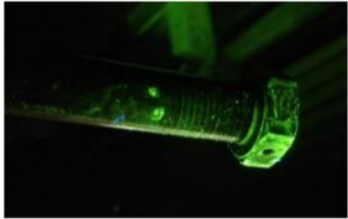
3.2.3 Potential sources of error with MT and assumptions that need to be made

Potential Sources for Error	Reasoning
Visual Inspection	Results gained from some MT practices will require visual inspection in order to determine if discontinuities are present or if they are in fact defects. These inspections can often result in decisions being made which could vary in consistency depending on judgement.
Preparation	The surface of a material being placed under MT has to be cleaned prior to the test commencing. If not cleaned thoroughly enough, the results and test may be invalid.
Demagnetisation	A vital part of the process to ensure the future life of the tested component is not affected in any way detrimental to its intended operation. A process whereby this stage may be forgotten or missed, could result in large future issues.
Flux Leakage Detection	Flux leakage is dependent on the orientation of the indication compared to the magnetic field (Eriksson, 2013). Effectively if the crack is perpendicular to the magnetic field then the flux leakage will reach its maximum value, however cracks are only detectable within an angle of 45°-90° to the magnetic field. This may result in cracks going undetected.
Magnetic Field Strength	Easily monitored and overcome but may be overlooked and a low strength magnetic field may result in weak data or the detection of discontinuities being minimal.

Table 6 - Potential Sources of Error with MT

3.2.4 Typical applications within manufacturing that use MT

Widely used in industry for final inspection of manufactured components, MT ensures quality control and early detection of discontinuities during in-process inspections are identified and eliminated or corrected earlier resulting in lower associated costs to inadequate components.

Application	Use of Application
Aerospace Industry	In a study by Uludag (2016) MT is used to identify discontinuities within aircraft propeller mounting bolts. It is critical these parts are fit of use and not showing any defects at all to ensure safety is paramount. Highlighted in the image below are slight discontinuities within one of the mounting bolts tested.  (Uludag, 2016)
Power Generation Components within Industry	Often used to identify any defects within components subject to sudden changes in torque such as crankshafts and camshafts. It is stated by AMTECH (2019) that the surface of the shaft will have double the weakness of the inside of the shaft, thus maximum operational force greatly affects the surface more where any defects will result in stress concentration and potential failures.
Petrochemical Industries	Used commonly in maintenance inspections to ensure equipment, pipes and infrastructure is fit for use due to potential failures resulting in catastrophic results.

Nuclear Industry	According to Harper (2016) “ <i>nuclear plants must supply uninterrupted power to the electrical grid. However, safety is of utmost importance, both that of the general public and plant employees. NDT techniques such as MT are proven to fulfil both objectives. Such techniques also meet the goals of enhancing reliability of plant assets</i> ”
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Table 7 - Applications of MT within Industry

3.2.5 How the results of MT can be used to improve stress analysis

Stress analysis is a fluid operation whereby the component under inspection will gradually degrade over time and therefore reliability becomes lower. In a study conducted by Uludag (2016) as previously noted in *Table 6*, a study regarding the degradation of propeller mounting bolts was conducted. Initially upon construction Uludag (2016) states that the bolts would have been designed to withstand the change in stress it was continually put under, however eventually the materials limits will be reached, and failure can occur. MT enables inspection of such parts in order to ensure that the expected life cycle of these components is correct, and failure can be avoided once discontinuities and defects start to accrue within the material.

Traditionally the integrity of structural parts used in construction or vehicles and aircraft would be calculated using material strength calculations. According to Viotti and Albertazzi (2014) this resulted in oversized, heavy components in most cases which caused problems in industries that demand lightweight constructions, such as the aerospace industry. As highlighted in Uludag’s study, the benefit of MT within aerospace parts has enabled strong, reliable, lightweight components ensuring all desired characteristics are met.

