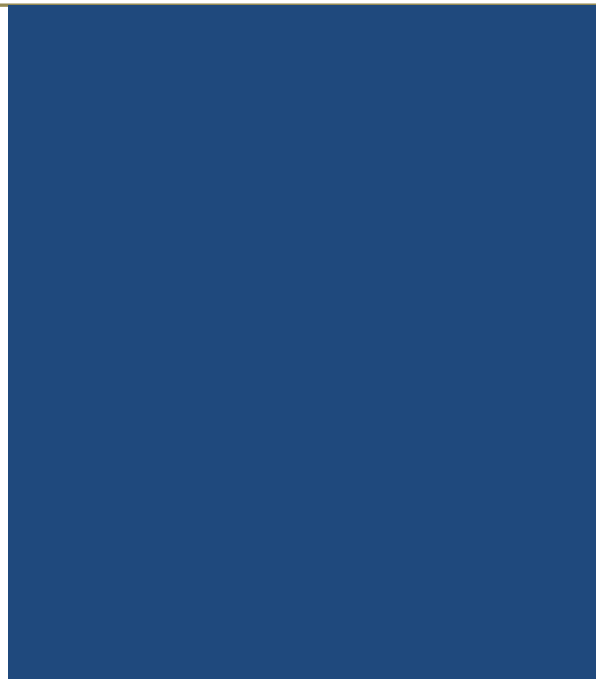


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Review of Weld Inspection Techniques

Dissertation Final Report

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P138679



Declaration of Authenticity

This Thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Date: 28/04/2017

Abstract

This review is about looking at the variety of different types of weld inspection and testing techniques that can be utilised and when each of the methods is more applicable to the material and weld application. The main findings from the review are that the variety of inspection methods available is extremely large. As there is non-destructive methods and destructive methods it also helped to identify when each method is utilised like before the material and weld is applied to an infrastructure or for in service inspection. At this point in time it would not be possible to replace the destructive testing methods with any of the non-destructive methods as both are used for very different reasons.

The weld types can be categorised into two sections fusion welding and solid phase. The fusion weld techniques are oxy-acetylene, fluxed core, shielded metal arc, tungsten arc gas shielded, submerged metal arc, electron beam and electro slag. The solid phase techniques include spot, seam, projection, friction, ultrasonic, explosive welding and diffusion bonding.

The non-destructive methods that can be used on welds are guided wave ultrasonic, alternating current field measurement, digital radiography, eddy current, full matrix capture, laser shearography, laser and manual ultrasonic testing, micro-focus x-ray, thermography, visual inspection, magnetic particle inspection and dye penetrant inspection.

The destructive testing techniques that can be used on welds include tensile testing, fatigue testing, hardness testing, bend tests and impact testing.

The types of weld defects that can occur include lack of fusion, porosity, inclusions, cracking and lamellar tearing. The testing methods mentioned above can be used to assess if there are any of these defects within the weld area and the effect these may have.

Case studies have been used in order to demonstrate how some of these methods have been applied to welds and what can be seen from the results of these testing methods.

The future of non-destructive testing is positive due to its ability to determine deterioration rates and potential failures before they occur therefore not affecting the operation of these components. Some of the research into developments of techniques has been discussed.

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Introduction

Weld inspection is important as it ensures a material that has been joined is of good quality and will not fail in application. It also helps to predict when a weld is starting to wear and helps to estimate maintenance plans. There are two types of methods of weld inspection these are destructive methods and non-destructive methods. This review looks at the different types of inspection within these two categories and also some case studies where these methods have been applied.

Destructive methods are normally carried out at production stage where the materials are being rolled at the mills to ensure the properties meet the correct specifications. They can also be done at product design stage to produce new products of required compositions. Another application of these methods are when a weld is done it can be tested to ensure the quality of the weld is good. It can be used as a method to choose material types for particular applications based on their strength, hardness, elasticity, and toughness.

Non-destructive methods are used as more of an inspection technique when the materials are in service. It does not require the part that is being inspected to be dismantled therefore it is still serviceable once the test is complete. It is a method for inspecting for any degradation in a material or weld; it can check for discontinuities in a weld and a difference in structure from one part to another such as thinning or build of unwanted deposited material (ASNT, 2016)

The aim of this review is to determine the types of inspection that are used within the weld industry and what each method is used for. It also shows through the use of case study where the inspection techniques have been applicable and why those were chosen. It highlights why these testing methods are important. This review has been done to try and understand non-destructive methods and their potential future applications along with the future of destructive testing.

Case studies have been reviewed to understand and show how these methods are applied within industries. From these studies it is easier to identify how these methods work and also how and to what they can be applied. Considerations and recommendations have also been made from reviewing the study where necessary.

Case study one is related to copper diffusion bonding and the aim of the study was to inspect bond interference and the quality of the bonding mechanism. The testing methods used in this study were ultrasonic testing, micro tensile and micro hardness. Considerations and recommendations have been made on this study.

Case study two is based on defect sizing in copper lids, tubes and welds within vessels used in a processing plant. The aim of this study was to ensure that the size of defects was measured

accurately. The testing methods utilised in this study were ultrasonic testing and x-ray. Considerations and recommendations have been made in relation to this study.

Case study three is a study based on a poor maintenance schedule within a processing plant. The main inspection method was visual inspection every couple of years. Dye penetrant testing had also been used. The aim of the study was to determine a more appropriate inspection maintenance plan based on the failures that had occurred at the welds. Considerations and recommendations have been made in relation to this study.

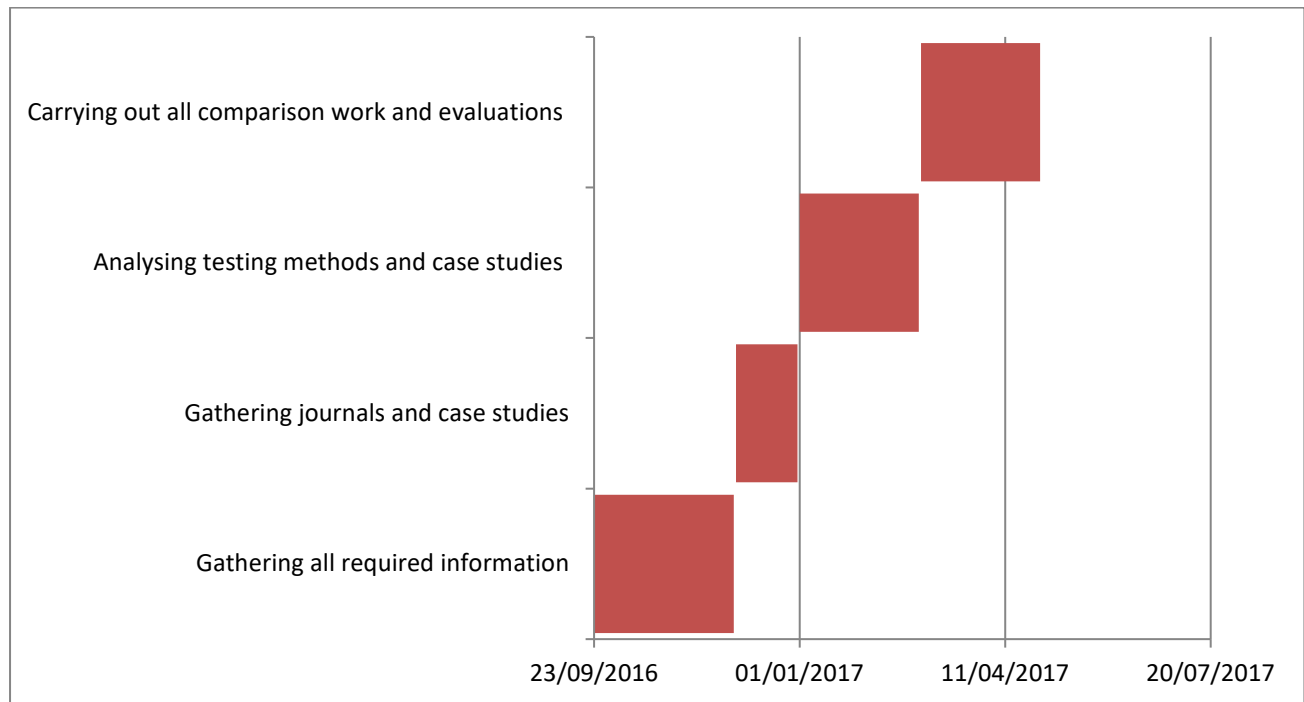
Case study four is based on tensile testing on resistance spot welding. The aim of this study was assess the properties of the weld on three different high strength steel sheets of different compositions. The only test method used was tensile testing. Considerations and recommendations have been made in relation to this study.

Case study five is about tension properties in spot welds. The aim of this study was to determine the weld properties in interstitial free steel. The testing methods used in this study were shear punch test, microstructure testing, micro hardness and tensile testing. There were no considerations and recommendations made on this study due to the wide range of testing methods that were utilised.

Case study six is based on impact loading on fillet welds. The aim of this study was to determine if displacement affected the properties of the fillet welds. The testing methods used in this study were impact testing, tensile testing, hardness testing and quasi-static testing. There were no considerations and recommendations made on this study to the range of methods that were used in this study.

Timing Plan to Start

Before starting the review a timing plan of the work involved was drawn up in order to track progress. This shows what the original plan and layout of the project entailed but this had changed drastically throughout time and at the end of the review is another timing plan that shows the actual progress and changes that had taken place.



History of Welding

Welding can be traced back to the middle ages and specifically the Bronze Age. They pressure welded in order to make small gold boxes over 2000 years ago. Then during the Iron Age the Egyptians and Mediterranean's made tools in order to attach pieces of iron together and these tools can be dated back to 1000 BC. Also during the middle ages blacksmithing was created and iron was hammered together but this did not develop into welding until the 19th century. In 1800's acetylene was discovered and therefore the arc between two carbon electrodes using a battery was made. Due to this discovery an electric generator was developed and arc welding started. After the discovery of this an early electrode holder was made and then they allowed carbon arc welding that was used for iron and for lead. In the 20th century a coated metal electrode was developed that had a coating of clay or lime, this tool allowed for a more stable arc. During this century resistance welding occurred where spot welding, seam welding, projection welding and flash welding developed. Gas welding and cutting were also created at this time. Alternating current welding was developed just after the First World War and then in 1920 automatic welding appeared. A lot of time was put into researching shielding the arc and the area surrounding the weld by using gas. But then issues occurred where the oxygen and nitrogen atmosphere around the weld made it more porous and brittle. In 1930 stud welding was developed for attaching wood decking to a metal surface. This method became very popular within the ship building industry. Gas shielding metal arc welding was improved in 1948 with the use of a continuous fed electrode. The first use for this method was for nonferrous metals initially. More recently friction welding was developed; this method used speed and pressure for friction heat. The costs of this method is high therefore it is used in situations where there is a high volume needed to be welded. The latest development of welding is laser; it is used for metals and other materials and is common within the automotive industry (Technology, 2004)

Automatic welding is when welding equipment requires occasional observation of the weld. There is no manual adjustment required the only human interaction is when the machine equipment is set up ready to run the welding cycle. The operator plays the role of quality controller looking for discontinuous welds (Noruk, et al., 2001) The most applied method of automatic welding is when there is a fusible wire wound around a coil that is continuously fed into an arc, the weld area is filled with a flux beforehand in order to prevent oxidisation. The arc is moved along the line of the weld through an automatic machine (KHRENOV, 1979)

Types of Welding Techniques

There are two types of welding processes they are fusion welding and solid phase process. The fusion welding process is when the surface of two components are cleaned and placed close together and then they are heating in a protective environment that prevents oxidation. Once it is heated a molten metal pool forms and this results in the components connecting. Solid phase is when the two components are attached through friction. The two surfaces are passed over each other causing friction heat and this softens the metal. Then the load is increased to join the two surfaces together (Grieve, 2009)

Fusion Welding

The fusion welding processes include oxy-acetylene, flux cored, shielded metal arc, tungsten arc gas shielded, submerged metal arc, electron beam and electroslag welding. Oxy-acetylene is when the heat is from the reaction of acetylene in oxygen and this gives a flame temperature of 2700 degrees Celsius. It is used for welding steels up to five millimetres by using a filler rod to assist with the joint. It is a manual process and is most common when attaching aluminium to thin steel components. Shielded metal arc is when a machine applies a current to an electrode that is coated in flux. It is welded by tapping the electrode against the material and this reaches about 6000 degrees Celsius instantly to form a molten pool and the joint is formed. It has to be used on sheets above three millimetres thick. Gas metal arc welding is when the filler metal is stored in a spool and rollers move the metal through a tube into the joining area. It is a continuous and long process and therefore the welds are uninterrupted. An inert gas is also injected into the tube and this causes a high temperature around the torch area. Flux cored arc welding is similar to shielded metal arc but it uses an electrode that is filled with flux and no inert gas is used. Tungsten inert gas is when a tungsten electrode is used and an arc is created between the electrode and material, with an inert gas environment to protect the material from oxidation. It is used for non-ferrous metals like aluminium and thin metal sections. Electron beam welding is carried out in a vacuum. (Grieve, 2009) Submerged metal arc uses a continuous and an uncoated electrode, the shield is provided by a flux. The electrode is continuously fed into the arc. This process is predominantly used for structural shapes (Marinov, 2007) Electroslag welding is when the heat is provided by current passing through electrode and a molten slag covering the material for welding. Flux is added to the gap between the materials before welding. This process is mainly used for steels (Kopeliovich, 2012)

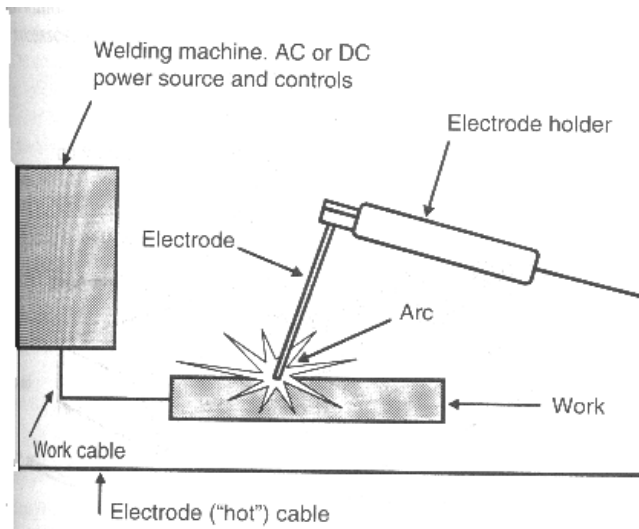


Figure 1 Arc Welding (Grieve, 2009)

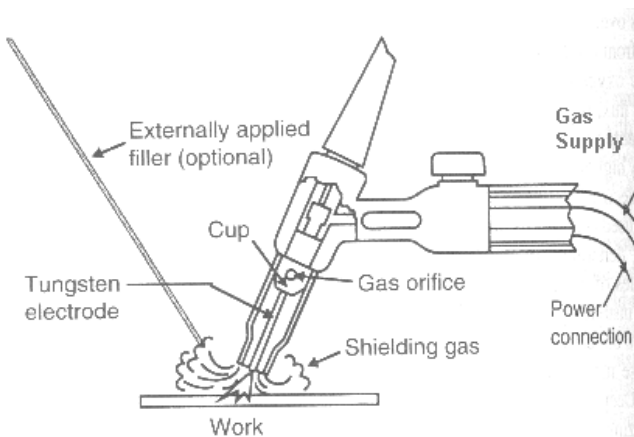


Figure 2 TIG Welding (Grieve, 2009)

