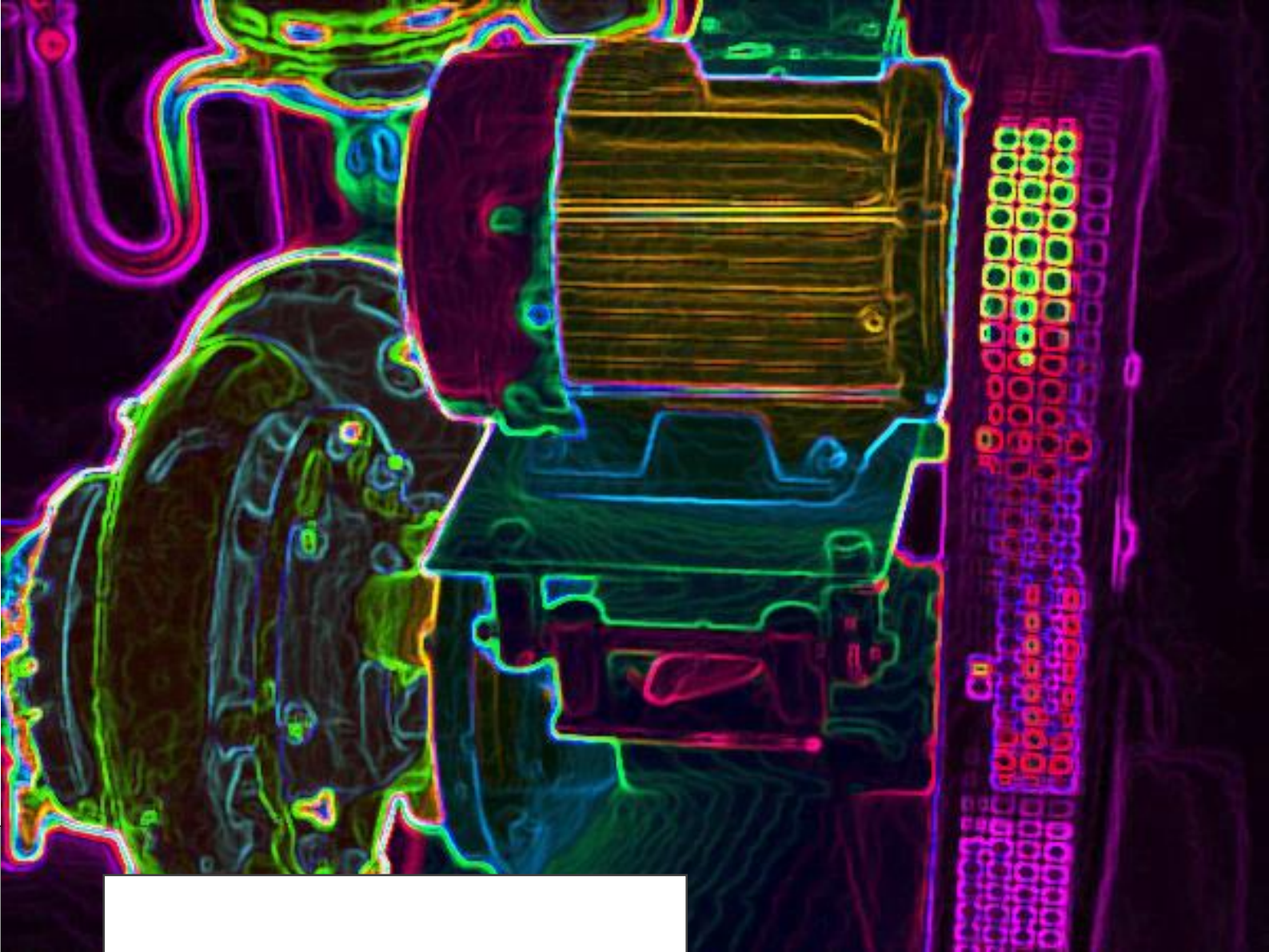




NDT Techniques

Advanced Stress Analysis & FEA
(M6X00420)

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2. Abstract

This report examines NDT techniques within industry, and how they are used to ensure quality assurance of our structures such as bridges and pipelines. A parallel may be drawn between NDT and traditional destructive testing, some NDT techniques are used to determine material properties and key characteristics which enable us to determine what material works best for a given application. NDT however is mainly used as a technique to locate and measure faults, commonly known as discontinuities within a material. The report analyses three NDT techniques; Radiography, UT (Ultrasonic Testing) and MPI (Magnetic Particle Inspection).