3.3 Radiography (RT)

3.3.1 The scientific principles behind Radiography

One of the oldest methods of NDT used widely, RT still has advantages over other methods however health and safety concerns have resulted in alternate methods being used. RT is based upon the absorption of ionizing radiation in a material, which will vary depending on the density and thickness of a material (Broberg, 2011). Broberg states that when a defect is present in a material, its absorption rate will vary from the base material, hence becoming visible in a radiographic test. One of the main volumetric testing methods, along with UT, RT is useful for when UT is not strong enough to penetrate the thickness of a material. RT is also favourable in other situations, for instance RT provides a permanent reference for the internal soundness of the object that is being tested (Dwivedi, et al., 2017). RT emits either short-wave-X or gamma rays and directs it at the part in question. Furthermore, Dwivedi specifically states that an x-ray has the ability to penetrate metals, however due to them a sensitivity nominally 2% of the materials thickness, i.e. void detection up to 0.5mm in a 25mm thick piece of steel, parts will often be tested in different planes. Multiple plane radiography tests are further supported due to thin cracks that do not show up unless the x-rays run parallel to the plane of the crack.

RT highlights defects by aiming its rays at an object and capturing the rate of penetration possible through that object on photographic film. A high density/thicker object absorbs more radiation causing a reduced amount to hit the film on the other side resulting in a lighter image as shown in *Figure 11*.

1.

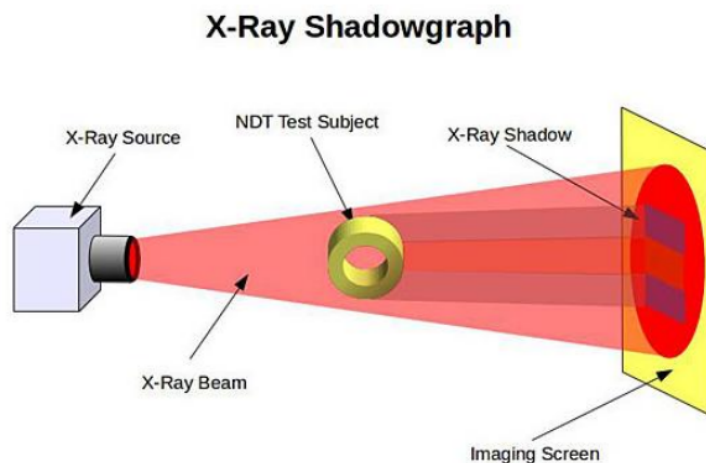


Figure 11 - X-Ray Shadowgraph (Achterkirchen, 2014)

Therefore, defects within an object will result in a less dense area internally where the defect is situated, which produces a slightly darker mark on the film indicating a discontinuity which may be deemed a defect as shown in *Figure 12*.

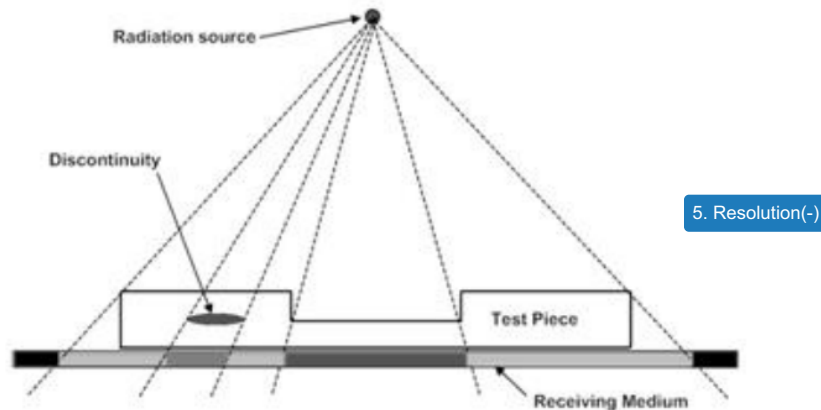


Figure 12 - Varying Levels of Radiation With Defects (The American Society for Non-Destructive Testing, 2019)

A x-ray image cannot be seen immediately, it needs to be developed. The initial unseeable image is referred to as the latent image (The British Institute of Non-Destructive Testing, 2015) and the quality of the resulting image once developed is dependant on three considerations:

- **Density** – Simply the degree of blackness on a radiograph. Further evidence suggests there is a minimum and maximum amount in order to make the results clearly visible at the desired sensitivity. Most densities are within boundary conditions of 1.5-3.5 and as they are a ratio of the following equation, they have no units.

$$\frac{\text{Incident Light}}{\text{Transmitted Light}}$$

Whereby:

Incident Light – Measures the light falling on to the object where how light or dark the object is has no bearing on the exposure reading (Sekonic, 2019).

