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Realization of system detecting defect in materials

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Dedicates.

This work is dedicated to all my family members; friends and professors of Mechanical engineering Faculty in Mohamed Khidar University whom supported me during realize this project.

I would love nothing more than students or readers enjoy reading it.

Take your time, do it right and enjoy.

That's the best advice I can give you…

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General introduction

All metals contain defects. These can range from faults on an atomic scale that are inherent to crystallographic structures, to larger defects that are introduced during processing. These latter defects may be avoidable, or at least reduced to a level whereby they pose no threat. The complex chemical and physical reactions that take place in the both the molten and solid state can produce effects resulting in both inhomogeneities and defects in the material. Non-uniform properties can present problems during the processing, fabrication and subsequent service of metal components. Defects that are introduced during the processing cycle will enter the fabrication route and may cause further problems by either initiating a failure during fabrication, or when the component enters service. The misapplication of the manufacturing process or lack of control at any stage may introduce defects and residual stress that can affect the performance of the structure in service, making it susceptible to failure. Defects that may be produced include holes, cracks, segregation, inclusions, surface marks, notches and undesirable or unintentional metallurgical changes within the material. In this thesis, I would like to highlight this problem then, aiming to create a system to detect earlier defects using my own knowledge.

The Non-Destructive Test (NDT) is group of tests which can be performed without damaging our materials, but which ones is suitable for me? After deep search with different manufacturers and suppliers, such as "Eddyfi" company which provides advanced highest performance Non-Destructive Testing (NDT) inspection technologies in the world, "EKOSCAN" which provides a portable Ultrasonic system made up of a USB ultrasonic board and software. I found that the quicker and the efficient method is using eddy current due to low cost and easy to use.

To find out this defect I picked up this challenge to create two tools to tell me where the defect is.

In this project I aim to create using my own means two tools able to detect a surface and sub surface defects with eddy current technology in deferent metals within carbon steel.

Chapter I

Intern and Extern Defects in Metals

1.1 Introduction

A perfect crystal, with every atom of the same type in the correct position, does not exist. All crystals have some defects. Defects contribute to the mechanical properties of metals. In fact, using the term "defect" is sort of a misnomer since these features are commonly intentionally used to manipulate the mechanical properties of a material. Adding alloying elements to a metal is one way of introducing a crystal defect. Nevertheless, the term "defect" will be divided into 3 types in this topic [1].

1.2 Types of defects

The defects can divide on three types (Internal, External and Weld defects)

1.2.1 Internal defects

The internal defects can also be divided in different categories:

1.2.1.2 Crystallographic defects: Are divided on four categories as following:

a) Point Defects.

b) Substitutional impurity atom.

c) Linear Defects–Dislocations.

　▪ Planar Defects: Grain Boundaries in Polycrystals.

d) Bulk Defects: Bulk defects occur on a much bigger scale than the rest of the crystal defects. Voids are regions where there are many atoms missing from the lattice (Fig I. 1) [1].
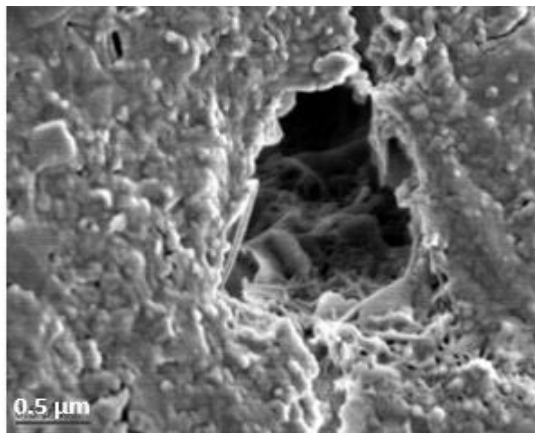
Figure I. 1. A void in a piece of metal the image was acquired
using a Scanning Electron Microscope [SEM] [1].