3. Introduction

NDT (Non-Destructive Testing) is a technique used to analyse possible flaws in a product or material with the benefit of maintaining the structural integrity of the test piece [1]. A defect or flaw within a material may weaken the products performance, ultimately leading to failure as claimed by Certz 1996 [2]. NDT has been used as an industrial application for many years, with the first recognised technique being that discovered by Wilhelm Conrad Röntgen in 1895, the x-ray [3] [4]. The importance of safety grew and therefore testing became more important, the benefits of NDT became apparent, with new technologies being developed, the next of those being MPI (Magnetic Particle Inspection) [3]. NDT today is widely a digital technology [5], it is claimed that due to the rapid rate of how NDT methods have developed at times throughout history, new technology is emerging prior to the current technology being recorded [5].

NDT is used for many applications spanning a wide range of industries, aerospace, energy and medical [1] [6]. NDT is used on an array of materials such as metals, polymers, even wood [7] and cardboard [8], but increasingly so in composites [5] [9], used for applications like pipelines [10] and concrete structures [11] to name a few. NDE (Non-Destructive Evaluation) is another form of NDT, whereas NDE could be considered more quantitative. An example of this is where NDT may be used to test a sample to discover a defect, NDE may be used to evaluate the size and characteristics of the given defect [1], although due to the techniques overlapping considerably, both NDT and NDE may not be regarded as mutually exclusive [1].

One may require NDT due to the simple fact that other techniques, being that of destructive testing, renders the test piece unfit for use post-test, it is not preferential to build a structure such as a bridge and then to destroy a proportion of it in a destructive test. NDT may be regarded as a method used to detect defects that may ultimately lead to failure through an array of factors such as general stress and strain or fatigue [1].

4. Specific Techniques

4.1. Radiography

4.1.1. Scientific Principles

Radiography is a volumetric testing method, used to detect flaws within a component. Traditionally, x-rays are passed through one side of a component and through onto a sensitive film known as a radiograph, this is known as a film-based technique. A solid metallic object will absorb the x-rays, whereas a flaw such as a crack or inclusion within that material will absorb less of the rays, thereby creating a radiographic image [12].

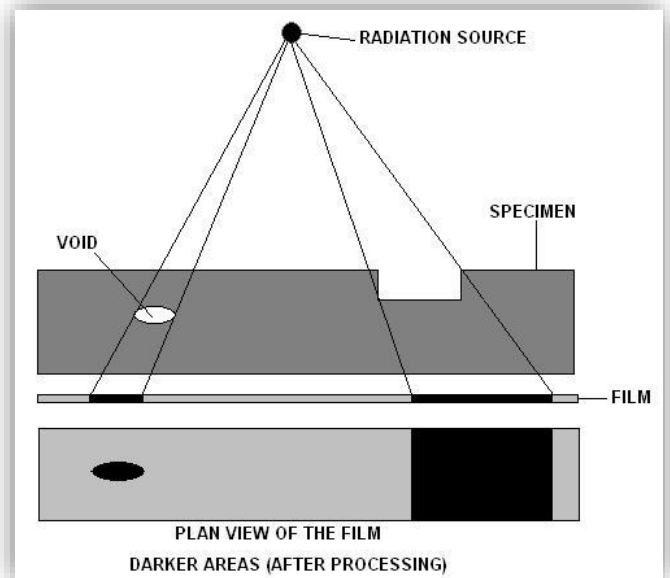


Figure 1 Radiography film-based technique (www.ndtdavari.com, 2019)