Solid Phase

The solid phase processes include spot, seam, projection, friction, ultrasonic, explosive welding and diffusion bonding. Friction welding is when two cylindrical materials are contacted by pressure when rotated. Pressure is then applied to form the joint; this method is used for steels and many alloys. Explosive welding is when the two materials are joined by impact pressure applied through a controlled explosive charge. The charge is placed on one of the two pieces and then it is detonated. It is used for joining of two different metals such as copper and steel. Diffusion welding is when the materials are subjected to temperatures just below their melting point and the two surfaces join together by the diffusion of atoms into one another. It is carried out in a vacuum to stop oxidation taking place. This process is used for joining difficult metals such as steel and tungsten. During ultrasonic welding the two pieces of metals are joined by high frequency acoustic vibrations being applied. The vibrations cause friction and that bonds the two materials. It is used for joining small components (Kopeliovich, 2012) Spot welding is using two copper electrodes that are above the joint area, the two pieces of material are attached the electrodes and an electric current is passed

through to join them together. It is used for metal shapes that are gauged under 3millimeters (Gache, 2008) Seam welding is a continuous weld, it is used for fillet or butt welds due to its robust nature. These weld types are common in pipes and tubes (Blue, 2012) Projection welding is an electric resistance process, the heat is generated by the resistance of the materials against the flow of current. It is used for low carbon steels, variety of alloys and ferritic stainless steels (Jiang, 2011)

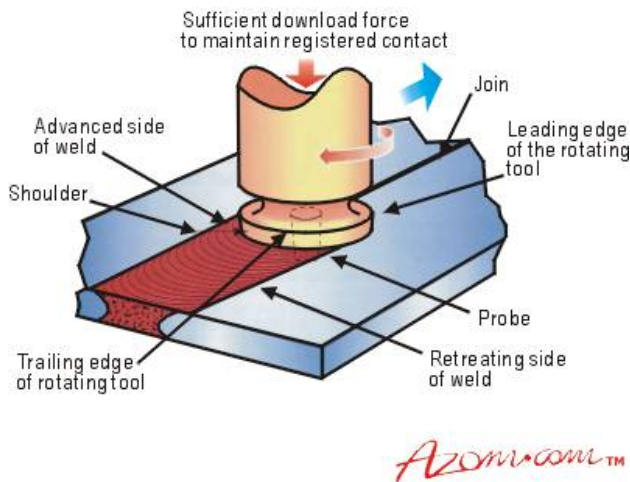


Figure 3 Friction Welding (Johnson & Kallee, 1999)

Joint Types

There are five main joint types associated with welding these are Butt joint, T-joint, Lap joint, Corner Joint and Edge Joint. For each of these joint types there is a variety of welding types used for Butt joint there is predominantly butt weld. T-joint has fillet, plug, slot, bevel-groove, J-groove, flare-bevel-groove and melt through weld. Lap joint includes fillet, plug, slot, spot, bevel-groove, J-groove and flare-bevel-groove. Corner joint uses fillet, spot, square-groove, V-groove, bevel-groove, U-groove, J-groove, edge, flare-V-groove and corner flange weld. Edge joint has a variety of welds these include square-groove, butt, V-groove, J-groove, U-groove, edge flange and corner flange. There are also double welds, these occur when the weld cannot be made from one side of a joint. There is often shrinkage when butt welds are carried out therefore there is an allowance made within the weld quantity in order to counter act the shrinkage. The main problem within fillet welds is that it does not fully penetrate the joint. Not much joint preparation is required when single and double fillet, plug slot or spot welding as they are more commonly used for static load applications. Tack welding can often cause distortion and therefore it is not used within thinner gauges of materials and therefore is limited to heavy materials and structural applications. Within edge welds the weld does not fully penetrate the joint and therefore should not be used under stress (Minnick, 2008)

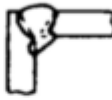
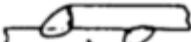
BUTT JOINT			
	SQUARE	SQUARE (OPEN)	
			
	SQUARE (WELDED BOTH SIDES)	SINGLE V	
			
	DOUBLE V	SINGLE BEVEL	
			
	DOUBLE BEVEL	SINGLE J	
CORNER JOINT			
	SINGLE V	SINGLE V AND FILLET	SINGLE FILLET
	EDGE JOINT		
		SQUARE	SINGLE V
LAP JOINT			
	SINGLE FILLET	DOUBLE FILLET	
TEE JOINT			
	DOUBLE FILLET	SINGLE BEVEL	
			
	DOUBLE BEVEL	DOUBLE J	

Figure 6-26. Typical weld joints

Figure 4 (Guru, 2017)

What is Non-Destructive Testing?

Non-destructive testing methods for industrial application were first developed after World War two when more testing equipment was required to inspect flawless components. The instruments made for NDT and were continually improved. One of the first methods developed and applied industrially was X-ray, the first application and development for x-rays was in the medical field but this was before it was identified that the rays were harmful to the human body. Marie Curie has previously used this with radioactive isotopes. Magnetic particle crack detection was established before X-ray and it was used to detect cracks in gun barrels. The industrial applications were started in 1929 and the first detector was created in Italy and this method was later used for welded constructions. Penetrant testing was also developed in the 19th century and was firstly used on railway components and soon after it was utilised it was replaced by Magnetic particle crack detection. During World War two nonmagnetic materials were used in the aircraft industry therefore dye penetration had to be utilised. Eddy current was first introduced into industry after 1933 and instruments were developed to measure conductivity. Later on in the developments the issues for testing hot wires was resolved by using pre-magnetisation eddy current for ferritic bars. Ultrasonic testing was one of the latest techniques to reach industry application; it was developed as the other method of NDT could not resolve issues such as non-metallic inclusions in hot rolled products (Deutsch, 2000)

Non-destructive testing is important as it does not compromise the materials use. It can take measurements and inspect a structure without damaging the material and therefore is advantageous as it can be done on site and the structures can still be utilised. This differs from destructive testing as these tests cannot be carried out on site and also once the test is done that material cannot be reused. Destructive methods are normally carried out on a batch of materials before they are applied to an infrastructure whereas non-destructive is used to measure deterioration of a material in its working environment (Verma, et al., 2013)

There are many testing methods used that are non-destructive these include contact and non-contact methods. The contact methods include traditional ultrasonic testing, eddy current testing, magnetic testing, electromagnetic testing and penetrant testing. The non-contact testing methods include transmission ultrasonic, radiography, thermography, shearography and visual inspection. The ones I will be evaluating in the report are guided wave ultrasonic testing, alternating current field measurements, digital radiography, eddy current testing, full matrix capture, laser shearography, laser ultrasonic testing, manual ultrasonic testing, micro-focused x-ray, thermography, visual inspection, magnetic particle inspection and liquid penetrant inspection because they are used for different weld types and applications. (S.Gholizadeh, 2016)

What is Destructive testing?

Destructive tests determine data in order for it assist in choosing particular materials for specific applications. The main use of this data is to determine how much force a material can undertake before a fracture occurs. Other factors that destructive test data is used for is the composition of materials so that the correct material can be selected for joining procedures and operational applications. The test methods can be separated into two categories quantitative and qualitative. Quantitative is used to decide the design limitations of the material and qualitative is mainly used for comparison to other test methods and whether any other testing methods would be successful or useful (Mathers, 2017)

Rockwell hardness testers have been around since around 1920 and it is a quantitative test. The first hardness tester was Brinell and this was developed in 1900 by a Swedish metallurgist, this method uses a steel ball to make an indentation on the surface to be measured. In 1914 the Rockwell hardness method was developed and it had the ability to compensate for the not so desirable issues that were associated with Brinell. This method was able to carry out tests are large and small loads (Chinn, 2009)

It is thought that the original theory behind tensile tests came from Leonardo da Vinci work done in 1500 but unfortunately the results were misinterpreted so it was not until 1906 that the work he had carried out had been used to develop testing methods that worked. After researching in 1939 by Parsons it was found that Da Vinci's theories were not necessarily incorrect but that the samples tested were not all the same sizes are therefore the results were varied (Lund & Byrne, 2000)

Impact testing was first approached in 1898 and then later in 1901. It was given the name Charpy as Georges Charpy worked on the equipment and for his theory contributions and later on his leadership on developing the robust equipment. This method was established due to failures in rails and axes at a very high rate therefore more ductile brittle testing of materials were required (Tóth, et al., 2002)

Non-destructive testing techniques

There are many testing methods used that are non-destructive these include guided wave ultrasonic testing, alternating current field measurements, digital radiography, eddy current testing, full matrix capture, laser shearography, laser ultrasonic testing, manual ultrasonic testing, micro-focus x-ray and thermography. Each of these is used for different weld types and applications.

Guided Wave Ultrasonic Testing

Guided wave ultrasonic testing is a method used for finding corrosion within the pipeline industry. The ultrasonic waves are spread along the whole pipe, it enables the whole pipe to be inspected not just a smaller surface by using just one transducer. The range of the waves can be around 10 metres in either direction (Evans & Vogt, 2010)

This method works by clamping a set of transducers around the pipe in one location. The computer system then sends guided waves in either direction along the pipe. The system then processes the returning echoes and an A-scan is displayed. The scan shows the location and amplitudes of the features along the pipe and changes in cross section. These changes include welds, branches, flanges, corrosion patches and cracks (Lowe & Cawley, 2006)

Probably of detection in Guided Wave for a defect size is defined as for UT by the probability that the defect signal amplitude is greater than the pre-defined detection threshold. For an example assume the probability distribution for guided wave signal amplitudes, a signal with amplitude at the detection threshold would have a POD of approximately 58%, and a signal with amplitude of twice the detection threshold a POD of more than 99%. The equation used to calculate the probability of detection is $POD_{GW}^{Total} = \int_0^L POD_{GW}(x(s))p(s)ds$ (Evans & Vogt, 2010)

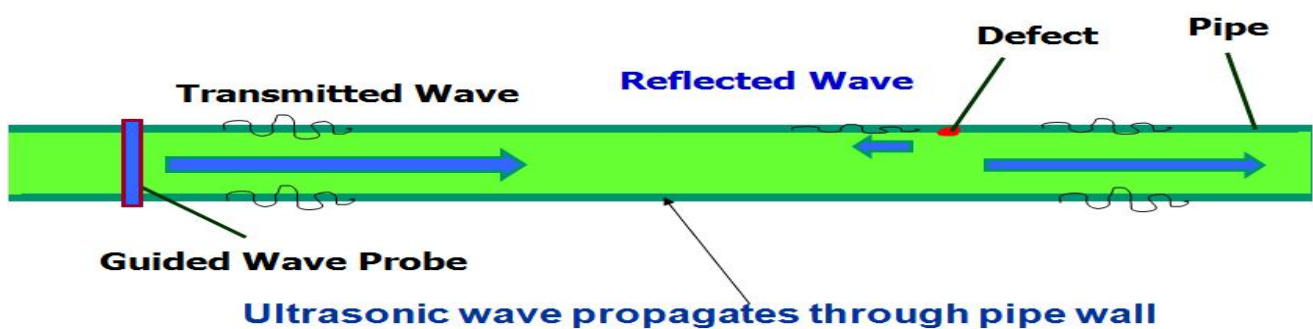


Figure 5 (Kim, 2007)

There are many applications of this method, firstly, in the railway industry, where the ultrasounds travel along the length of the rail and broken or defective parts of the rail are reflected through the use of sensors. Secondly, boiler tube inspection over long distance, it is utilised for this as the tubes can only be accessed from one side; transducers are required on the surface to aid the measurements. Thirdly, aircraft industry, for energy travelling along joints, within aircrafts it is used

for rudders and transmission beams to inspect for crack propagation. Fourth, concrete that is reinforced with steel, this method allows for the ultrasonic waves to move along the steel rods without removing the concrete, it allows for corrosions and cracking in the plate to be identified (Rose, 2002)

<u>Advantages</u>	<u>Disadvantages</u>
Testing deterioration in pipelines over large areas.	Distance is dependent on type of defect, condition, age and environment.
Range from 100 to 200 metres.	Cannot be done on sharp bends where pipes have been welded together.
Very useful in areas with lack of accessibility such as road crossings, insulated pipes, wall penetrations and pipe racks.	In supports the range is limited as the weld can reflect and transmit signals.
	If there is a large object in area then this can reflect the signal from the transducers.

Figure 6 (Lowe & Cawley, 2006)

Alternating Current Field Measurement

Alternating current field measurement was developed for the detection of fatigue cracks on offshore structures. It is an electromagnetic technique and the alternating current flows over the surface and a flaw is identified by the current going around the area instead of straight over and a magnetic field is created on the surface and if there is a defect the magnetic field will be disturbed (Raine, 2000)

This technique involves the alternating current flows in the thin skin near the surface of the conductor. When a constant current is fed through the area the defect would be highlighted by a disturbance in the currents flow. If a crack was present the wave would go around the area. There is a magnetic field present above the area of inspection and therefore if a defect was present it would disrupt the magnetic field. There is correlation between the amount of disturbance to the magnetic field and the size of the defect. Therefore it is used as a quantitative measure of the field disturbance size and defect size (Raine, 2000)

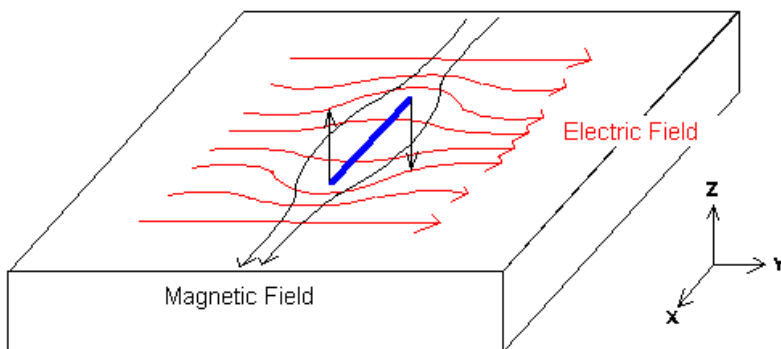
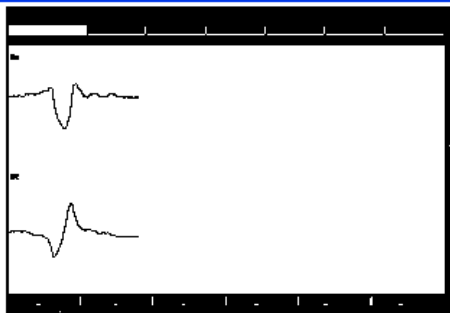


Figure 7 (Topp, 2000)

Figure 8 shows two components of the magnetic field, the top line in the diagram shows the length of the defect which responds to the surface current density and gives an indication of the depth. The second line shows the negative or positive response at either end of the defect and it gives an indication of the length. Figure 9 shows the two components that have been plotted against each other and the complete loop indicates that there is a crack present (Raine, 2000)

TIME BASE ACFM DATA

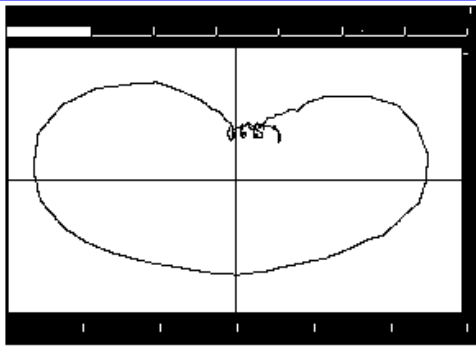


Typical Bx and Bz traces as the probe passes over a crack



Figure 8 (Raine, 2000)

ACFM BUTTERFLY PLOT



By plotting the Bx and Bz plot together, the classic *ACFM BUTTERFLY PLOT* is displayed



Figure 9 (Raine, 2000)

It is used in many applications such as offshore structures, public safety, petrochemical, civil and mechanical engineering within all these industries this method is used to identify fatigue cracks. It was initially used for carbon steel welds; normally nodal welds are used for this material. Probes were developed to inspect welds that had been subjected to grinding. It is used for inspected the drill threads on casting tools that allows a decision to be made on the spot whether the drill is good enough to use. It has been developed to allow testing off offshore structures that have coatings. It can be used on ferritic, austenitic stainless steels, aluminium, duplex and super duplex steels. The coatings it can be utilised on include flame sprayed aluminium, epoxy, paints, ferritic based paints and also copper coated components (Raine, 2000)

<u>Advantages</u>	<u>Disadvantages</u>
Can detect defects on a component that has a few millimetres of coating. Therefore coating does not need to be removed.	Not effective when defects are clustered together. It can only detect one defect.
Can be used on a large range of materials such as plain, welded, ferritic and non-ferritic.	Defects can be underestimated or overestimated as it is not accurate.
Can be used in many situations such as hot surfaces, underwater and irradiated areas.	The probes can be sensitive to change of geometry.
Can detect defect size up to 25 millimetres accurately.	Sensitivity is reduced when there is coatings on the material and if the material conducts electricity.