1.2.1.2 Primary Production Defects

Defects may be introduced when raw materials are made into a shape suitable for further processing. The main defects types may be classified into the following:

- **Segregation**: The distribution of chemical elements in ingots may not be uniform and some regions may become enriched in certain elements or phases while other regions are impoverished (Fig I. 2). It can be microscopic or macroscopic in nature [6].
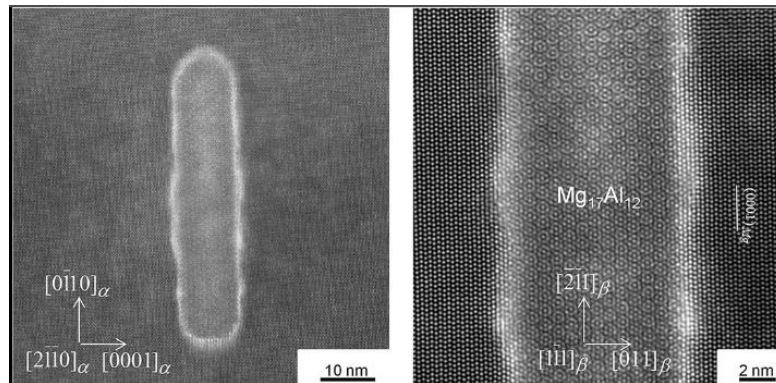
Figure I. 2. Image of Magnesium alloys Mg17Al12
response Segregation Ag addition (SEM) [28].

- **Holes and porosity:** Molten metal has a much higher solubility of gas than the solid. As a result, a proportion of the gas that becomes dissolved in the molten state becomes ejected and trapped on solidification (Fig. I. 3) [5].
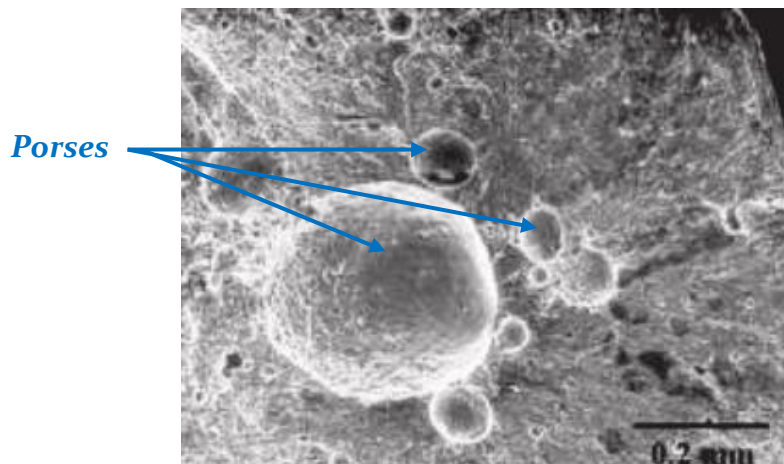
Figure I. 3. Image of air porosity in Al alloy (SEM) [20].

▪ **Inclusions:** There are two different types of inclusion, indigenous and exogenous. Indigenous inclusions are small intermetallic particles such as sulfides, oxides and silicates formed by chemical reactions between the various constituents of the alloy and with the atmosphere (Fig I. 4) [1].
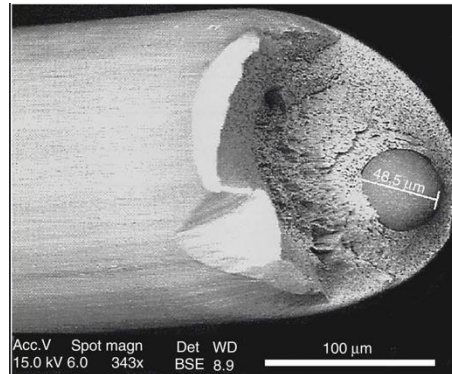
Figure I. 4. Fracture caused by a large Non-Metallic Inclusion during cold drawing of steel wire. The approximate size of the inclusion is indicated. SEM, Backscattered Electrons (BE) [28].

1.2.2 External defects

1.2.2.1 Primary Production Defects: The main types are:

- **Shrinkage and piping defects:** Solidification from the outer inward, as it in turn cools and contracts (Fig I. 5), a depression is formed in the top [6].
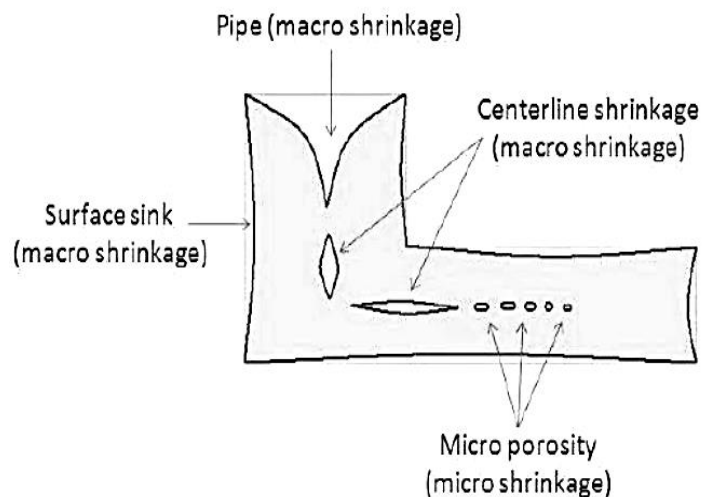
Figure I. 5. Schematic mechanism of Shrinkage developed after casting steel [28].