A digital technique is now most common, it offers the benefit of greater control for the inspector, providing them the ability to view the image in real time, adjusting and recording to optimise the results [12] [13]. Here is a typical set up for the digital method:

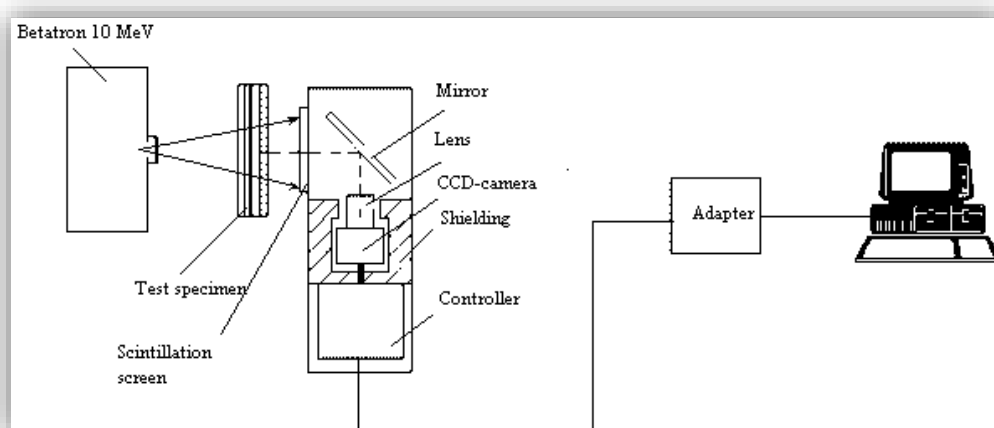


Figure 2 Radiography digital technique (ndt.net, 2014)

4.1.2. Typical Applications

Material type has a big effect on radiography, the density of the material determines how the x-rays pass through [5]. The graph shows how x-rays pass through material based on their thickness, as expected, lead prevents x-rays which is why it is used widely as an insulator or shield generally for x-ray equipment [5]. It is not only metallic objects that may be tested using radiography, it is often used to inspect concrete structures. An example of this is to inspect reinforcement within concrete, radiography may detect bar location, alignment, size and even corrosion [11]. Corrosion could occur when water may seep through into the reinforcement, this may not be visible from the outside of the structure. Bridge maintenance could benefit from radiography by inspecting corrosion and cracks of wires [14].

As well as structures, radiography is also used on composite and polymer materials [9].

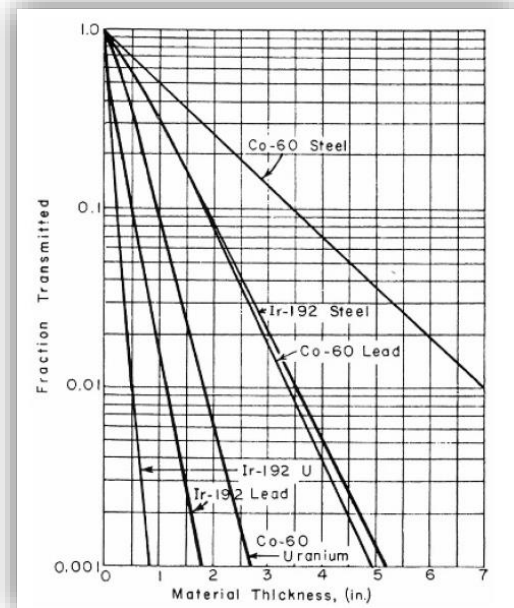


Figure 3 Radiographical material conductance chart (E. Mix, 2005)

4.1.3. Advantages, Disadvantages, Potential Errors and Assumptions

Benefits of radiography may be used to detect internal flaws deep within an array of solid materials, including metallics, polymers and ceramics. Digital radiography can be adjusted in real time to display a wide range of defects within the test piece, adjusting the intensity and size of the image to create a high definition image, allowing quantifiable activities such as measurement of the defect [13]. If an assembly is to be inspected, assembly defects may be identified which could in turn impact the structural integrity of the product.