Figure 10 Advantages (Fisher, 2017) Disadvantages (Al-Dalabeeh, et al., 2012) (LeTessier, et al., 2002)

In relation to weld defects this method is used for the detection of fatigue cracks and hydrogen cracking. It allows transverse defects to be differentiated from longitudinal defects and cracks detected on the inner surface and the outer surface. It gives reliable sizing and detects surface defects (Raine, 2000)

Digital Radiography

Digital radiography is an x-ray that is created by putting electrons in contact with a metal. It allows even small defects to be found without any particles surfacing. This method is used within the medical field for soft tissue examinations (Bansal, 2006) It is used for weld inspections within the oil and gas pipeline industry (OLIVEIRA, et al., 2010)

The method works by the absorption of radiation through the material under inspection. Due to a variation in density, thickness and absorption characteristics caused by the variations in material composition different areas of a material can absorb different levels of radiation. This absorption rate can then be detected through film or electronic detectors. The variation in the absorption rate assists to indicate if there is a defect in a material (OLIVEIRA, et al., 2010)

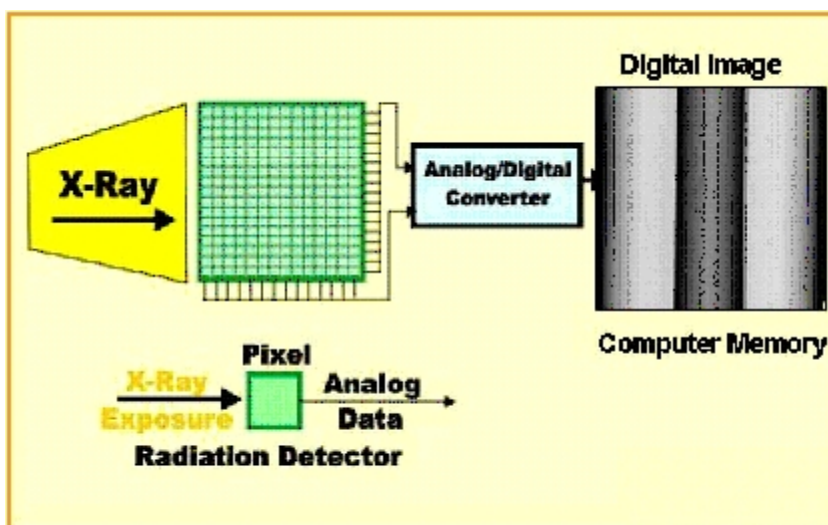


Fig.3. FPD based DR Scheme

Figure 11 (Ravindran, 2008)

There are a few types of digital radiography these are film digitization, direct radiography and computed radiography. Film digitization is a process whereby the radiograph is produced through a film that is then placed into a reader. It can gather more information and can be archived easily; the downside of this is the hazardous chemicals that need to be used. In direct radiography the image is portrayed straight onto a panel and transmitted straight onto a computer and is good for inspecting materials that have a medium or fine grain size. The disadvantage of this method is that the detector cannot be shaped around the component. The computed radiography method utilising a sensitive imaging plate, the image is portrayed as a visible light when the plate is connected with a laser (Patel, 2005)

There are many applications of each of the different types in many industries such as oil and gas processing plants, petrochemical, nuclear power, aircraft, automotive, compressor stations, rail and ship building. The main applications of computed radiography are corrosion detection on pipes, and

measuring the wall thickness through pipelines. Film digitization is used for valve inspections. All the types of digital radiography can be used to inspect for weld defects, turbine blade inspection, casting operations, rotor blades, engine components, reinforced concrete and composites (Patel, 2005)

<u>Advantages</u>	<u>Disadvantages</u>
Most versatile of the NDT techniques.	Testing equipment is very expensive.
Good on thick pipes as the rays can penetrate through the pipe.	Resolution is lower than that achieved by film radiography.
Extremely efficient as the image appears in minutes.	
Image quality is exceptional.	
Effective at identifying defects quickly.	
Exposure time is limited making it a safer process.	
Environmentally friendly as no chemicals are used in the test.	
Profitable process as testing time is reduced.	

Figure 12 Advantages (Pincu, 2008) Disadvantages (Patel, 2005)

In relation to welding this method helps identify weld defects and flaws that are internal. It shows on an image that the x-rays can be absorbed differently dependent on the structure and quality. The intensity of the penetrated waves is different when there is a flaw apparent in the weld (Wang & Liao, 2002)

In terms of resolution there are a few types spatial resolution is when an imagining system has the ability to differentiate two objects. Low spatial resolutions means that it cannot differentiate two objects if they are situated close together (Jones, 2016)

Eddy Current Testing

Eddy current testing is a very powerful method that allows you to measure the thinning of walls in pipes (Mao & Lei, 2016). This method works by introducing electromagnetic waves into the material that is being inspected in order to determine the properties of the material. It is the interaction between the magnetic field source and the material in question. It allows for crack detection in a large variety of conductive materials including ferromagnetic and non-ferromagnetic whereas other methods that use a magnetic method can only be utilised on ferromagnetic specimens (García-Martín, et al., 2011)

This equation shows the coil characteristics that is a complex number and defined as $Z_0 = V_0/I_0 = R_0 + jX_0 = R_0 + j2\pi fL_0 = R_0^2 + X_0^2$ $\angle \phi = \tan^{-1}(X_0/R_0) = |Z|\phi$. When an alternating current energises a coil it creates a magnetic field which causes magnetic lines of flux that is concentrated at the centre of the coil. Eddy current is based on Faraday's law which is where the time-varying magnetic induction flux density induces current in a conductor and is represented by $\epsilon = -d\Phi B/dt$ (García-Martín, et al., 2011)

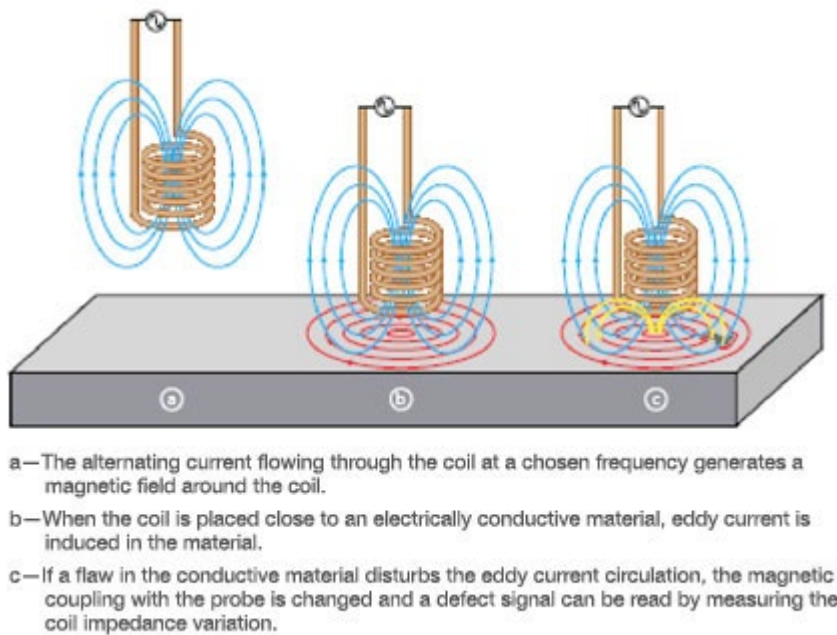


Figure 13 (Nelligan & Calderwood, 2017)

It is predominantly used within the aerospace industry for inspection of materials that are very thin. It can also be used for testing for conductivity in materials. It is based on electromagnetic induction; an alternating current flows and creates a magnetic field. If there is a defect in the surface it will interfere with the pattern created by the magnetic field. It is used for friction stir weld applications, it checks the surface for any cracks on weld caps and any heat affected area around the weld (Nelligan & Calderwood, 2016)

<u>Advantages</u>	<u>Disadvantages</u>
High Sensitivity to defects.	May not work correctly if magnetic permeability changes.
Can penetrate through many layers and surface coatings.	Only works on conductive material.
Conductivity measurements are accurate.	Cannot detect a defect that is parallel to the surface.
Can be automated.	Cannot be used over large surface areas.
Very little preparation required on the material before testing.	Can be complex to read the signal.
Easy to transport between job sites.	Cannot store images if it is not automated.

Figure 14 (Mathers, 2017)

Full Matrix Capture

The full matrix capture is an advanced method of phased array. It captures and stores all time-area signals from all the transmitters in the elements. Phased array uses multiple ultrasonic transmitters; the system has a time delay to each probe for an ultrasonic beam to be producing acoustic characteristics of the material. With full matrix capture it allows for off-line processing of the software and it captures and recorded all time-domain signals from every pair of elements in each array. From all the data collected the results can be produced per beam, these results include aperture, refracted angles and focussing. The big draw to full matrix capture is not the test itself but what can be determined from the data collected (Tremblay & Richard, 2012)

Full matrix capture works simply by a way of collecting time-domain data for all the possible array combinations. The first array element is pulsed and the scattered waves are recorded from all elements and then these are stored separately, then the second array is pulsed and the data once again is stored. This method is repeatedly carried out on all array elements. The data is then used to create a matrix and the axes are generated by the element, detection element and time. Each data point represents amplitude (Petcher & Dixon, 2015)

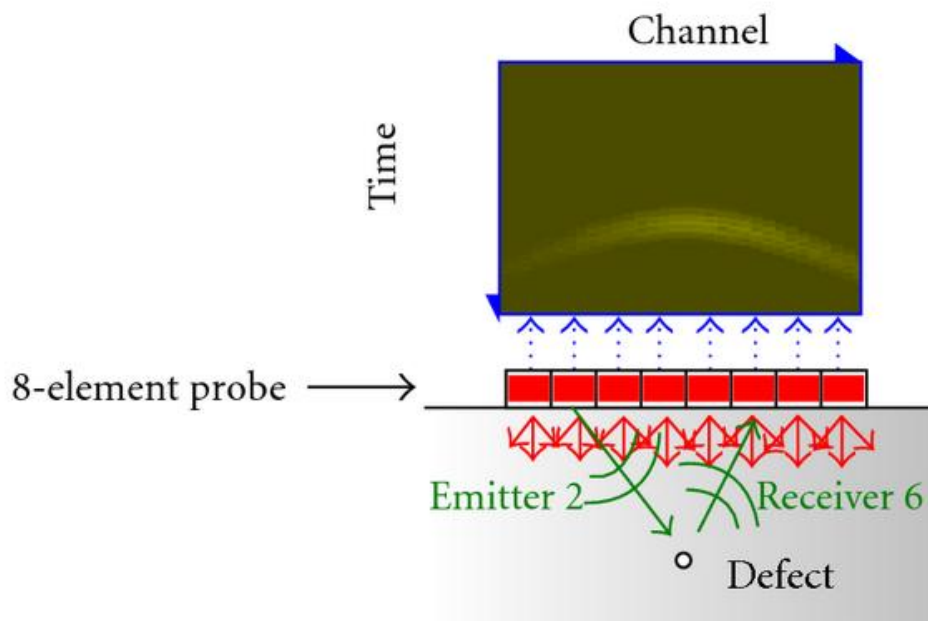


Figure 15 (Baqué, et al., 2012)

This method is used for the detection of defects in welds due to lack of fusion, weld pools and hot cracking. It collects the data for array elements and from the data the axes of the matrix are formed (Petcher & Dixon, 2015) This method has more recently been developed for testing girth welds in corrosion resistant alloys and clad and J-bevel carbon steels within the pipeline industry (Weston, 2015)

<u>Advantages</u>	<u>Disadvantages</u>
Post-processing benefits.	Capabilities are not as high as they could be.
Can record all time-domain signals from every transmitter.	Data transfer rate is slow due to the amounts that need transferring.
Can be optimised offline during analysis.	Data files are considerably large therefore saved directly to drive.
	Energy levels of received signals are low as it only operates on a single element emission.

Figure 16 (Tremblay & Richard, 2012)

Laser Shearography

Laser shearography is an optical measuring technology using coherent light to determine any interference in the surface area being tested. The sample undergoing the testing is illuminated using a laser and projected into a camera through an optical shearing element. This element allows for a superposition of two images side by side, based on two waves the interference of the wave of sample and a reference. This method is used to identify if there is a defect induced temperature change or surface deformation (Pezzoni, 2000) It is most commonly used for spot welds as it has a very high sensitivity measurement (Mishra & Mahoney, 2007)

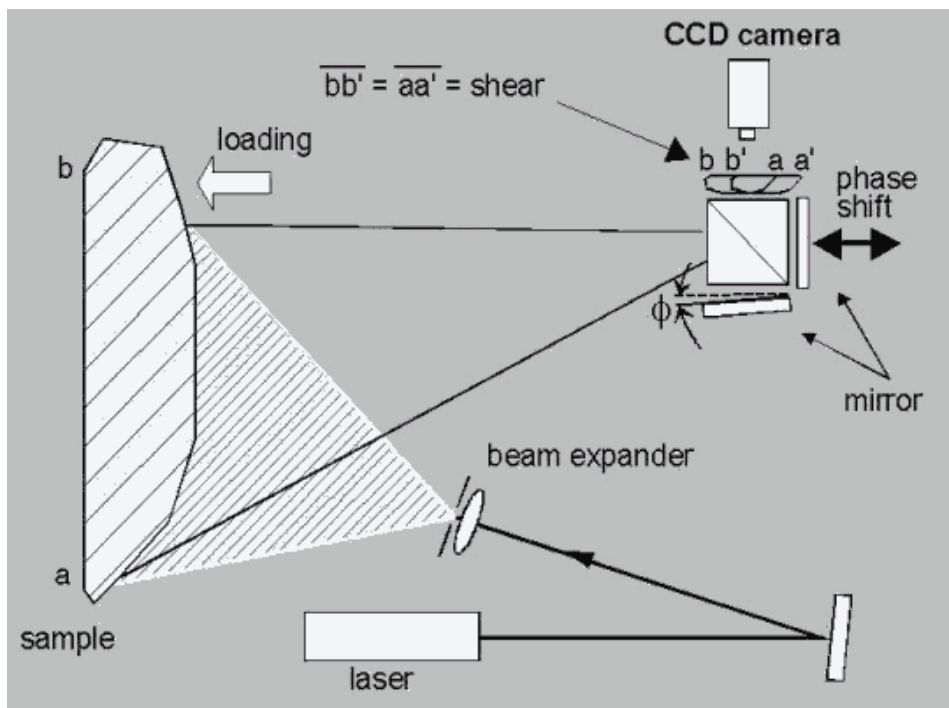


Figure 17 (Pezzoni, 2000)

The main application of this method is within the aerospace industry, it is used to inspect the components on aircrafts. It is used during the processing and production of the components, assembly of the components onto the aircrafts and for inspection during maintenance and repair work on aircrafts. The ability for it to work at a high sensitivity even with complex composite materials makes it very desirable. It is used for helicopter rotor blades and seals in jet engines, especially in maintenance inspection (Krupka & Walz , 2006)

At the welding seam there is normally localised stiffening. Therefore there is more strain in this area due to pressure variations. Cracks appear within this region. This method can be utilised to identify these cracks (Ettemeyer, 1996)

<u>Advantages</u>	<u>Disadvantages</u>
Optic and contactless	Complex to interpret results.
Can detect defects in the materials not the components.	Must have good lighting in the testing environment.
No surface treatment required.	Surface of the material must have a degree of roughness.
Very reliable and easy to use.	