- **Shrinkage and hot tears:** This phenomenon represent the formation of an irreversible failure (crack) in the steel semisolid casting [6].

- **Surface defects**: Generally related to the deep drawing, pressing and cold rolling operations being used [3].

1.2.2.2 Defects Introduced in Service: The most common types are:

- **Pitting**: Is the deterioration of a metal surface, confined to a point or small area, results in the formation of a cavity or hole in the material (Fig I. 6) [6].
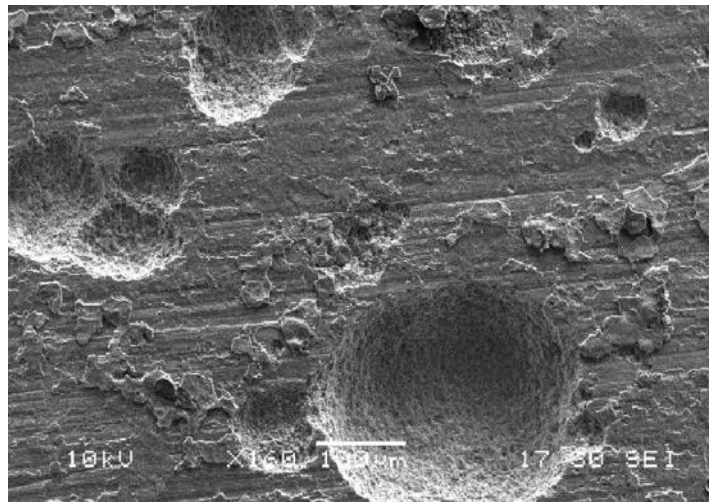
Figure I. 6. SEM micrographs of pitting corrosion in
high temperature/high-pressure process vessels [25].

- **Uniform Deterioration:** Uniform deterioration is characterized by corrosive attack that occurs evenly over the entire surface area [7].

- **Crevice Deterioration:** Is form of localized corrosion occurring at locations where easy access to the bulk environment is prevented [27].

- **Fatigue:** Metal fatigue occurs when metal parts are weakened due to repeated stresses, which can be divided into five groups [5].
  - ► **Environmental Cracking**
  - ► **Stress Corrosion Cracking.**
  - ► **Corrosion Fatigue.**
  - ► **Hydrogen Embrittlement.**
  - ► **Galvanic corrosion**.

1.2.3 Welding defects

1.2.3.1 Introduction: A weld discontinuity is defined as "an interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics". Welding defects are a type of discontinuity that compromises the usefulness of a weldment. Welding defects can be welding process-procedure-related or related to the chemical composition or metallurgy of the alloy(s) being welded [8].

1.2.3.2 Types of welding defects: We can highlight the height main types:

a) **Weld Crack:** It can appear on the surface, in the weld metal or the area affected by the intense heat. There are different types of crack:

- **Hot cracks**: These can occur during the welding process or during the crystallization process of the weld joint[8].

- **Cold cracks**: These cracks appear after the weld has been completed and the temperature of the metal has gone down. They can form hours or even days after welding (Fig I. 7) [9].
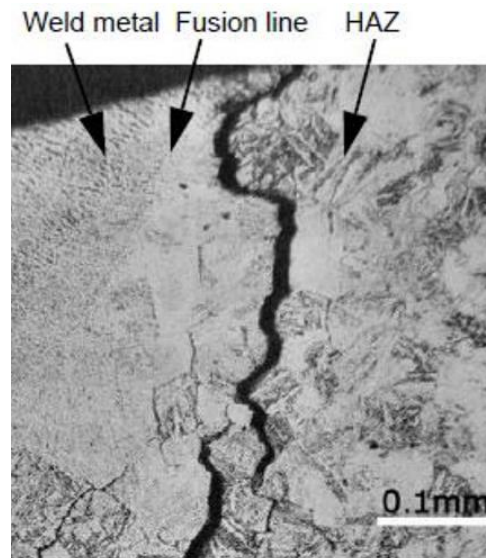
Figure I. 7. Typical SR cracks occurring in a 780-MPa high tensile strength steel weld (PWHT: 600°C × 2 h) [5].