Disadvantages include the fact that the technique requires access to both sides of the material being tested. Detection is limited to the orientation of the defect. The film-based techniques can be problematic, considerations must be made with regards to exposure time, this greatly

influences the radiographic image for inspection [12]. Components that are geometrically complex in nature may be difficult to analyse, this is simply a case of there being too much information to be able to focus on finding defects. The cost of radiography is generally high, both in terms of initial equipment cost and in terms of running costs such as consumables and labour. It is by no means an unskilled technique, experienced operators are required to carry out the testing. Finally, and by no means least important is the major health and safety factors associated with radiography testing. If the equipment is used incorrectly, it may be detrimental to the health of not only the people using it, but people within the surrounding area. According to reports, almost all cases of issues leading to accidents include failing to position the equipment in its protective shielded state [5].

4.1.4. Technique Summary

Radiography is a versatile method for testing both solid objects and assemblies, its ability with regards to depth of inspection is very good in comparison with many other NDT methods. The cost of equipment is high, although the quality of the result may warrant the high cost. The skill of the operator is a big factor, but then the results may be analysed later by others.

4.2. UT (Ultrasonic Testing)

4.2.1. Scientific Principles

UT is another volumetric testing method, it is used to detect discontinuities or defects within materials, and is widely used especially within the UK [6] [15]. UT equipment comprises of transmitting and receiving probe, the probe contains a crystal that vibrates at high frequency when subjected to a voltage, thereby creating ultrasound [15]. The sound travels through the material in one direction until it contacts the material wall or a discontinuity, at this stage, the sound travels back in the opposite direction to the probe. The probe generates an instant electrical feed signal, this feed a signal through the digital oscilloscope to a computer [6] [15] [16]. There are several different methods of UT:

- (a) Pulse-echo setup: The pulse is fired into the test piece, it will echo back when it encounters a flaw [16].
- (b) Pitch-catch setup: The pulse is fired into the test piece, the point at which it detects a discontinuity is accurately pinpointed by a secondary receiving probe [16]. The benefit of this is to gain better information of the size and shape of the defect.
- (c) Through transmission setup: like setup 'a' but it provides better outline profile of the flaw.

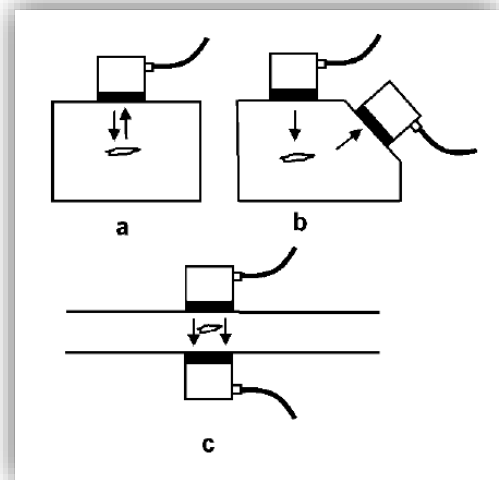


Figure 4 UT setup examples (Schmerr, 2016)

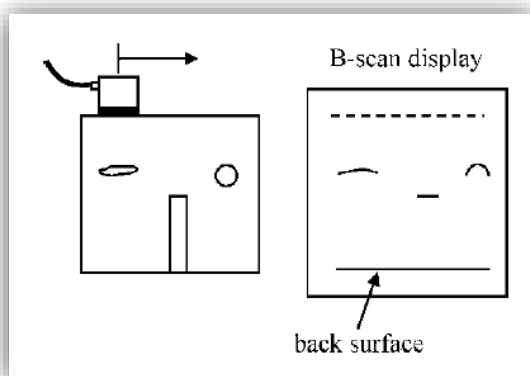


Figure 5 UT results of setup 'b' (Schmerr, 2016)

Figure 5 displays an image of a pitch-catch setup, this is effectively a side view image of the defects [16]. It is worth noting that this may be used if a pitch-echo setup is insufficient in determining enough detail about the defect.