Figure 18 Advantages (Huber, 2017) Disadvantages (Sleigh, 2011)

Laser Ultrasonic Testing

Laser ultrasonic testing is when the acoustic waves are generated and detected by optical equipment. In order to generate the acoustic a short pulse laser is used and then for detection a long pulse laser is utilised. There are three main consequences of this testing method these include detection from a distance; coupling is suppressed and no sensitivity on the surface (Petillon, et al., 2000)

In this technique the ultrasounds are generated from the absorption of light at the surface of a material. This creates a heat source which then produces the thermoelastic stress at the ultrasound origin. When the laser power is increased a thin surface layer is vaporised, this in turn causes a recoil effect that produces normal stress levels at the ultrasound origin. The principle is to make the wave scattered by the surface to interfere with itself after a delay. This interference is then used to determine if it highlights a defect (Monchalín, et al., 1988)

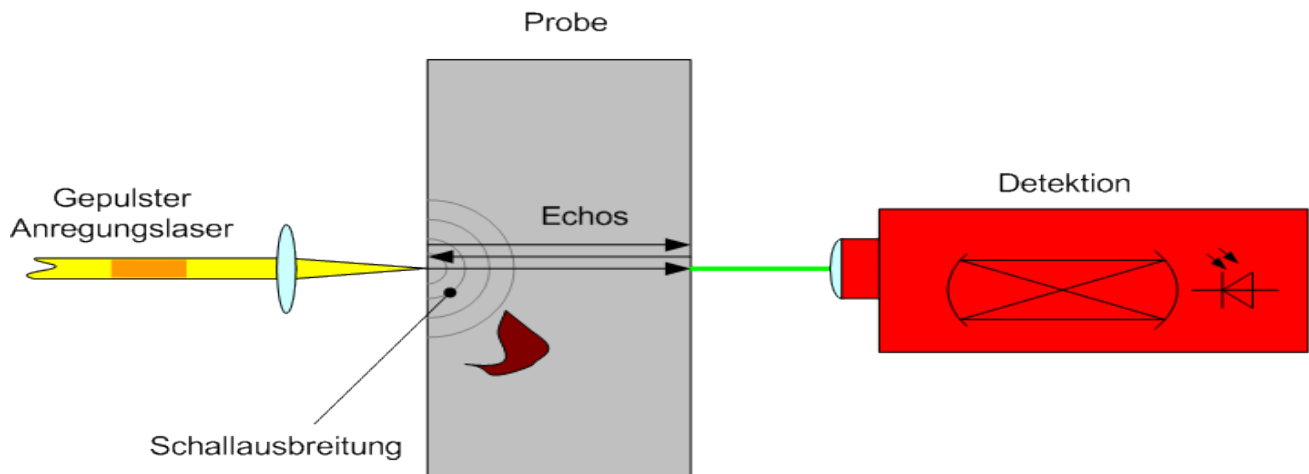


Figure 19 (Reitinger, 2007)

This method is used for laser weld beam applications, it has a high cost and very consuming process (Passini, et al., 2011) Other applications of the process are components that are exposed to elevated temperatures. It can measure the wall thickness in steel tubes at 1000 degrees Celsius. It can be used to inspect complex geometry components on aircrafts (Blouin, et al., n.d.)

This method is used to identify cracks, porosity, pinholes and lack of fusion. It is used greatly for laser weld inspection and in this application helps to identify if the nugget size is correct. The nugget is formed between the base material and the material being attached (KLEIN & BODENHAMER, 2004)

<u>Advantages</u>	<u>Disadvantages</u>
Measures the thickness of walls in seamless pipes.	Cost price is high.
Can be used for in-line inspection.	
Can prevent defects occurring.	
Accurate and time efficient.	

Figure 20 (Jain, 2011)

Manual Ultrasonic Testing

Manual ultrasonic testing is a method normally applied to butt welds. It is carried out by applying shear waves at a determined angle and the transducer is manipulated to inspect the whole weld area. The pulse-echo equipment with an A-scan can generate, receive and display screen pulses. It provides a continuous increase in amplitude in respect of time and travel distance. If the material for inspection comes from a rolling mill then the surface is smooth enough for inspection without preparation being required. If a sample has loose scale, flaked paint, rust or pitting then it would have to undergo grinding before the inspection could take place. For base metal inspection if there is lamination present on the metal it can be rejected. They may mask part of the weld from the ultrasonic beam. The laminations can be detected through a straight beam ultrasonic test. The test has to be carried out from the other side of the weld due to the laminations on the surface. Longitudinal defects can be found by directing the beam normal to the length of the weld and by moving the transducer forwards and backwards. The entire weld area and heat affected zones need to be scanned. It is used to look for poor fusion in the welds or discontinuity of the weld material. (Rea, 1970)

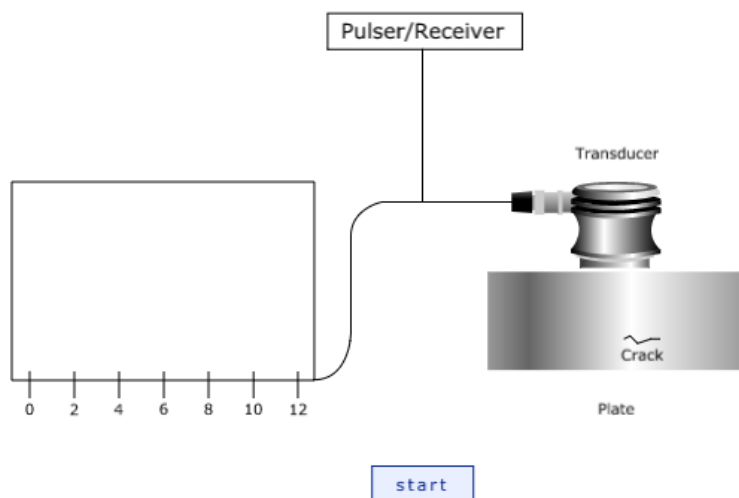


Figure 21 (Hijazi, 2011)

There are many applications of this process they include forging and casting inspection, welds, difficult materials such as tube and large components like generator shafts (Büchler & Berke, 2002). It is also used for fusion welded joints in metallic materials (Carpentier & Rudlin, 2012).

This method can detect cracks, incomplete penetration, lack of fusion, multiple varieties of porosity and slag inclusions. The porosity variations include cluster, scattered and very severe porosity (Rea, 1970).

<u>Advantages</u>	<u>Disadvantages</u>
High Sensitivity	Issues with specimens with poor geometry.
Can detect minute defects.	Not as accurate with materials that have poor internal structure.
High penetration capabilities and therefore can be used on thick gauge specimens.	The orientation of the defect can affect detection.
High accuracy in flaw size measurement.	High cost of equipment.
Fast response and therefore an efficient automatic inspection.	Skilled personnel required to carry out test.

Figure 22 (Khan, 1999)

Micro-Focus X-ray

Micro-focus X-ray gives a sharp definition of the surface area it is applied to. There is a focal point on the x-ray tube and this focal has to be as small as possible in order to achieve the sharpness. This technique is similar to conventional X-ray but it is the focal point that differentiates the two methods. There are two methods of micro-focus x-ray these are film technique and real-time method. The film technique means that the alignment of the components has to accurate and therefore the set up time is longer. The time of the image shot can vary from two to fifteen minutes, but then the film has to be developed. Therefore the initial set-up is done by using the real-time method. With the real-time method the conventional radiography film is replaced with a fluorescent screen and an electronic intensifier that converts the x-rays into a visible image. The evaluation times can range from fifteen seconds to several minutes depending on complexity. The images are enhanced and used to inspect the quality of welds and many other components (Towell, 2015)

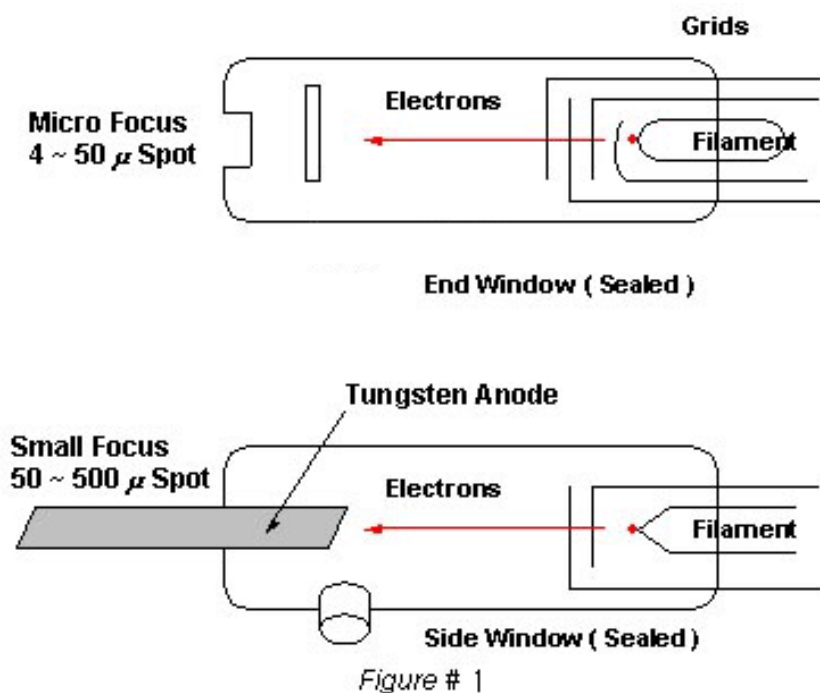


Figure 23 (Chun, 2013)

The applications of this method includes solder joints on circuit boards, die and wire bonding, inspections of sensors, relays, fuses and coils, examination of plastics, ceramics, light alloys and steel for inclusions, porosity and defects. It can also be used for examining samples in the medical, biological and forensic industries (Towell, 2015)

This method can be used for longitudinal, sagittal and transverse cracks, lack of penetration and porosity (Lima, et al., 2013)

<u>Advantages</u>	<u>Disadvantages</u>
Very good image quality. Higher magnification used.	If geometric unsharpness is larger than flaw it may not detect the flaw.
Geometric sharpness is good.	Poor material use on the beam (Polychromatic spectrum beam with flux)
Reduced exposure time.	
Can be carried out in restricted area.	

Figure 24 Advantages (Alloys, 2010) Disadvantages (Tisseur, et al., 2007)

Thermography

Thermography is a method that identifies heat flow on a surface; it helps to see if a part is not working effectively as it would appear as a hot spot on the image produced (Centre, 2016) It helps to monitor the condition of an object. There are two parts of the process these are qualitative and quantitative. Qualitative is where the heat patterns on the surface of the object are measured. Quantitative is where the temperature measurements are taken in order to determine high temperature regions in comparison to lower temperature regions (Thomas, 2007)

There are a few methods of thermography dependent on the application. The images are produced by scanning a detector or using focal plane array. The simplest technique of scanning is carried out by pointing a camera at a component and looking for any areas that appear uneven in heating or for looking at localised hot spots. This requires very high scanning speeds, therefore a series of elements are usually scanned. This reduces the scan speed requirement but it is still high. The frame movement is provided through scanning optics or line scan imagers. The method of focal plane array is a group of sensor elements that are presented in a rectangular grid. It is focused on the array and each element cell provides an output dependent on the radiation falling on that element. The spatial resolution is determined by the amount of pixels in each detector array (Centre, 2016)

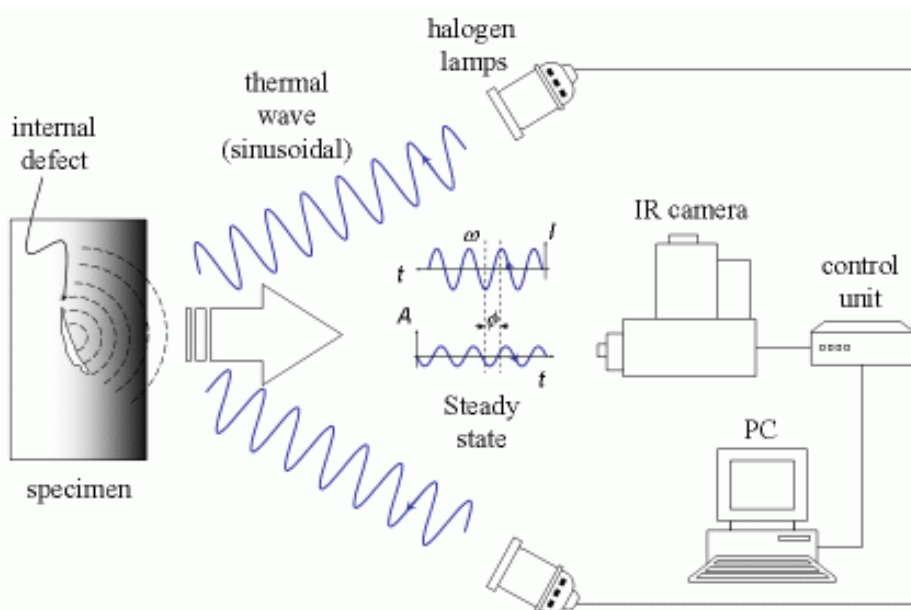


Figure 25 (visioimage, 2008)

It is used for the inspection of spot welds and also for identifying surface cracks, it allows testing without contact with the material therefore is extremely useful when there is restricted access to the material being tested (RUNNEMALM, et al., 2014) It can be used within the medical field but it is important that the specimen being analysed has to be in a controlled environment. It has been used

for identifying cancer, diabetes, neurological disorders, gynecology, transplants and brain scans (Lahiri, et al., 2012)

This method is used to detect lack of penetration, lack of fusion and inclusions within weld joints. It can detect and estimate the depth of the defect (Lahiri, et al., 2012)

<u>Advantages</u>	<u>Disadvantages</u>
Can be utilised over large areas.	If temperature is in close range can produce misleading information.
Significant practical uses.	High equipment costs.
Real time recording.	Only utilised by large companies that can afford the cost of purchase.
Finds defects in pipes.	