b) **Weld Porosity:** Weld metal porosity is a cavity-type of welding defect formed by gas entrapment during solidification as a result of contamination by certain gases, such as hydrogen, oxygen, or nitrogen [9].

c) **Weld Undercut:** This welding imperfection is the groove formation at the weld toe, reducing cross-sectional thickness of the base metal [10].

d) **Incomplete fusion:** This type of welding defect occurs when there's a lack of proper fusion between the base metal and the weld metal [1].

e) **Incomplete penetration:** Incomplete penetration occurs when the groove of the metal is not filled completely [8].

f) **Slag inclusion:** Is one of the welding defects that are usually easily visible in the weld. occur when the flux, which is the solid shielding material used when welding, melts in the weld or on the surface of the weld zone [9].

g) **Spatter:** Spatter occurs when small particles from the weld attach themselves to the surrounding surface. It's an especially common occurrence in gas metal arc welding. No matter how hard you try, it can't be eliminated. However, there are a few ways you can keep it to a minimum [9].

1.3   Methods of analyzing defects (Non-destructive Test)

1.3.1 Introduction

Non-Destructive Testing (NDT) is a mechanism used by engineers to detect defects in materials and structures, either during manufacturing or while in service. Typically, the methods used such as UT, radiography, MPI, EDT and visually [10].

1.3.2 Visual Testing

a) **Description of the methods:** Visual Testing is the most widely used method of non-destructive testing (NDT). Large sections of industry tend to take visual testing for granted and pay little attention to training it can divide to:

- Direct viewing – viewing of an object in the operator's immediate presence.
- Remote viewing – this can only be done using special equipment [10].

b) Advantages and disadvantages of visual inspection

Advantages	Disadvantages
Can be a very simple but effective, not need expensive equipment or training.	Many variables can lead to discontinuities being missed.
Many different surface-breaking discontinuities can be found.	It relies totally on the human factor.
Virtually any component can be examined anywhere on the surface	Sub-surface flaws will not be seen.

Table I. 1. Advantages and disadvantages of Visual Inspection [15].

1.3.3 Radiographic Testing

a) **Description of the method:** Radiographic Testing (RT) is a non-destructive testing (NDT) method which uses either X-Rays or gamma rays to examine the internal structure of materials identifying any defects. (Fig I. 8 & 9) [9].
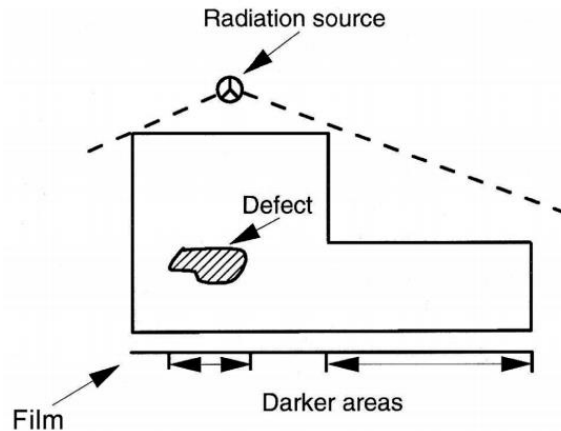
Figure I. 9. Resultant radiograph [8].
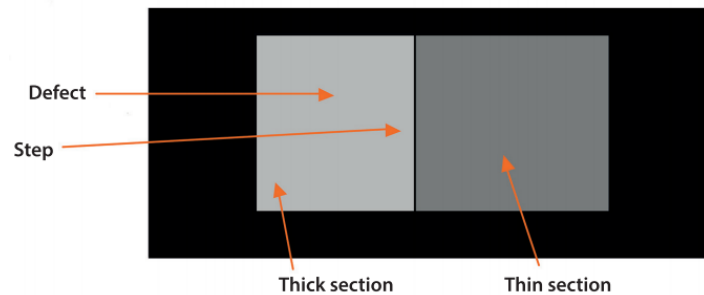
Figure I. 8. Variation of different levels of radiation reaching film – side elevation [8].

a) Advantages of industrial Radiography

Advantages	Disadvantages
Radiography can be used with most solid materials.	Radiography can only detect defects that are in a certain orientation.
Radiography has the ability to detect internal flaws.	Radiography has difficulty detecting very small defects.
Radiographic is being carried out improves the quality of welding	It is impractical to examine parts of complex geometry.