Figure 6 displays an image of a through transmission setup, this is effectively a plan view image of the defects [16]. A disadvantage of this method is that it is more difficult to determine the depth of the flaw as pitch-catch setup does, but it provides a better view of the shape of the defect, depending on its shape and orientation [6] [15] [16].

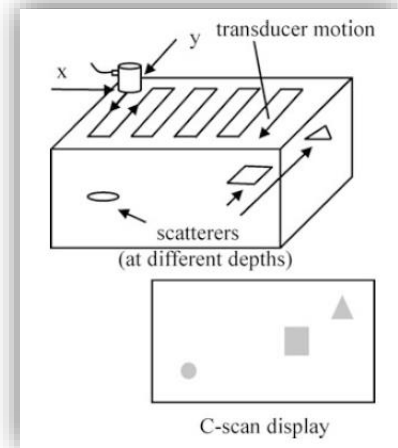


Figure 6 UT results of setup 'c' (Schmerr, 2016)

UT generally operates at a range of between 0.5 MHz and 25 MHz, in comparison, the audible range for the human ear is between 16 Hz and 20,000 Hz. The frequency range is significant as it can be finely adjusted to improve both sensitivity and resolution, sensitivity is the ability to detect small defects whereas resolution is a term used to describe closely spaced defects separately on the instrument screen [15].

4.2.2. Typical Applications

UT works well on a variety of materials within industry, metals, polymers, ceramics and even some composites [6]. UT is used widely in the petrochemical industry as it works well on pipelines. UT can inspect pipelines to a typical range of 182m, this condition is best case scenario and requires a metallic clean straight pipe or a Kevlar wrapped pipe [10]. If the pipe were to be corroded, or if the pipe was concrete, the expected efficiency range may be between 1m and 50m [10].

UT is also used on other large structures e.g. a bridge, these are subject to vibration created by traffic, they are also subjected to forces in multiple directions, both from traffic and adverse weather such as high winds [14]. UT is not solely a method for larger structures, it is used on smaller products such as engine components for automotive and aerospace industries [6] [17].

4.2.3. Advantages, Disadvantages, Potential Errors and Assumptions

Benefits of UT includes accessibility and portability, due to the lightweight of the equipment it is a portable inspection method, which allows inspection of difficult to reach components, access to only one side of the component is required using the pulse-echo technique [6]. As a volumetric NDT method, the entirety of the component is scanned from one surface to the other [15]. It is an incredibly sensitive method and can detect a defect size, position, orientation and shape [15]. Computer processing can determine material properties and defect characteristics, this may be done on painted or coated products without the need to remove coatings to prepare the surface [6] [15]. Results are instantaneous because returning signals are displayed in real time, this allows immediate analysis of the results, but results may be saved for further analysis later [15].

Disadvantages of UT include difficulty in interpreting results, especially if the operator is not highly experienced [15]. Adding to difficulties, a good surface contact is very important, meaning components that have corrosion or rough surfaces may be difficult to inspect [16]. The correct probe type is important for inspection, i.e. single-crystal probes contain what is known as a dead-zone, whereas twin crystal probes may not be used on a shallow depth range [15] [16].

4.2.4. Technique Summary

In summary, this may be regarded as a relatively comprehensive method due to its versatility in testing all parts of both large and small object. Access to the material is often not an issue, the portability of the equipment is also a big benefit as it can be carried from site to site. The results are instantaneous, although they may be difficult to interpret if the operator is not fully trained or experienced, and training may be expensive and so is the initial cost of the equipment [6] [15] [16].

4.3. MPI (Magnetic Particle Inspection)

4.3.1. Scientific Principles

MPI equipment generates a magnetic field using alternating current and applying it to a component, this occurs both at the surface and just beneath it, making it an excellent method for detecting surface and near surface cracks in ferro-magnetic materials [15] [18].

Two electro-magnets are placed against the surface of a material, a magnetic current is generated that then travels through the material. Discontinuities within the material, often in the form of a crack will generate flux leakage, this is most prominent when the defect is at 90° to the direction of travel of the magnetic field, although identification may also be possible if the defect sits at only 45° to the direction of the magnetic field [15].