Figure 26 (Johnson, 2017)

Visual Inspection

Visual inspection has to be carried out before, during and after the welding process. It is a standard requirement expected as there is zero point in exposing a weld to other inspection techniques if the bad weld is visible. There is little equipment required in order to carry out visual inspection, alongside good eyesight and good lighting in the environment only a ruler, a weld size gauge, magnifying glass and straight and square edge in order to check straightness, alignment and if it is perpendicular. Before commencing the welding process the specimens are required to be checked for quality, type, size cleanliness and for possible defects. If there is any grease, paint, oil, oxide or scale it should be removed. During fabrication the visual inspection can reveal defects such as cracks, poor penetration, inclusions, porosity and undercut. After the welding process is complete visual inspection can be used to detect surface flaws such as cracks, porosity and unfilled craters, the surface has to be cleaned prior to inspection (HAYES, 1998)

<u>Advantages</u>	<u>Disadvantages</u>
Low Cost.	Can only be used for surface defects.
Applied during processing.	No records recorded.
Allows for fault correction.	
Gives indication of incorrect procedures.	

Figure 27 (HAYES, 1998)

The main application of this is mainly used to determine if a material or component has been fabricated correctly. It can be used within the navy to examine torpedo tubes on submarines. The air force can utilise this to view an engines high pressure turbine area. Other applications include inspection of bridges and aircrafts. It can be used on any size system from large aircraft skins to small electric circuit boards (MATZKANIN, 2007)

Within the welding industry other equipment requirements can be used fillet gauges to measure the width of the fillet weld, undercut gauges, angle gauges, and skew fillet weld gauges, pit gauges, contour gauges and many other items to ensure quality control (MATZKANIN, 2007)

Magnetic Particle Inspection

Magnetic particle inspection is a method to locate and define discontinuous patterns in magnetic materials. It is excellent at detecting surface defects in welds even when the discontinuities are so small they cannot be seen with the naked eye. In this method probes are placed on each side of the area in which the inspection is taken place. High amplitude is passed through the workpiece between them. A magnetic flux is produced at angles to the flow of current. When this force comes into contact with a defect in the weld they are diverted and leak through the surface, this creates magnetic poles or attraction points. A magnetic powder is then placed onto the surface and this will attach itself to the leak area this helps to indicate where the defect appears. For this to happen the discontinuity must be angled against the magnetic lines of force, therefore the current is passed longitudinally through the specimen (HAYES, 1998)

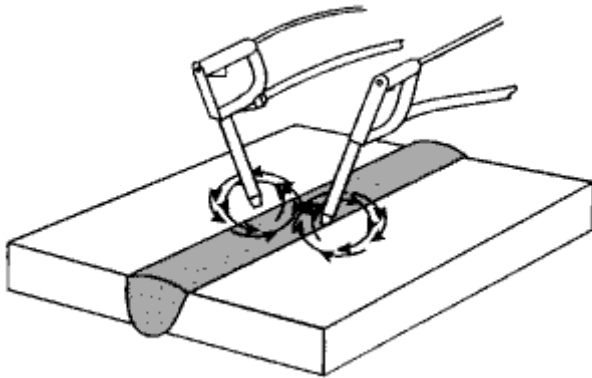


Figure 28 (HAYES, 1998)

<u>Advantages</u>	<u>Disadvantages</u>
It is a simple method.	Can only be used on ferromagnetic materials.
Controlled sensitivity.	Takes a skilled person to interpret patterns.
Relatively low cost inspection method.	Difficult to use on rough surfaces.

Figure 29 (HAYES, 1998)

It has many applications it can be used with the automotive industry for inspection of drive shafts and crank shafts (VETTERLEIN & GEORGI, 2006) When applied to welding it can be used to inspect plate edges prior to welding, in process inspection of each pass or layer and post welding for evaluation and repairs (HAYES, 1998) It has the ability to help in the medical field for cardiovascular, neurological and peripheral to identify tracers that have been admitted to patients (Borgert, et al., 2012)

Within the welding industry the method is used to look for defects such as discontinuities that include hairline cracks, seams and inclusions. It can detect defects under coatings and a layer of contrast paint is sometimes applied to the surface to improve visibility of the defects (Bainbridge, 2000)

Dye Penetrant Inspection

There are many steps in the process of dye penetrant these are surface preparation, cleaning, application, dwell time, removal, development, observational and recording, cleaning and the final report. The liquid used for dye penetrant is usually red penetrant. Once the dye has been sprayed onto the surface the excess is then removed before a developer is applied in order for it to draw out the defect and indicate the defect area. It is extremely sensitive when used for round defects. The crack gape can indicate the dwell time required whilst the presence of oxide layer or other defects in the area can cause detrimental issues (Bainbridge, 2000)

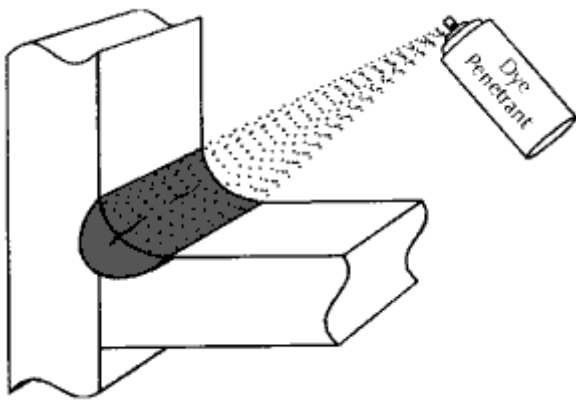


Figure 30 (HAYES, 1998)

<u>Advantages</u>	<u>Disadvantages</u>
Can be used on magnetic and nonmagnetic materials.	Only shows surface defects.
Simple technique.	Cannot be used on hot assemblies.
Relatively low cost inspection method.	.Requires very good surface finish.

Figure 31 (HAYES, 1998)

It can be used on metals, glass, ceramics, rubber and plastic. It can be used to identify fatigue cracks, quench cracks, grinding cracks, overload and impact fractures, porosity, laps, seams, pin holes in welds, lack of fusion and braising on bonding line (Centre, 2016)

In welding the defects it looks for are surface cracking and leaks in weldments. It cannot detect any defects that are lower than the surface and also it cannot identify how big or how deep the defect goes from the surface (HAYES, 1998)

Destructive Testing Techniques

There are many destructive testing techniques used within the welding industry these include tensile testing, fatigue testing, brinell and vickers hardness testing, bend tests and impact testing. These are all used for different types of welding applications.

Tensile Testing

Tensile testing is used in order to determine the amount of force a material or component can undergo before being deformed and broken. It is when you place a sample of material between two grips, top and bottom and it is clamped into place, the sample measurements are known before the piece enters the machine. Gradually weight is applied to the material from one end whilst the other end is fixed into position. The weight applied is slowly increased and whilst the sample is undergoing the test the measurements are taken throughout in order to calculate the difference in cross-sectional area from before and after the test. The results are transposed onto a graph. From the graph, four stages can be identified these are elastic region, yield strength, maximum strength and fracture. The elastic region is where the material still has the ability to return to its original shape if the load was removed within that period. The yield strength is when the material is then starting to change composition and will no longer return to original state. Maximum strength is where the tensile strength is determined and this is where the material begins to fracture. Fracture is when the sample material is no longer in one piece and at this point the load is released (Mathers, 2017) this method of testing welds is most commonly used in welded wire reinforcement where steel wires are welded together in a grid formation for reinforcing concrete (Shaffer, 2008)

Tensile testing allows you to determine whether a material will be suitable for its future application. For it to be as accurate as possible multiple test are normally carried out but all have to be prepared and processed in the same way and come from the same part of a material. The problem with this is that you need to ensure all samples are entered into the testing grips the same and are aligned accurately. It is used for a variety of different materials these include metals, alloys, plastics, elastomers, ceramics, ceramic matrix, fibre reinforced composites and components (Davis, 2004)

Tensile testing of metal and alloys is utilised to determine the compatibility of a material for future applications and to compare the different materials to assess the results in order to choose the correct one for the application, when tested these materials will fracture due to ductility. The results from the tensile test need interpretation due to the variety of factors that can affect the measurements such as temperature, microstructure and strain rate (Davis, 2004)

Tensile testing of plastics is used for engineering plastics that are either thermoset or thermosetting resins. The aim of a tensile test within plastics is to determine their viscoelasticity and anisotropy. With viscoelasticity the data has to be used with caution as there are many factors that can affect the test such as the mounting of the test piece and response curve only gives a limited amount of

insight into the behaviour of the material. The plastics can be anisotropic due to the fact that when they are molten they are viscoelastic and therefore during shaping alignment of the molecules occur. The data is not definite as there is a wide array of variations within the processing such as flow geometry and specimen geometry. Evaluations can be expensive and uninformative (Davis, 2004)

Tensile testing of Elastomers is based on big molecular polymers such as polystyrene and polyethylene. They must have the ability to return to its original shape if pulled, stretched or distorted. The properties that are required from tensile testing these materials are ultimate tensile strength, ultimate elongations, modulus and tension set. The characteristics of these materials are very adverse due to the complexity of the structures. The properties of these can be impacted by molecular matrix, compounding, sample preparation, type of sample, temperature and vulcanization parameters. The data is limited when it comes to the utility of any compound when required for a particular application (Davis, 2004)

Tensile testing of material applied to welds. The deposited weld material can be tested just like other metals but a large volume of the material is required to enable a test sample to be taken. Arc welds are in the longitudinal direction and therefore the weld material is also tested in this direction. To test the weld material is done on a round cross section and occasionally a rectangular cross section is used. Testing of welds that are already combined with the base material does not record a huge amount of data. If the test is done in the transverse direction then the only results that would be reliable are ultimate strength and fracture location, other results would vary due to the difference in material types. When longitudinal tests are carried out the strain rate should be uniform across the material but ultimate strength is the most common result used (Davis, 2004)

<u>Advantages</u>	<u>Disadvantages</u>
Ensures the material is safe, high quality and effective for the application.	Only gives results for tests carried out at one temperature.
Material selection properties.	Does not identify strength at different strain rates.
Large range of industrial applications.	Does not show asymmetry in the strength of material
Good for development of new products.	Cannot differentiate how the material would act

in different environments and processing methods.

Figure 32 Advantages (Weiler, 2013) Disadvantages (Perreira, 2016)

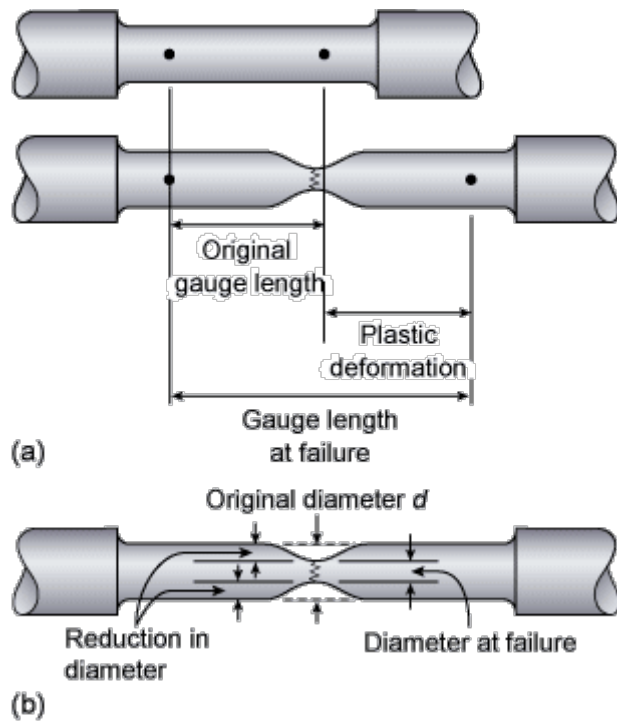


Figure 33 (Mathers, 2017)

Fatigue Testing

Fatigue testing is when a material is gradually changed structurally and it is a permanent change. These fatigue fractures occurs when cyclic stress, tensile stress and plastic strain all change at the same time. The cyclic stress is when the fracture begins to occur. The tensile stress increases the size of the crack. If one of the three aspects is not within the material than fatigue fracture will not happen. The fracture is localised to an area of the material that is defective or weaker than any other area on the piece. The amount of fatigue that a specimen can undertake is determined by the amount of stress and strain cycles that the specimen can be subjected to before the fracture will occur (Boyer, 1986) Fatigue testing is associated with fillet welds which can be used on steels and aluminium (Haagensen, et al., 1998)

Fatigue testing is used on a variety of materials due to their fatigue resistance properties. Steels and cast irons fatigue tests are carried out as they have high fatigue strength and can be processed at a relatively low cost. Main steels used are martensitic as it provides high homogeneity. The grain structure of these is fine and therefore offers a high fatigue resistance. Non –ferrous alloys do not have an identifiable endurance limit, the fine grain size alloys with no inclusions are advantageous for fatigue applications and aluminium alloys combine fatigue resistance, corrosion resistance and lightweight. Within plastics the viscoelasticity can make the fatigue resistance complicated, it affected by loading, temperature and environment. They have low conductivity therefore the fatigue resistance can be greatly affected and can cause thermal fatigue. Composite materials can be complex due to shrinkages within fibres. The strength in the direction of the reinforced fibres can be better than some metals but is significantly reduced when not tested in the same orientation (AZEER, 2013)

<u>Advantages</u>	<u>Disadvantages</u>
Low processing costs	Limited data gathered.
Can be used on a variety of materials.	Not always effective.
Compares old and new products for improvement.	It can take a long time to retrieve results.
Determines the capability of products.	

Figure 34 (Fett, 2010)

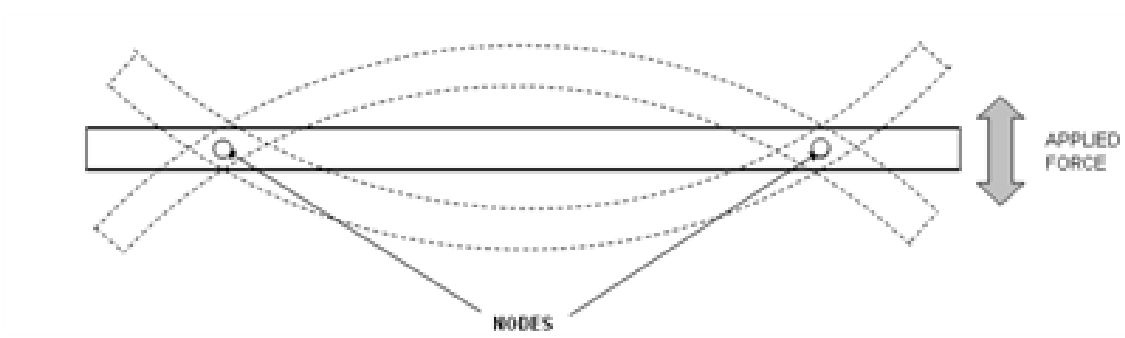


Figure 35 (Johnston, 2017)

Hardness Test

Brinell hardness testing is when an indentation is made onto the surface of material; this indentation is made by applying a force onto a steel ball that makes contact with the specimen surface. The force applied can be between 1kgf and 3000kgf dependent on the material type. After the indentation has been made a measurement is taken of diameter of the indent. A microscope is used in order to take the measurement. The hardness is then determined by calculating the area of the curved surface of the indentation multiplied by the load applied. The curved surface area is determined by using the diameter amount and multiplying it by itself and then halving the result (Hayward, 2013) Brinell hardness testing is usually associated with bulk metal testing as the area tested is larger than other hardness testing methods and therefore it measures an average of heterogeneity and is not always affected by the surface roughness. It cannot accurately measure the hardness on weld joint as it covers a much larger area than Vickers (Mathers, 2017)

<u>Advantages</u>	<u>Disadvantages</u>
Results are not affected by surface roughness or scratches.	On small specimens it is less effective.
Multiple loads can be used.	Less effective on stressed areas.