Table I. 2. Advantages and disadvantages of Radiography Inspection [9].

1.3.4 Magnetic Particle Inspection

a) Description of the method:

Magnetic Particle Inspection, involves "magnetizing" or placing a magnetic field into a part, and then reading the strength of the implanted magnetic signal. Since areas with surface defects will allow air into the cracks or scratches (Fig I. 10) [12].
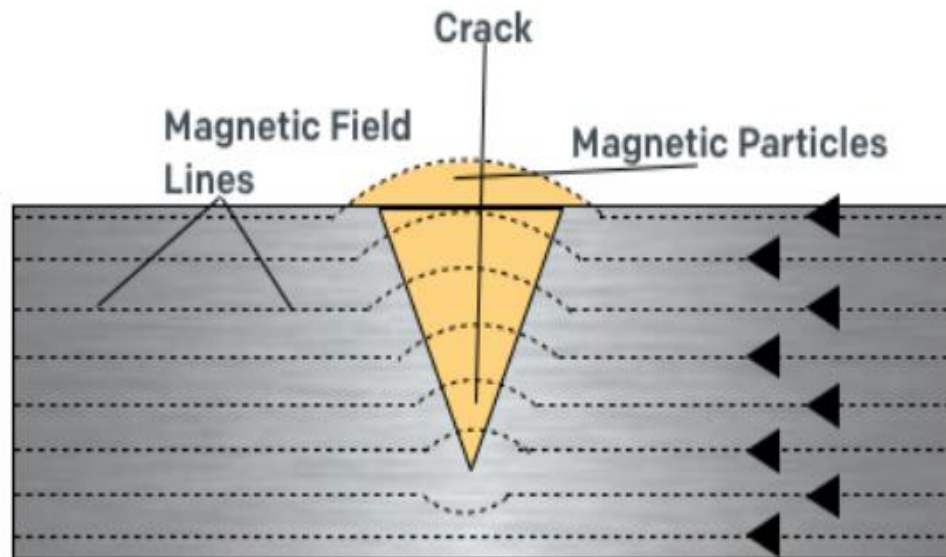
Figure I. 10. Magnetic field lines and magnetic flux leakage [12].

b) Advantages and disadvantages of MPT:

Advantages	Disadvantages
It is highly portable, generally inexpensive.	The material that is being tested must be ferromagnetic.
MPT is one of the best options for detecting fine, shallow surface cracks.	The method only detects surface and near-to-surface defects.

Table I. 3. Advantages and disadvantages of MPI Inspection [16].

1.3.5 Liquid Penetrant Testing

a) Techniques and Methodology: Modern liquid penetrant inspection, or dye penetrant inspection, utilizes fluorescent dye that is applied on a part and drawn into the surface flaws by capillary action (Fig I. 11) [12].
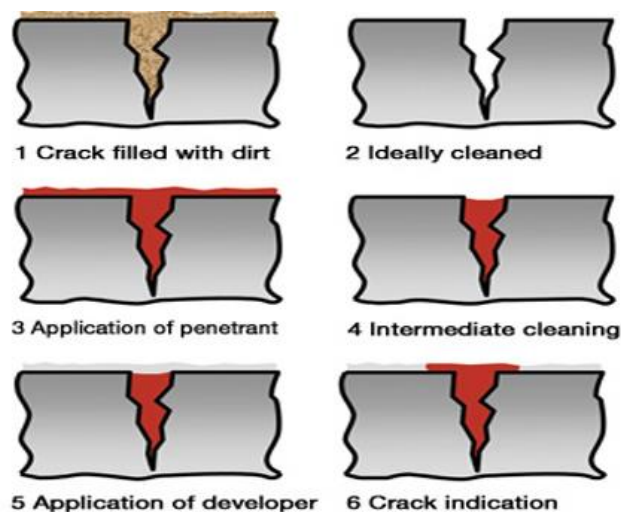
Figure I. 11. Schematic representing the steps for Liquid Penetrant Testing [12].

b) Advantages and disadvantages of penetrant testing

Advantages	Disadvantages
Very sensitive method	Can only detect defects open to the surface.
Can be use on magnetic and non-magnetic metals	The method takes time and can rarely be completed in less than 30 min.
Small objects, with awkward shapes, can be inspected.	The method cannot normally be applied to painted objects.

Table I. 4. Advantages and disadvantages of LPT [10].