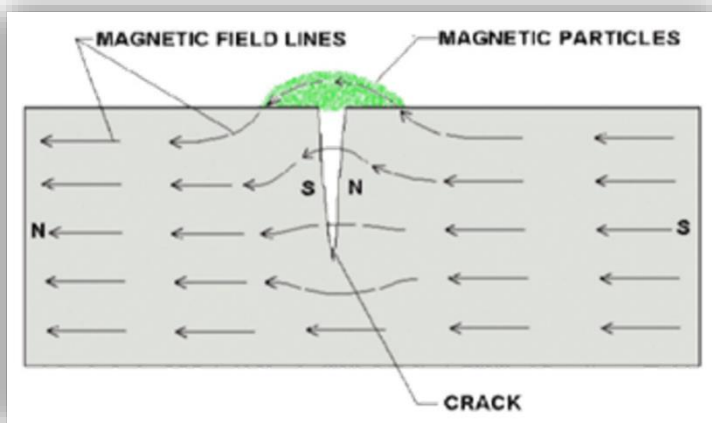


Figure 7 MPI diagram (nde-ed.org, 2019)

Any ferro-magnetic particles applied to the material will attract to the flux-leakage, gathering to form a visible indication of a surface defect. These ferro-magnetic particles may be applied using both wet and dry methods [15].

The wet method application (known simply as 'ink') generally uses a red or black dye, alternatively, a fluorescent dye is a very common method to aid with identification of the defect [19].

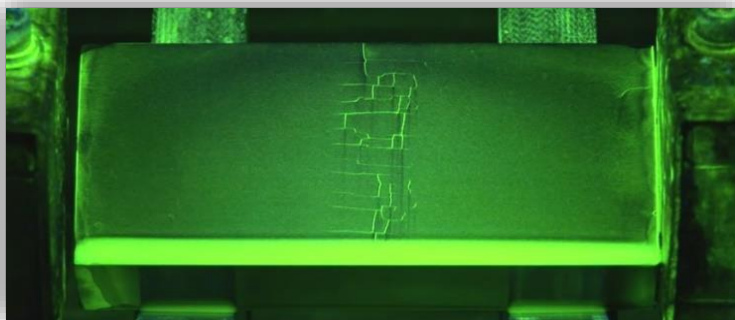


Figure 8 Test piece with fluorescent magnetic dye applied (MaterialsScience2000, 2014)

Figure 8 is an image of a test piece with its defects highlighted using a fluorescent dye, this is best viewed in dark conditions, therefore is not ideal for testing outdoors such as on site [19].

4.3.2. Typical Applications

MPI can be used on small components like pipes that have been bent or welded, to large components such as welded pipelines or bridges [10]. It is often used on smaller components when compared with other techniques such as UT, generally focussing on casting, forgings, welds and heat-treated components. During the hardening process, a material's crystal structure is changed, if the cooling rate is not controlled, rapid shrinkage of the structure will result in cracking. The reason for its high usage on welds is due to slag inclusion, porosity and simply cracking, making it a method well suited for end of line inspection in a manufacturing environment [20].

4.3.3. Advantages, Disadvantages, Potential Errors and Assumptions

Advantages for MPI include that it is highly sensitive to discontinuities within materials, foreign object debris, especially non-metallics, such as slag inclusion in a weld may be detected relatively easily, and the result from testing is instantaneous [20]. The equipment is portable and can be used during manufacturing, or even taken for on-site inspection of structures, such as bridges and pipelines. Finally, MPI requires little training in comparison with UT or radiography, it is not heavily reliant on an experienced or highly skilled operator [1] [15].