Figure 36 (H-Rasheed, 2017)

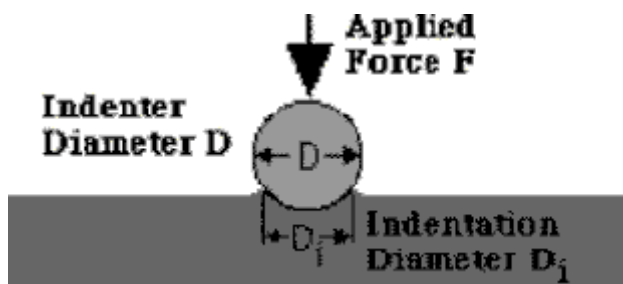


Figure 37 (England, 2000)

The Vickers hardness testing uses a diamond in an upside down pyramid to make an indentation on the surface of a test specimen. The force applied for the diamond to make the indentation is between 1 to 120 kgf. The aim with hardness testing is to see how much force a specimen can undertake before it goes past plastic deformation. The results are known as the pyramid number and this can then be converted in Pascals. It is calculated based on the load applied to the material over the surface area of the indentation. It should be carried out more than once on a specimen and when repeat testing each indent should be a minimum of 2.5cm apart due to work hardening around the previous test area (Hayward, 2013) This method can be used for fusion welding, friction stir welding and self-reacting welding (Bohanon, 2009)

<u>Advantages</u>	<u>Disadvantages</u>
Very accurate.	Expensive to buy as it is free standing.
Only type of indenter required for all materials.	

Figure 38 (England, 2000)

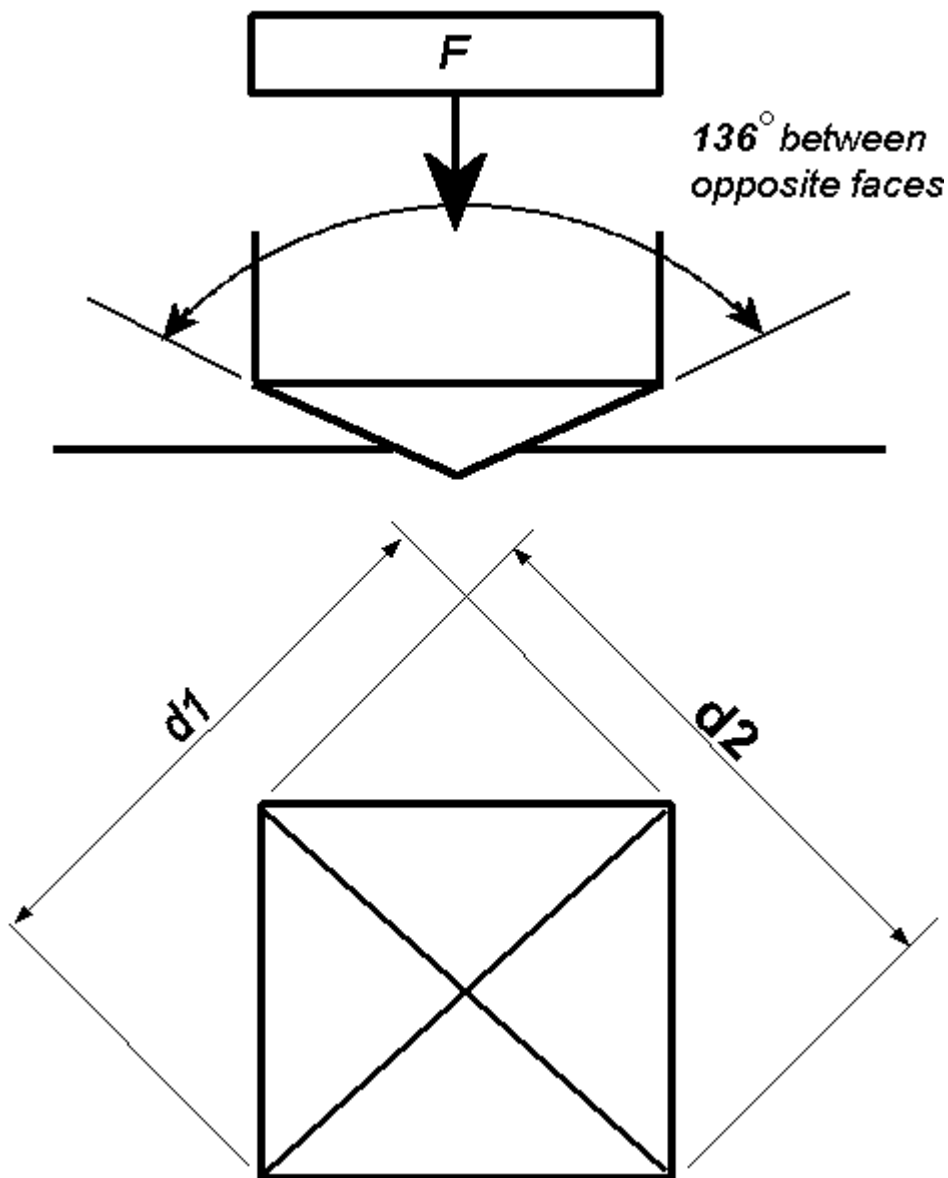


Figure 39 (England, 2000)

Bend Tests

Bend tests in relation to welding is when two pieces of material are welded together and from that, one test piece is taken from the welded plates. It is then stretched into a U position. It is used to determine whether the two pieces of welded samples are fused together properly. It determines the quality and ductility of the weld. If it is not appropriately fused then tearing will appear on the surface (Blodgett, 2006) These tests can be carried out on most of the welding methods including Metal Inert Gas, Tungsten Inert Gas, Gas Tungsten Arc Welding and Gas Metal Arc Welding (Metaltest, 2013)

<u>Advantages</u>	<u>Disadvantages</u>
It is inexpensive and simple qualitative measure.	Longitudinal tests don't always show defects such as lack of fusion and penetrations.
Samples are easy to prepare and test procedure is simple.	The test can be invalid in some situations such as if the sample is sheared.
Can be free formed or guided.	Sharp corners can cause premature failure.
Can identify defects all over the material in different directions.	In weld joints if the material is not uniform it fractures on the weaker of the two materials.
The transverse side test highlights across the thickness of the weld.	
Longitudinal are for testing whole width.	

Figure 40 (Mathers, 2004)

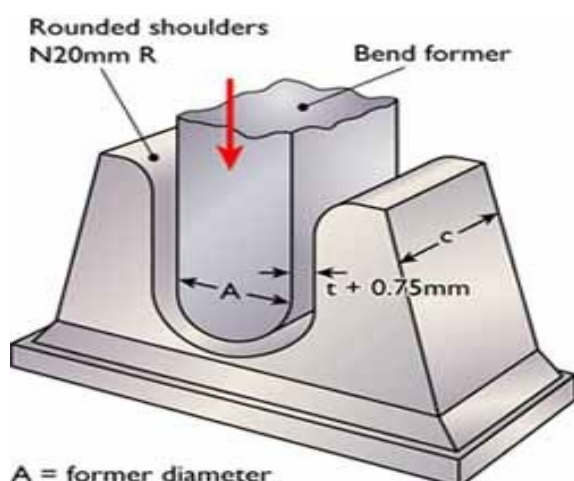


Figure 41 (Mathers, 2004)

Impact Testing

Charpy V-notch impact testing can be carried out with two methods either a drop weight system or a pendulum. The aim of this testing method is to see how much energy the specimen can withstand before failure. It is measured in Joules and can be done in both longitudinal and transverse direction of sample material. A small test specimen is notched with a determined size and the sample size is also determined. Then the notched sample piece is placed into a machine where the load is then dropped onto the test specimen and the amount of energy that is absorbed by the piece before failure is measured (Leis, 2013) This method can be used for fillet welds in structural industry (Gilmer & Frank, 2009)

<u>Advantages</u>	<u>Disadvantages</u>
.Ability to identify notch sensitive materials.	Does not measure flaw size or stress rate.
Simple procedure.	It is hard to keep the notch size accurate and the equipment can wear quickly.
Helps determine the minimum and maximum temperatures that a material can be exposed to.	

Figure 42 (Hussin, 2013)

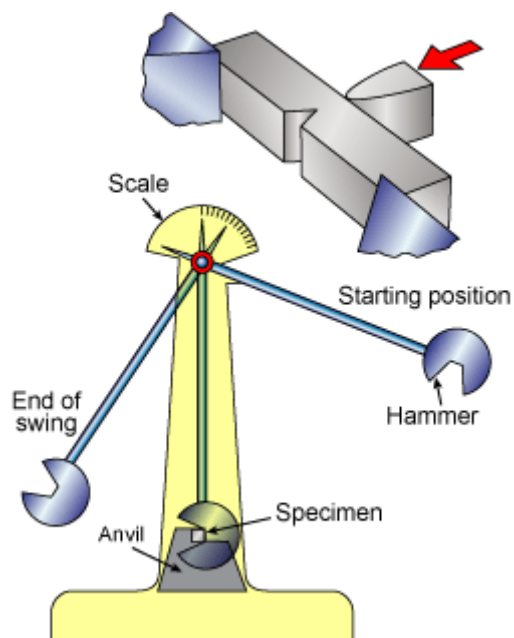


Figure 43 (Mathers, 2017)

Izod impact testing is similar to the Charpy test but instead of the sample being horizontal in the test machines it is placed vertically and the notch is placed facing the pendulum instead of facing

away. It can be used for plastic materials whereas Charpy is only used for metallic materials. The load interacts with the test specimen on the end of the piece instead of the middle (Harvey, 2016)

<u>Advantages</u>	<u>Disadvantages</u>
Can be used for metallic and plastic materials.	The notch is extremely critical and has to be done with precision.
Lowers ductile fracture and distortion.	The amount of energy the can absorb can be highly affected by the notch.

Figure 44 (Hussin, 2013)

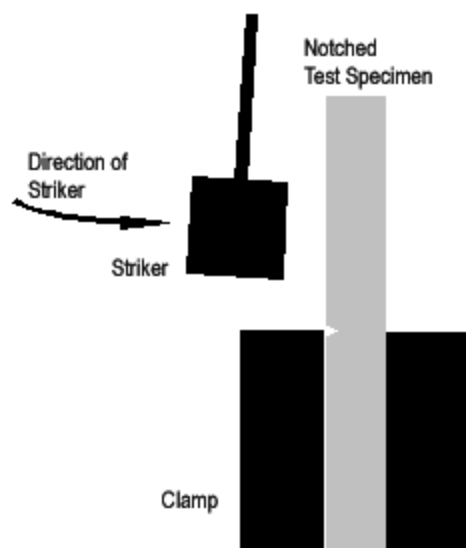


Figure 45 (AZom, 2005)

Types of Weld Defects

There are many defects that can occur in welds. These include lack of fusion, lack of penetration or excess penetration, porosity, inclusions, cracking, undercut and lamellar tearing. All these can have significant consequences within the application; they can give high stress intensities that can cause sudden failure (Greive, 2003)

Lack of fusion, penetration and excess penetration

In order for the fusion to be of good quality it has to cover the full thickness of the sheets being joined. If the material is thin it can be welded in one pass. If the material has a thicker gauge would need a few passes to make the weld successful. Lack of fusion can result from too little heat inputted or a too rapid traverse of the welding equipment. Excess penetration is a result of too high a heat being inputted or slow speed of traverse (Greive, 2003) When lack of fusion occurs the biggest consequence is the notch effect, where failure occurs due to the notch in the weld. In figure 6 the top diagram shows the lack of fusion on the side walls and the one below show lack of inter-run fusion (RIHAR, 2000)

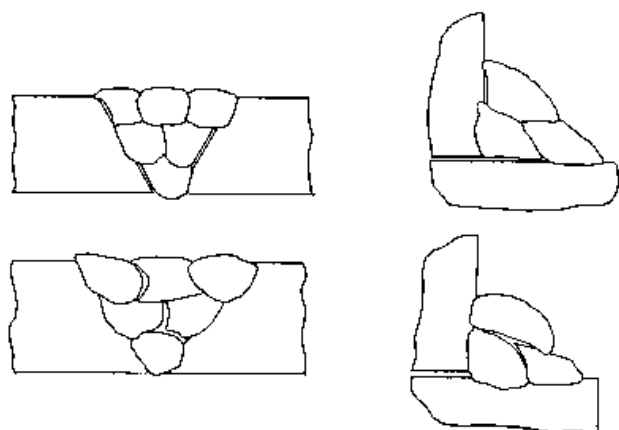


Figure 46 Lack of fusion (RIHAR, 2000)

Porosity

Porosity occurs when there is gas trapped in the weld metal when it is in the process of solidifying. It can happen due to moisture in consumables, metal or from dirt such as oil or grease on the area of the weld. To avoid this, consumables should be stored in a dry place and the area should be kept clean (Greive, 2003) Strength can be reduced when the area fraction is increased. Fine porosity can also reduce strength. There is loss of tensile strength in the transverse direction is proportional to the loss of sound in metal area. With increasing porosity fatigue life is reduced (Rudy & Rupert , 1970)

Inclusions

Inclusions can occur when several passes are made on a V joint when thick materials are being joined using a flux and the slag is not totally removed once the pass has been made before the next

pass is carried out (Greive, 2003) Inclusions make the welds more susceptible to hot cracking and lamellar tearing (ZORC, et al., 2014)

Cracking

Cracking can occur due to thermal shrinkage or a combination of strain phase change and shrinkage. In welded stiff frames a combination of bad design and poor welding procedure high residual stress and cracking can occur. To prevent cracking pre-heating could be carried out and once the welding has taken place post cooling in stages should be done. This would increase the strength of the joint but would also increase the cost of the weld but in high strength steels there is no alternative. Solidification cracking also known as hot cracking and they occur immediately after the welding process and occasionally it can happen during. It occurs due to sulphur and phosphorus and is more common in high carbon steels. There are three factors that can increase the risk of this occurring these include insufficient weld bead size, welding under excessive restraint and materials with high purities (Greive, 2003) Hot cracking means that the material cannot be worked at high temperatures as the strength at the grain boundaries is reduced and cannot withstand tensile plastic deformation (ZORC, et al., 2014)

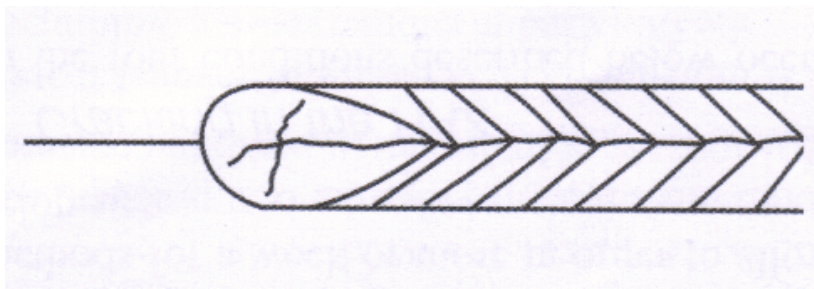


Figure 47 Centreline cracking (Greive, 2003)

Under Cracking

This is when the thickness of one or both the sheets is reduced at the toe of the weld and happens due to incorrect procedure or machine settings (Greive, 2003)

Lamellar Tearing

This is a problem within steels of low quality. The plates normally have low ductility in the through thickness direction that can be caused by inclusions such as sulphides and oxides that have elongated through rolling. It can occur in fillet and butt welds and in T joints and corner joints where joining is parallel to rolling direction. To prevent this occur higher quality steels could be used or covering the area with a ductile material and redesigning the joint (Greive, 2003) Lamellar tearing reduces the strength. This can be improved by using different welding techniques (Farrar & Dolby, 2001)

Case Study 1

Destructive and non-destructive evaluation of Copper diffusion bonds

This study was completed by the National Institute of Technology in Tiruchirappalli, India. The study was done by S Suresh Kumar and B Ravisankar that work in the Department of Metallurgical and Materials Engineering.