Transmitted Light – The amount of light wave able to pass all the way through a material without being absorbed (Wood, 2017)

- **Contrast** – Contrast is the amount of difference between two or more images where black and white would be considered high contrast, and tones of a similar shade would be low contrast. In terms of RT, it is the difference in densities. Black and white images would be considered as a high contrast as the properties of the test subject is showing a large degree of difference in density, whereby similar shades show similar densities i.e. low contrast. The BINDT (2015) states that contrast can be enhanced to provide a clearer image by altering the film used and the developing process used dependant on the tested component itself, screens, filters and the wavelength of radiation used/required.
- **Definition** – The degree of sharpness on the far edges of the density region i.e. the sharpness of the boundaries on the radiographed image. The definition can be adjusted by controlling the focal spot of the x-ray to be as small as possible, reducing the distance between the object and the film but increasing the distance between the radiation source and the object that is being tested.

3.3.2 Advantages and disadvantages of RT

When compared to other NDT techniques, RT has the following:

Advantages

- Can perform NDT testing into thicker materials compared to that of UT.
- Deeper penetration capabilities enable detection of internal flaws.
- Creates a permanent long-lasting image of test for future inspection.
- Internal images can be gathered for assembled units without deconstruction required.
- Radiographic testing improves quality of welds by highlighting corrosion, slag, undercut and stress cracking present in weld joints as shown in *Figure 13*.

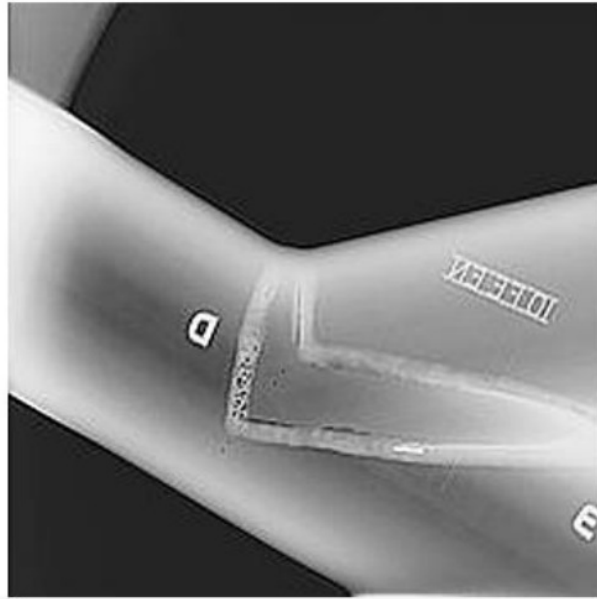


Figure 13 - Radiography NDT Highlighting Flaws in a Welded Joint (Achterkirchen, 2014)

Disadvantages

- Considerable Health and Safety concerns when using radiation equipment involved with RT. With over forty years of application in industry, the safety record with radiography is very good, with negligible risk to the public or risk on the workers. However, bad practice examples have been published and a high dosage rate of exposure can result in injuries within minutes or even seconds.
- Results are delayed by the development time and experience required to produce high quality imagery.
- Inexperienced workers may use incorrect film or filters, or operational boundaries of which detection of defects may not be thorough.
- Traditional equipment is large and bulky, not portable. Portable methods are expensive to purchase and require a new skillset to set up and operate correctly requiring further training.

3.3.3 Potential sources of error with RT and assumptions that need to be made

Potential Sources for Error	Reasoning
Incorrect operating boundaries used	Inexperience or human errors of another nature can result in incorrect testing procedures and therefore unreliable results may occur, possibility of unclear imagery developed and defects being missed.
Single plane testing	Cracks or defects of a smaller scale can be missed if not tested on multiple planes.
Surface Preparation	Welds being tested need to be sufficiently free from irregularities or dirt that may mask or interfere with the resulting image produced from the test.
Calibration Standards	Equipment must be regularly calibrated and verified to be in full working order. Also, the density reading of the resulting image can be measured using a densitometer to ensure the results are accurate.
Defect Detection and Human Error	Stated by it is generally accepted industry wide that during test calibration a number of small wires are tested and the smallest wire that can be detected for a minimum continuous length of 10mm provides the reliable capabilities of the current set up. Therefore, incorrect calibration at a previous stage may result in smaller defects being missed upon visual inspection whether due to clarity, test failing or human error.