One of the most prominent disadvantages is the requirement for a permeable material, some materials magnetise easily, some can but with difficulty, where others do not at all, thereby rendering many materials such as polymers, ceramics and composites unsuitable for testing [15]. The method used to generate a magnetic field, being that of introducing a high current to the material, meaning stray arcing often occurs to other metallic objects, which can render the test piece scrap if it is highly aesthetic [20]. Prior to testing, it is usually necessary to prepare the surface of the material, often by applying a degreasing agent [15]. The removal of the ferromagnetic particles is required post-test [15], this takes some time that could otherwise be spent testing another product, also it is generally messy. Finally, the material will require treatment if the prior coating has been removed as part the preparation process.

4.3.4. Technique Summary

MPI is good for testing ferro magnetic materials, it is efficient at detecting both surface and near surface discontinuities. The mobility of the equipment is attractive also, as is the fact that it does not require a highly skilled operator to use it. Yet it cannot detect defects deep into the material, which is a big issue depending on the application.

5. Destructive Testing Methods

Destructive testing is not always possible, indeed it is not always required due to NDT methods, but it has its place and is still very important. Here are examples of testing methods, including a summary of how they work and what their intention is.

Tensile testing

This involves securing a test piece of material into a tensile testing machine, then a constantly increasing load is applied up to the point the material fails. The tensile test provides data so that the tensile strength, yield strength and ductility are determined, a graph is produced in

the form of $\sigma = \frac{F}{A}$ [21].
 $\epsilon = \frac{\Delta L}{L}$

This test is important as the material selection is critical to most applications, e.g. some structures require tough material, but not hard, such as a suspension bridge, where a brittle material in this instance would be catastrophic due to the possibility of high winds. Similarly, train tracks need to be hard due to surface wear from the

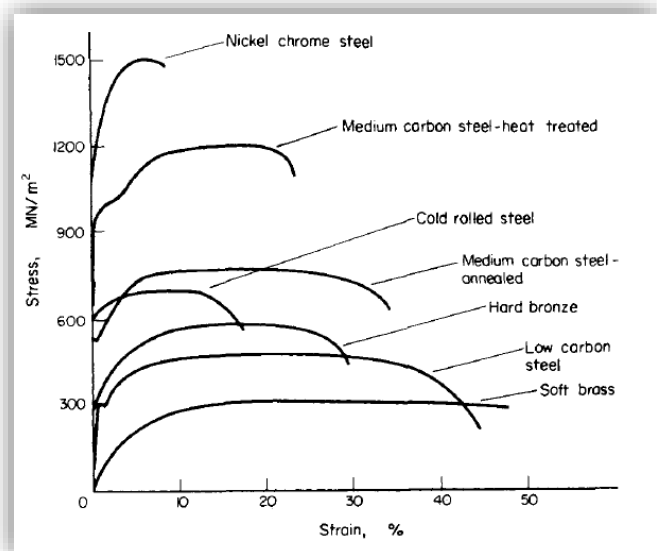


Figure 9 Stress Strain Graph (Hearn, E. J., 1997)

metallic wheels of the train, a softer more flexible material would not suffice in this instance. The main purpose for destructive tensile testing is to determine the strength of a material or product.

Charpy V-notch impact testing

This test is named after the creator of the method in 1901 [22], this is for impact testing a material to determine how much energy may be absorbed by it at different temperatures. A series of identical test samples are created that all contain a small (2mm) v-shaped notch, they are heated to different temperatures, placed in a machine and struck by a force in the form of a pendulum [22]. The importance of this test is to determine how materials perform when

subjected to sudden abuse loads, and furthermore how they perform at a range of different temperatures. The importance of temperature is that some materials require different operating temperatures such as nuclear pressure vessels, furnaces and generators, they are required to be hard due to the operating forces but must not be brittle and crack [22].

Metallography and microstructural evaluation

Grain structure evaluation is the aim with this process, a simple test piece of a material is sectioned, highly polished, an acidic etching solution is applied to the prepared surface and the grain structure is viewed under a microscope [20] [22]. The grain structure of a material determines its strength, its ductility and brittleness, this process may also be referred to as micro-etching.