The study was based on the diffusion bonding of copper to copper. Once the materials were bonded the regions characteristics were studied using light and scanning electron microscope images. Then the bonded strength was evaluated using both destructive and non-destructive testing methods. The quality of the bond was also analysed through non-destructive testing methods. The grain growth equation was applied to determine the bonding mechanism. The connection between destructive and non-destructive testing methods was studied. The main aim of the study was to analysis the bond interface and the quality of the bond that was determined through the testing. Also there was a comparison of the Pilling's model with the copper/copper system in order to assess the void properties during diffusion.

During the investigation the commercial grade of copper was used, the samples were prepared to a size of 50 millimetre diameter and 20 millimetre length. Before testing the samples were cleaned and degreased using an ultrasonic bath and acetone. The experiment was carried out in a diffusion bonding chamber with a vacuum resistant heating unit. The samples were then heated from room temperature to a bonding temperature that was known. There were various parameters put in place throughout the testing such as temperature, pressure and time. The samples were then cooled in a furnace till they had returned to room temperature. Then the first stage of testing was done through the c-scan ultrasonic method at different conditions. The samples were then sliced for destructive testing to be carried out. These destructive tests included micro tensile and micro hardness. For the micrographs to be done the samples were polished and electrolysis was done in a solution of water and nitric acid, this method helped to obtain the grain size and boundaries of the samples. Tensile testing was carried out at room temperature on two specimens, the bonded and un-bonded specimens in order to obtain the strength ratio. From the strength ratio the characteristics of the bond quality and interface can be assessed. The hardness testing was carried on the bonded samples and on different sections of the specimen including the base metal and the bonded area in order to determine the effect the processing had on the material. The Vickers hardness testing machine was utilised for the experiment. The diffusion mechanisms were also observed through the grain growth and atom migration at different temperatures. The results were also compared to the Pilling's model in order to determine the bonding mechanisms. This model is an equation that describes the kinetics of the bonding under stress. It calculates the time it takes for the full interface to bond by using the reduction in area of voids from the start to the end of the bonding process.

During the ultrasonic testing the joints were assessed. Ultrasonic works through the conversion of mechanical to electrical energy to produce waves. The tests were carried out under water using the pulse echo method, the pulse is started using a probe and then this probe receives the signals from the bond joint. The images were then achieved from the bonded area using ultrasonic testing; the transducer was set up to 0.05mm in two directions and then was moved over the samples, the signals were less on the weld area.

The results include the relationship between temperature and coefficient that has been calculated from the grain growth equations. The results concluded that a major controlling factor of bonding was the diffusion in the grain boundaries. The results also show the best conditions for the bonding to be carried out based on temperature and stress, this is the occurrence of diffusion was greatly affected by the grain boundary diffusion. The results were compared to the Pilling's model where it states that the full interfacial contact time should be obtained by the rate of reduction in area of voids. Creep flow was used to consider the void closure rate and also the grain boundary diffusion was used. It was observed that the values obtained from the experiment were not compatible with the plastic collapse conditions but they were more closely matched to the diffusion mass transfer. It was confirmed through all this that grain boundary diffusion was the bonding mechanism that had taken place. The grain size in the sample that had been bonded was larger than the original piece of material the specimens were taken from. At 750 degrees Celsius the bonded area of the sample was good but was very thin. The hardness was the highest value at this temperature whereas at a higher temperature the hardness reduces. The quality of the bonds was determined by the ultrasonic testing, the imperfect bonds shows peaks in the scans carried out on the specimens. The peaks represent the reflection of the front, back and the bond interface. In the perfect bonds there are only two peaks that represent the front and back wall reflections. Again the better bonds were at 750 degrees Celsius. Through both the destructive testing and NDT types it shows that the strength ratio decreases when the reflection coefficient increases. This was then used to determine strength ratio by using the two NDT parameters, it aided the quality of bond determination. For determining the bond quality the NDT methods were more desirable. The three conclusions drawn from the experiment were that a perfect bond was formed with copper to copper at 750 degrees Celsius, diffusion bonding is determined by grain boundary diffusion and a theory was started through the results of the C-scan and strength ratio to determine the quality through the ultrasonic scans (Kumar & Ravisankar, 2016)

Considerations

From reading and looking at this study there are few things that have to be considered copper conducts heat and electricity therefore the temperatures of testing and joining cannot be too high or the copper would melt. An oxide layer can form on the surface that is why the process was carried out in the vacuum chamber to prevent the oxide layer from forming on the joint. The test specimens

were small and were all carried out in controlled environments and therefore it has to be considered how the materials and testing methods would apply in the environments in which the materials are being utilised.

The best results were attained from 750 degrees Celsius. If it could be reduced to 700 degrees Celsius it could save time and money as the higher the temperature the more energy that is used. The strength ratio at 700 degrees Celsius was 0.41 with a pressure of 15 mega Pascals and a soak time of 60 minutes. They could have tried increasing the time to 90 minutes or even 120 minutes in order to establish if the results could be similar to those at 750 degrees Celsius.

The typical applications of copper/copper diffusion bonded samples are for pipework for splitting the pipes into two directions and adding a valve or joint piece. It is used for intricate areas and therefore the testing was done on small specimens. Therefore testing would not be required on a large scale as the bonded pieces are small and intricate.

Recommendations

They could have used the bend test method to assess the bond but it will only show the quality of the bend and does not give specific measurements therefore it would not be utilised on its own as it would not give the hardness and it could not give a comparison to the base material.

When considering the non-destructive techniques eddy current and full matrix capture could have been utilised. Eddy current is a suitable option for testing copper, but it would not be used in this circumstance as it does not work well on complex geometries and it requires more skill to interpret the results. Full matrix capture is appropriate for testing of copper welds, it may not have been used in this instance due to the capabilities not being as good as they could be and the files are too big therefore a lot of work to be carried out after the initial test is carried out.

Case Study 2

Defect sizing using PA-Ultrasonic Testing and acceptance in Copper Lid, Tubes and Welds for disposal canister

This study was carried out by employees of three different organisations. J. Pitkänen of Posiva Oy in Finland, this business is an expert in nuclear waste management. A. Lipponen, H. Raiko and D. Braddock of VTT in Finland and this is a technical research centre. Lastly, G. Brekow of BAM in Germany, this is a federal institute for materials research and testing.

This aim of this study was to ensure that the canisters were able to withstand years of use without being affected. The canisters must meet three requirements a good tightness, good corrosion resistance and sufficient mechanical strength. They must have the ability to limit the radiation exposure on the outer surface not to make transporting and handling an issue. The NDT testing has to be done on each section to ensure it meets all the standards. The main reasons for the inspection process is for manufacturing and for eliminating defected components. To inspect the tubes, lids and welds two of the NDT techniques were utilised, ultrasonic and eddy current. The linear phased array probes in the ultrasonic testing were used firstly and then for sizing the phased array probes were used.

These were the methods used throughout this study. Linear phased array was applied through dropping the amplitude but through the method the sizing of the defect is not very reliable when looking for surface defects. When applied to inner surface defects it is still not usable if there is no other technique available to assist. Through this method the amplitude used for indication was maximised and the probe is moved in the opposite direction until the amplitude drops and then the probes were reversed in order to estimate the size of the defect. The tip diffraction method is one of the most accurate ways of sizing a defect. There are often three dimensional defects in copper welds and through matrix phased array it allows for the detection of defects to be improved. Time of flight diffraction technique measured the amplitude of the signal but this again is not a method that can accurately size the defect due to it being dependent on the crack orientation. In this method two probes are used where one transmits an ultrasonic pulse and the second receives the pulse from the other. SAFT phased array is able to pick up defects by scanning at different angles. By combining these methods it produces a large field of sound to improve the detection and sizing of larger and deeper defects.

For the components to be approved for use there are four aspects that have to pass through the inspection methods. First the analysis of the defect detected after the inspection process, secondly, the size of the defect, thirdly, comparison of the results with the minimum component acceptance requirements and lastly, the wall thickness should be at least thirty five millimetre defect free and the defects should be no more than fifteen millimetres.

The conclusions from this study were that all the sizing methods were successful when applied to the copper components. The actual sizing could not be estimated to the full extent because not all of the studies were completed. Overall the SAFT Phased Array was really good at detecting the defects compared to the basic linear array. It also detected more than the x-ray inspection that was carried out. This method also allows defects to be detected from the front and the back and this cannot be done by using x-ray. The time of flight diffraction was shown as a simple and quick method for sizing the defect. This method was inaccurate due to the sensitivity of lateral waves as the defect size was small (Pitkänen, et al., 2013)

Considerations

The two welding techniques that were used on the copper components were electron beam welding and friction stir welding. Electron beam welding is a popular method used within the nuclear industry due to the minimal distortion achieved through this technique. This technique minimises distortion which is extremely useful in the case of copper because copper has a high thermal expansion coefficient and this can result in distortion if not welded correctly. Friction stir welding can be easily applied to copper due to it being a soft material and this method can give a smaller grain structure at the joint and also a higher tensile strength.

The copper component had to undergo tensile testing to ensure that it had good mechanical strength and this cannot be achieved through any NDT techniques. The inspection techniques utilised are dependent on the typical types of defect that could occur. The main and reoccurring defects that can occur within the component being inspected are hot crack, tearing, porosity and lack of fusion.

Recommendations

The most common and versatile non-destructive techniques were utilised in this study but another method that could have been used is alternating current field measurement as this method is very good at sizing defects and it has a range of sizing a defect up to twenty five millimetre which in this case is sufficient as if the defect is larger than fifteen millimetre it is rejected.

Case Study 3

Inspection/Non Destructive Testing – NDT Case Study 1

This study was carried out by the Health and Safety Executive; they are company that aim to protect employee's health within workplaces and help prevent injuries and illnesses that can be cause through working environments.

This study was based on a processing plant that had been operating with two vessels for twenty one years. The vessels were made of stainless steel and the contents were flammable, mildly toxic and contained chlorides of up to 500 parts per million. The vessels were vacuumed up to fifteen psi and twenty cycles per day. There was also an agitator within the vessel contents that was used as part of the process. When the vessels were first put on the process line they had been hydraulically testing up to seventy psi but had not been testing again in the whole twenty one years they had been in operation. Due to the material choice of stainless steel being used the company had not expected them to break and therefore no leak detection equipment had been put in place to monitor the life and quality of the vessels. They were visually inspected every two years by an external company and they only inspected to a generic standard not to a standard that could have been more appropriate for the use of the vessels.

The first concerns raised were that with the combination of stainless steels and chlorides the possibility of stress cracking increases. The cracks were likely to occur on the inside of the vessel and therefore the external inspection would only potentially pick up through wall cracks. It was highlighted by one of the people operating the vessels that a weld repair was required and the reason it hadn't leaked was due to the contents being to viscous. Once the weld repair was done the vessel underwent another hydraulic test and these revealed that the psi had dropped by forty. From this the two yearly inspection standards were adjusted to include an internal inspection and also a dye penetrant test on ten percent of the welds.

Even with this new amendment to the inspection standard there were still areas of concern such as the access to do the internal inspection was not possible on the second vessel. There were cracks on most the welds on the vessel so why would only ten percent be inspected. The dye penetrant inspection may not work if the internal cracks had been filled with the contents of the vessel.

The conclusions drawn by HSE were that the competent person that worked on the vessels was highly depended on to make the decision if the vessel was fit for purpose. The inspection standards were poor and therefore were not suitable and had to be majorly adjusted in order for it to be sufficient. Even though cracks had been identified there was no sizing carried out or growth rates determined.

Considerations

The company utilising these vessels made a decision not to put in regular inspection methods due to their assumption that stainless steel should not break but they should have been more vigilant and still monitored due to the possibility that something could happen. They hadn't accounted for the fact that the contents include chlorides and this does not always work best with stainless steel and therefore the choice of material may have been inappropriate to start with.

A lot of pressure was put on the competent person operating the vessels to know through smell if there was a leak but this may not be the most appropriate method as they could be too busy to notice or they could notice too late and a massive accident could happen if that vessel was to break during operation.

The company had not used the trained and experienced resources available to them who have knowledge in the materials chosen, the inspection requirements, and what inspection processes would be best suited (HSE, 2003)

Recommendations

More regimented inspections carried out on a more regular basis rather than two yearly due to the contents of the vessels as the chlorides could react with the stainless steel and break it down quicker than expected.

Ultrasonic testing can be utilised very well within this application as it can inspect the whole weld and in this case they were only considering testing ten percent of a weld. It can be used on thick gauged specimens and these vessels based on their application would probably be quite large. It is also extremely good at determining flaw size therefore a defect may be detected and at that point it may be too small to have detrimental affect but it could be put down for more regular inspection to estimate its growth to see when it was likely to become an issue.

Case Study 4

Experimental Study of Tensile Test in Resistance Spot Welding Process

This study was carried out by Lebbal Habib and Berrekia Habib, who work for the department of mechanical engineering at the University of Science and Technology Mohamed Boudiaf in Algeria. Ziadi Abdelkader who works for the Laboratory of Intelligent Structures in the University of Ain Temouchent in Algeria and Boukhoulda Farouk Benallel who works for the Laboratory of Mechanics of Structures and Solids Sidi Bel Abbes in Algeria.

Resistance spot welding is a method that is most commonly used within the automotive industry as it is one of the faster and easier methods to use. It is a method whereby a localized spot is melted at the interface of the sheets of metals being joined and this is followed by a solidification under a pressure water cooled electrode and a flow of electrical current for the duration of the weld process. The materials in this study were joined by a lap joint. Before welding the machine has to be set to the correct settings to ensure the weld is of a good standard.

There were three materials tested in this study and these were DP450, HSLA350 and TRIP700 as these are all classed as high strength steels but they are also ductile which is a key requirement within the automotive industry. They are also very lightweight which is advantageous.

The tensile test results showed that the orientation of the tensile specimen did not have a significant effect on the properties. But the best results were produced by the TRIP700 which has the highest carbon content of all the three materials. From the results of the tensile test it helps determine the properties of the welded joint. This test helped to show if the resistance spot weld properties and strength is influenced by angle of rolling direction, overlap length, material type and thickness. Overall the best material for spot welding was the TRIP700 (Habib, et al., 2016)

Considerations

The aim of this study was to see how the resistance spot welding method can be applied to different materials of different chemical compositions. It was done on high strength steel as these are the most commonly used within the automotive industry,

This method of testing was carried out before the materials had been put in applications. Tensile testing is usually carried out on products before they are made into the final components.

This was a trial study just to compare the results from all three materials.

Recommendations

Hardness testing could have been done also to test the hardness of the weld spot but it would not be able to give all the results that tensile testing can produce. It would be more applicable is the

materials were not known and the aim is to get a basic understanding of the chemical composition of the material.

Case Study 5

Assessment of tensile properties of spot welds using shear punch test

This study was carried out by S Acharya and K K Ray of the department of metallurgical and materials engineering at the Indian institute of Technology that is situated in Kharagpur, India

Testing of spot welds through standard procedures is very difficult due to the small size of the weld. Therefore in order to assess the tensile properties of spot welds shear punch test has been trialled on interstitial free steels sheets. To coincide with the shear punch test some microstructure examination was done through the use of SEM and TEM, Standard tensile test, micro hardness testing, and fractographic were applied to the material.