Table 8 - Potential sources of error with RT

3.3.4 Typical applications that use RT

Application	Use of Application
Airport Security	Real-time x-ray systems are used to scan baggage, packages and passengers to ensure security and safety is maintained to a high level.
Aircraft Industry	Neutron radiography used to inspect water entrapment and corrosion in aircraft wings.
Explosives	Neutron radiography ideal for locating light material within dense materials, i.e. explosives inside a metal casing/shell.
Fabrication	Radiography can benefit inspection on welds and castings. RT can be utilised to inspect small, thin wall tubing welds that commonly contain defects such as porosity.

Table 9 - Applications of RT

3.3.5 Explain how the results of RT can be used to improve stress analysis

Stress analysis with NDT is commonly discussed around the effects on a component or material during fluctuations in the loads placed upon it. Often looking at components such as bolts and fixtures, however stress analysis on wear and tear of components over time such as the inside of a pipe system is equally crucial. Due to the nature of a piping system, the internal walls are enclosed and therefore inaccessible unless damaged or split. However, RT is an NDT method whereby the condition of the piping system can be inspected without causing the any compromising damage to the pipe. Due to increases in temperature and the expansion/contraction witnessed in the atom make-up of metals, piping will over time inherit related issues as shown in *Figure 14* where an internal crack has become present. Using RT, as stated by Basavaraju and Sun (2004) can inspect if any cracks, change in material properties or potential developing issues are becoming present. This allows to therefore safely plan a repair strategy to prevent the stress overcoming the weakness and causing further damage or safety implications.

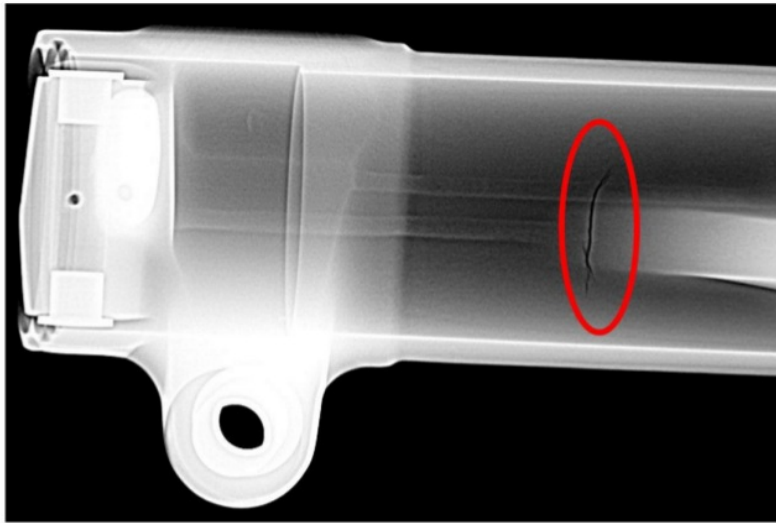


Figure 14 - Radiographic NDT revealing internal crack inside a pipe (Vidisco, 2019)

When considering the automotive industry, RT is applicable in circumstances where the casting development of the block and head manufacturing process is to reduce material required while maintaining operational efficiencies and safeties. Radioscopy can focus on mass production issues and the internal stress analysis of the castings is critical to the product, therefore without having to destroy the tested block, X-rays allow visual guidance and inspection of any internal flaws as shown on the aluminium casting in *Figure 15*.