6. Relationship between NDT & DT

It is possible to determine characterization of material properties using UT, there are four metallurgical characteristics that control material properties; microstructure, crystal structure, dislocation density and chemical composition [16] [23]. UT has successfully been used to correlate material properties such as grain structure, specifically grain size, hardness and Young's modulus of elasticity. Grain size may be measured by calculating the frequency (f), scattering parameter (C_r), scattering co-efficient (α_s) and grain size (D). Scattered co-efficiency is given by: $\alpha_s = C_r \cdot D^3 \cdot f^4$ [23]. Furthermore, a report [23] states that there is a direct mathematical relationship between Young's Modulus and ultrasonic longitudinal and shear velocity. Indeed, there are several relationships to be made:

$$\text{Youngs Modulus; } E = \frac{\rho \cdot V_T^2 \cdot (3V_L^2 - 4V_T^2)}{V_L^2 - V_T^2} [23].$$

$$\text{Poisson's Ratio; } \nu = \frac{V_L^2 - 2 \cdot V_T^2}{2 \cdot V_L^2 - 2 \cdot V_T^2} [23].$$

Therefore, UT may also be used not only for defect finding but also for calculating materials properties, this makes it a universal NDT and goes to show why it is so widely used.

Consider a discontinuity within a material, cracks for instance may propagate thereby ultimately creating failure, in some cases this may be catastrophic, leading to high cost and may even result in the loss of human life. An example of failure is the collapse of the Tacoma Bridge in Washington in 1940, the bridge collapsed in high winds [24]. Destructive testing could have determined if the material used could withstand certain stresses, where there may have been underlying factors such as cracks in the structure through years of use which could be detected using NDT techniques.

The automotive industry deals in a high volume of components, a typical example would be that of a sheet metal component that requires resistance spot welding [17]. To ensure the repeatability of the weld itself, either a test piece may be produced, or an actual workpiece may be used for destructive testing, this type of test would consist of attempting to break the

weld to examine its structural integrity [20]. Using radiography in this instance it is possible to see if the material has fused correctly without the need for destructive testing.

Residual stress measurement is often analysed using time consuming laboratory fatigue testing methods, this can however be done using an ES (Expert System) of UCC (Ultrasonic Computerised Complex) [25] and by using a radiography technique named x-ray diffraction [26]. The definition of residual stress is “the stress that exists within a material without application of an external load” [26]. UCC ES is a technique by where biaxial and uniaxial of both residual and applied stresses are determined, thereby allowing us to determine the stress and strain in a wide range of materials, it helps to understand the redistribution of residual stress, this is used widely for welded joints [25]. The main importance of the technique is that it allows us to determine the residual and applied stresses in samples and real structure elements [25]. The changes of the velocities of longitudinal ultrasonic waves and under the action of tensile and compressive loads in a wide range of materials [25].

7. Conclusion

All techniques discussed within this report may be used to detect flaws, although it is important to not only detect a flaw, but to quantify it, UT and radiography do this well although MPI is not as affective. The depth of inspection is a consideration, if we were to check a for a surface defect, MPI would be a consideration. Radiography is good to inspect at more depth, but then is limited as the operator must have access to both sides of the material, whereas UT can inspect at great depth, but does not have the benefit of clear imaging as radiography does.

Welds are often subjected to testing, there are so many factors to consider, mainly penetration and inclusions or porosity. There are two very common methods for testing a welded joint, macro etching and LPI (Liquid Penetrant Inspection). Macro etching involves cutting a cross section of the welded joint, polishing it and adding an acidic fluid that highlights the weld from the parent material, thereby highlighting flaws [20], a similar method to that of micro etching.

The purpose of all testing methods is to detect discontinuities and to determine the mechanical properties of the material, this is done so that products may be safe for use, when a material is selected then stress analysis may be carried out in the form of written calculations or using a computer aided FEA method. Suffice to say, as most things, different processes exist for many reasons, therefore it is not possible to determine outright which technique is best. Without destructive testing, we would not know what we know today regarding the properties of materials. Without NDT we would not find faults in existing products, therefore these are both very important and will always continue to exist for the sole purpose of ensuring structural integrity of the products that shape our modern world.

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