The shear punch test uses the correlation between shear strength and maximum shear strength in the shear punch test along with yield strength and tensile strength produced from the tensile testing to determine the tensile properties of the weld. The main aim of this study was to determine the tensile behaviour of spot welds.

The microstructure tests were carried out by cutting samples from the sheet steel. They were mounted using resin and then polished using a diamond paste. The samples then were examined through a microscope and from this it could be seen that the structure was mainly ferritic in the surface sample and the longitudinal sample.

For the micro hardness testing the samples were polished and etched. They were then testing using a Vickers machines with a load of 100gmf for a test time of fifteen seconds. There was a minimum of fifty individual test carried out on the samples.

Pre-straining was also carried out on a number of samples and each underwent a different pre-strain ranging from five to fifteen percent.

The samples for tensile and shear punch test samples were taken from the original sample sheets and the pre-strained specimens. In order for the shear punch samples to be prepared correctly they were polished. The shear punch testing machine consists of steel dies and a flat punch. The punch diameter was three millimetre and the upper die had an inner diameter of just over three millimetre.

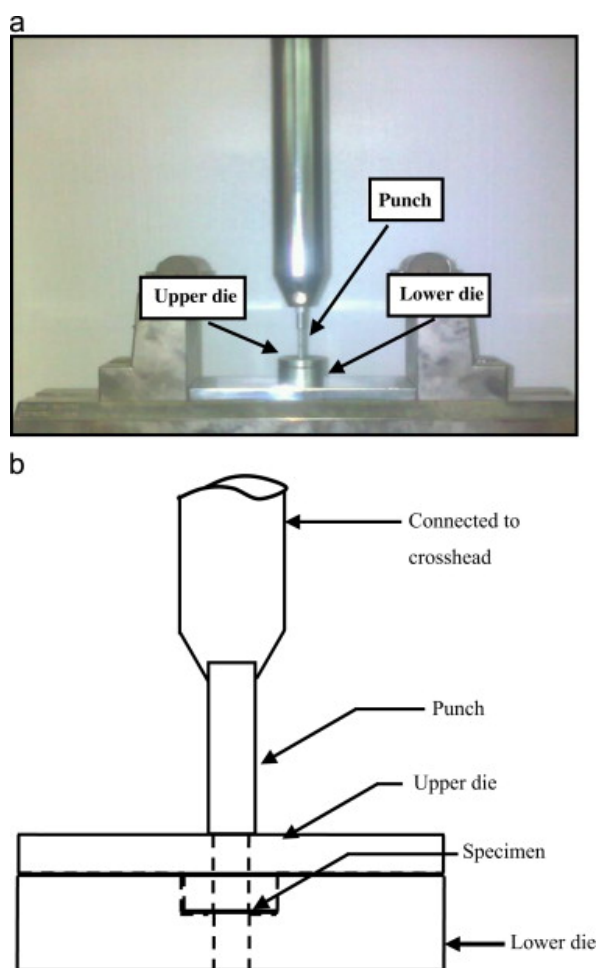


Figure 48 Shear Punch Test (Acharya & Ray, 2013)

Spot welding was carried out on the samples from the original sheet steel. They were done in a pedestal type inverter in an environment that was ambient using a copper chrome electrode and during welding the electrodes were cooled through a water cooler.

For macroscopic and microscopic testing on the welds sample were cut across the middle of the weld spot and then underwent surface preparation the same as the microstructure samples carried out at the beginning of the study. From this the size and shape can be examined.

For hardness testing along the weld the samples were ground, polished and etched. Then they underwent the testing through Vickers right across the weld nuggets.

For the shear punch test on the weld samples were cut from the weld joints with the weld nugget central. They were ground down and etched in order to identify the fused area. They then underwent the shear punch test exactly like the original samples.

The fractographic examination was carried out on broken specimens after the scanning electron microscope. These images were used to examine possible failure mechanisms.

From the microstructure the fusion zone, heat affected zone and base metal areas around the weld joint. In the base metal the microstructure was found to be mainly equiaxed ferritic grains. In the heat affect zone the structure appeared to be columnar ferritic grains that were parallel to the heat flow direction. In the fusion zone the structure was big ferritic and martensitic grains. From the TEM images it can be seen that there is a considerable amount of dislocation density that is caused by low carbon martensitic grains.

The hardness test results on the sample sheets averaged at around eighty-eight. Along the weld joint the hardness was averaged at one hundred and one and in the heat affected zone it was one hundred and seventy. The hardness lowers as you move from the heat affected zone to the base metal.

The tensile results from the sheet steel and the pre-strained samples should show similar results to those tested in other studies of similar metals. When the pre-strain was increased the yield and tensile strength also increased. This is due to work hardening that occurs in the pre-straining phase, with this increase in strength comes a decrease in ductility.

Once the shear punch tests were carried out the load-displacement data that was gathered was used to analyse the shear stress against the displacement. The results for the normal samples and the pre-strained samples were found to be similar. It was found that in the pre-strained samples the higher percent of pre-strain, the higher the shear yield strength and maximum shear strength.

The correlation between tensile and the shear punch test shows there is a linear relationship between these two test result values and also between maximum shear strength and ultimate tensile strength.

It was found that the tensile strength of the spot welds were 3.1 and 1.8 times higher than that of the base metal. The hardness and strength of the weld nuggets are due to the fast cooling rates during the welding process.

The three main conclusions drawn from this were that the yield and tensile strength of the sheet steel had a linear relationship with shear yield strength and maximum shear strength. The strength in the fusion zone was significantly higher than that of the base metal due to development of martensitic grains. The strain hardening at the weld nugget was valued at 0.12 using the shear punch test (Acharya & Ray, 2013)

Case Study 6

Fillet welds subjected to impact loading – an experimental study

This study was completed by E. L. Grismo, A. Aalberg and M. Langseth who are all part of the Structural Impact Laboratory and Centre for advanced structural analysis in the Department of Structural Engineering in the University of Science and Technology in Norway. A. H. Clausen was also a part of the team and works at the University Centre in Svalbard, Norway.

The aim of this study was to measure the force and deformation of fillet welds when subjected to impact loading. The test specimens were carried out in two directions transverse and longitudinal to the fillet weld itself. They were also made to ensure that the plastic deformation and failure occurred at the weld area. Even though the main testing method used in this study was impact testing they also carried out some quasi-static tests as a comparison method.

Two types of specimens were developed with specific requirements set such as the failure had occur predominantly at the weld, they had to be suitable sizes for impact testing and the force applied to the weld should be measured. The samples were cut through the method of laser cut and then joined together by using the shielded metal arc welding method. The welds were inspected and met the acceptance levels set by a standard followed, the inspection techniques were visual and magnetic particle inspection.

Uniaxial tension tests were carried out at different strain rates. Two samples from each type of testing specimens were taken one in each direction due to the expense in producing the correct size for the test. From this it showed that the strength in the weld area was higher than that of the base metal. The failure strain was calculated by the area of the fracture surface and the fracture strain.

Vickers hardness testing was carried out on three pieces, longitudinal sample, transverse sample and a butt weld sample. The highest result came from the weld and not the base metal. The hardness in fillet welds is also shown to higher than butt welds.

Five impact tests were carried out on each component. The results showed that the tests in the transverse direction were more resistant and less ductile compared to the results from the longitudinal tests. The average strain rates in both directions were similar.

In the tensile tests on the weld at elevated temperatures there appeared to be no reduction in the resistance of the weld material below 400 degrees Celsius. Due to this there would not be a significant decrease in force that could be caused by thermal softening during the testing procedure.

Four quasi-static tests were done on each component. The results from this testing showed that the transverse samples were 1.7 times higher maximum force compared to the longitudinal samples. It

also shows that in the longitudinal samples the deformation capacity was significantly reduces in the dynamic tests compared to what was produced in the quasi-static tests. This could be due to potential thermal softening. There was less plastic work in the transverse samples therefore these did not show a reduction in deformation capacity.

The conclusions drawn from this study were that the resistance of the fillet weld was unaffected by the displacement. The deformation capacities of the longitudinal samples were reduced when the displacement rate applied was increased. From the scanning electron microscope images it was seen that in the longitudinal sample surfaces there was an even surface that contained elongated pores in the impact load but in the quasi-static load there was an uneven surface and sphere shape pores. There was a stronger localized deformation pattern in the longitudinal samples in the impact loads that were shown on the micrographs (Grimsno, et al., 2017)

Future Developments in Non-destructive Testing

The future of NDT means that the equipment needs to be made more reliable and sensitive with as little chance of error occurring. There is a big push for the test methods to be automated with computer and processing to store the data obtained. There is also the potential to combine methods such as radiography, eddy current testing and ultrasonic. The inspection techniques will be more developed to be used online and inspection during operation (IAEA, 1999)

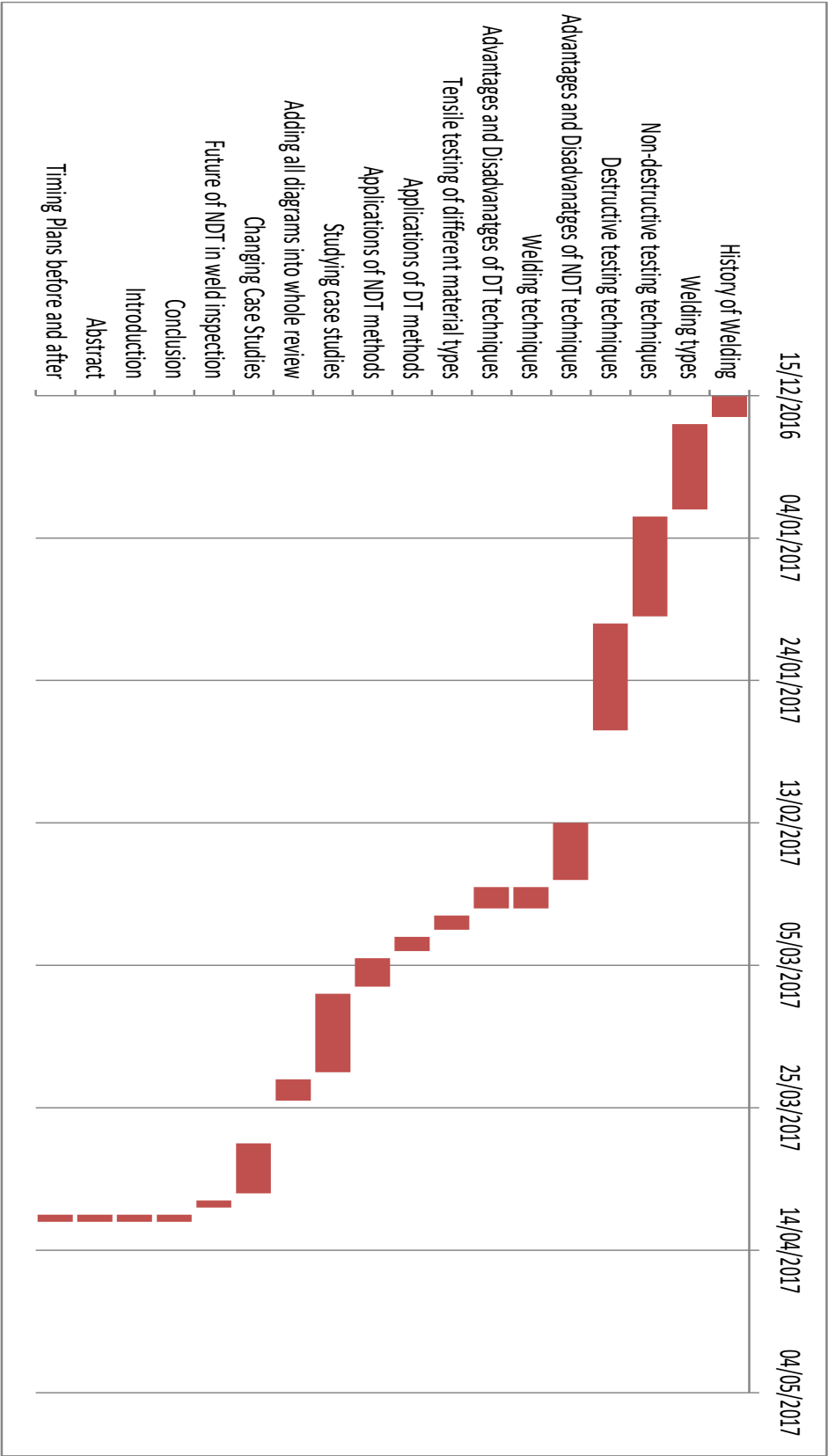
There is a possibility within spot welds where the use of thermography could be used automatically in order to detect porosity, expulsions and cracks. Before this can happen development of analysis program is required (Runnemalm & Appelgren, 2012)

There is a new inspection method being developed known as the Inverse Wave field Extrapolation. The method has the ability to extrapolate the wave field later in time and it can then do the opposite of identifying where the wave originates from. There are a number of elements in the system and the process works in stages, firstly, transmitting of first element, secondly, receiving the transmission from all elements, thirdly, transmitting second element, fourthly, receiving transmissions and this process continues until all elements have been used. The results obtained are used to produce a cross sectional image of an object. This can be utilised on welds and has the ability to improve the probability of detection and sizing. As it is an automated technique it limits the interpretation that could be made by human interference (Ent, 2012)

Three Dimensional radiographic inspections is also being developed as a potential technique for the future. The push for this testing comes from the limitations on inspection in basic radiographic inspection such as defects being undetected due to orientation, human judgement through interpretation, probability of detection and accurate sizing. The test method would inspect the weld through the weld in the x direction. This direction assists in the measurement of the height of the defects (Ent, 2012)

Final Timing Plan

This timing plan shows exactly what was carried out at what times from start to finish.



Conclusion

From this review it is easy to see that there is a large range of testing and inspection techniques within both non-destructive and destructive. Within the non-destructive techniques they can be used for different applications and they can be chosen based on restrictions applied such as the geometry of the components, limited access to the material, in-service inspection and online testing. The main benefit and importance of these methods are that the material does not get damaged during inspection and can stay in operation therefore it is a very advantageous sector for routine maintenance and inspection. These methods can help to determine deterioration and lifespan of a component within operation due to routine inspections.

The destructive methods are utilised for determining the composition of material. They are used to identify the strength, toughness, hardness and how they would react under certain constraints. These methods are most commonly used before a material is chosen for application, component design stage. They can also be used when a material composition is unknown. Within welding these methods can help identify how a weld would withstand forces.

This review was aimed at considering the methods to understand how the methods work and for what applications and from this could any of the destructive methods be replaced with non-destructive methods. Realistically it would be very difficult to replace these methods as the current non-destructive methods do not have the capabilities to determine compositions of the material. But these methods could be used alongside destructive testing for maintenance procedures so a company or organisation using the materials can understand the properties before they were applied. This could be beneficial for assisting in the maintenance plans.

The importance of this review was to understand the application of these types of methods when applied to the welding industry. When studying welding there are many issues that can occur from poor welding technique from human error to incorrect machine setup. There are also many ways to weld and therefore the choice of welding type chosen can be dependent on the final application of the component being welded.

From the case studies it can be seen that there is many situations where these methods have been utilised. One thing that can be noticed from the destructive testing case studies is that there were multiple test methods used for one study, this is due to the fact that at this point the materials were being investigated for application therefore the wider range of results can help determine the best choice of material based on the welding application that was used. The non-destructive inspection case studies show how they were used to inspect and check that the welds were still within accepted limits.

From this review it is clear that both types of methods have importance to the process. A lot more research needs to be carried out in the non-destructive sector in order to increase its capabilities to try and reduce the amount of destructive analysis as it would be more productive and cheaper in the long run to limit the testing done before the materials reach their final application.

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