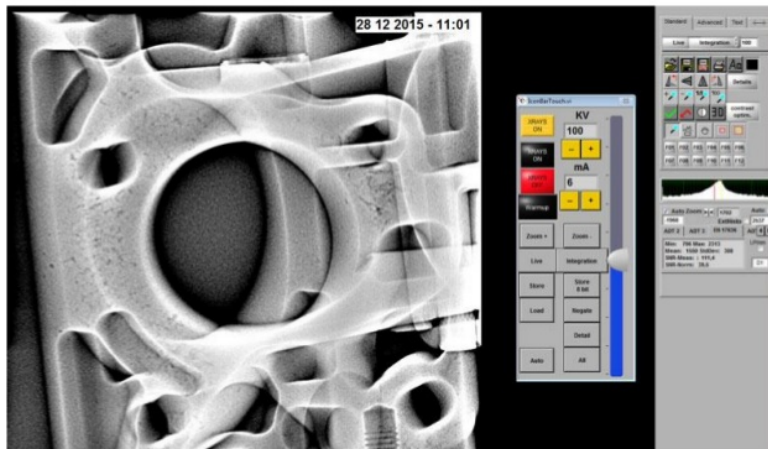


Figure 15 - X-Ray NDT imagery on an aluminium casting from an internal combustion engine (VisiConsult, 2019)

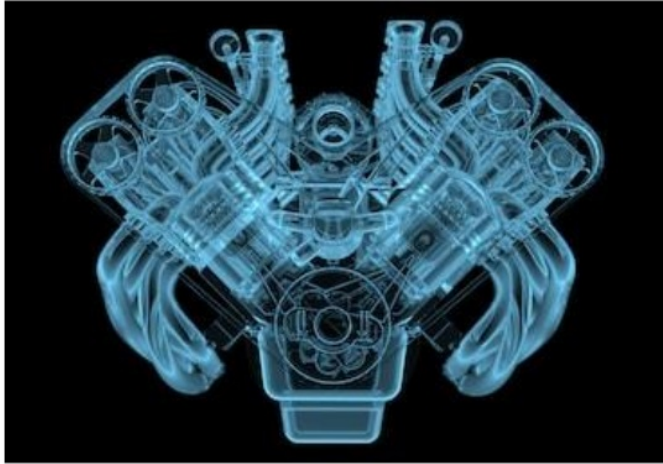


*Figure 16 - X-Ray image (head on profile) of an internal combustion engine
(Shutterstock, 2019)*

4. Conclusion

This report highlights that through non-destructive testing methods the scope of material usage and capabilities has changed dramatically over the years. Composite materials are being developed and tested to provide increased strength, reliability and reduce potential downfalls in industry due to their impressive properties. NDT has provided an increase in safety both by improving and continuously ensuring high quality produce, and by allowing maintenance to consistently monitor and inspect any wear on components and act accordingly prior to a failure.

NDT has reduced costs for manufacturers by ensuring quality remains high while material usage remains as low as is feasible, this is through testing materials and components to their limits in order to assess new ways to manufacture goods cheaper while maintaining the original properties required.

NDT has also reduced time constraints on inspecting materials and production, sealed components with internal components can be inspected and tested without having to be disassembled and this results in more tests being performed which will ensure quality failures are spotted quicker and corrected immediately. This has a large impact on the future customers who receive high quality goods, on time, with uniformed and reliable delivery which will drive future sales for the manufacturer.

When considering methods of NDT, it is apparent that each method has its strengths and drawbacks. This requires a company to ensure training and skills of the operating personnel to be of a high standard so that not only is the correct NDT method chosen but is also carried out correctly to provide accurate feedback. The cost implications for such thorough operations are heavily outweighed by the costs associated with high failure rate in produce and the knock-on effects to correct those issues and compensate future customers.

With everything considered, NDT has become a critical part of manufacturing in every area of industry, whereby quality and safety can be considered to go hand in hand, where a quality product is a safe one.

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6. Glossary of Technical Terms

Anisotropic – *An object or substance that has a physical property which varies in value when measured in different directions. i.e. Wood is anisotropic because it is stronger along the grain than across it.*

Magnetic flux – *The magnetic flux can be obtained at a specific area perpendicular to the flux when the flux density is homogenous. In simplified terms it describes how many magnetic field lines that are passing through a material.*

Magnetic Leakage Field - *Because air magnetic permeability is much lower than ferromagnetic materials, magnetic induction line will give priority to with high magnetic permeability, it forces magnetic induction line pass around defect and form a compression of magnetic induction line when defects exist on ferromagnetic workpiece. However due to the limitation number of magnetic induction lines that defect accommodated, magnetic induction line repels each other, therefore, a part of the magnetic induction line will through defects of discontinuous, by-pass defects and back to the workpiece, finally form a leakage magnetic field.*

Non-homogeneous – *Composed of parts or elements that are not all of the same kind.*



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