1.3.6 Infrared Thermography

a) Techniques and Methodology: Implementation Focal Plan Array IR cameras, which allow the simultaneous recording of the temperature time histories of hundreds of thousands points on the tested structure surface [21].

Photothermal converter thin film

Composite with two metallic inserts
50 µm x 20 mm x 20 mm

Microwave source of power P_0

P_0

$P_0/10$

depth = 1.92 mm

depth= 3.84 mm

(a)

(b)

(c)

Infrared camera

(a) Principle of the visualisation of an EM field by EMIR method

(b) Thermographic NDE classical front-face configuration by direct monitoring of the sample surface

(c) EMIR detection of defects by monitoring of the EM field resulting from the incident and reflected EM fields near of the sample surface

Incident EM energy density
110 mW cm^{-2}

Incident EM energy density
17 mW cm^{-2}

Figure I. 12. Visualizing the intensity of an X-band (centimeter wavelength) electric field by using an IR camera and a photothermal converter [21].

1.4 Partial Conclusion:

When comparing destructive and nondestructive testing, destructive testing is, in some ways, the most reliable method. However, nondestructive testing (NDT) retains a significant advantage over destructive testing because it covers more ground and saves on material costs.

Chapter II

Eddy Current Testing and Ultrasonic Testing

2.1 Introduction:

Detecting, quantifying, and sizing indications characterized as a "crack" in critical equipment have long been the global benchmark of asset integrity programs. Therefore, the increased precision that inspection programs obtain using advanced technologies can dynamically improve the overall assessment. Cracks open to the surface have traditionally been inspected with conventional nondestructive testing methods like Penetrant Testing (PT) and Magnetic Testing (MT). As in many procedures, secondary methods may be used to verify, qualify, or quantify indications. A derivative method of MT, Eddy Current Testing (ECT) and Ultrasonic Testing (UT), are also widely used to detect cracks in various materials by using a similar flux leakage principle [8]. In this chapter II, we will discuss theoretically these methods.

2.2 Description and methods of Eddy Current

2.2.1 Basic principles of Eddy Current testing:

The current in the second coil was, in fact, a current that was induced by the first coil (Fig II. 1 and 2). Michael Faraday had managed to produce an electric current in a secondary coil by changing the magnetic field surrounding a primary coil [12].
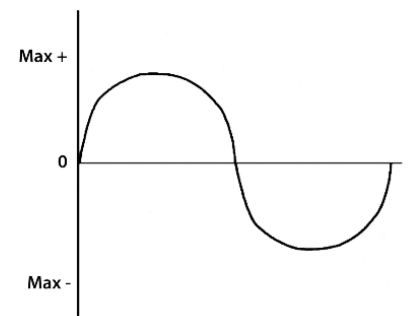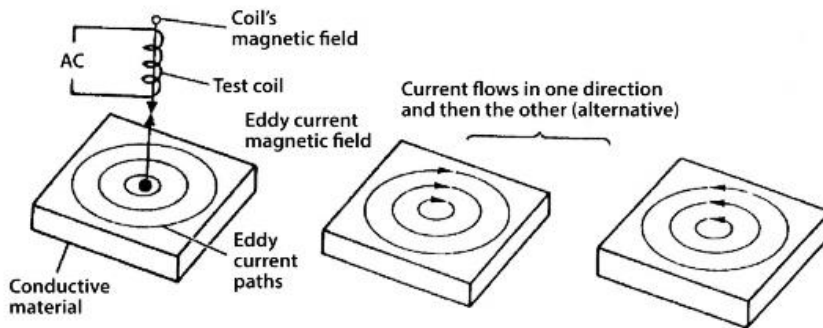
Figure II. 1. A primary coil inducing
eddy currents in a component [8].

Figure II. 2. AC sine wave [8].

Magnetic theory forms a large part of eddy current theory – the basis of eddy current testing is electromagnetic induction. Eddy currents can only be formed when using an alternating current (AC) as the current in the primary coil needs to constantly vary, *i.e.* zero to maximum positive and back to zero – zero to maximum negative and back to zero, which is known as a *sine wave* (Fig II. 2)[4].

Eddy current testing uses this basis by using a primary coil to induce eddy currents in the component under test. For this to happen, the component under test must be electrically conductive. Metals are good electrical conductors, but the conductivity of different metals varies considerably. The higher the conductivity, the more current is induced into the metal [1].

When using eddy currents, it is the change in impedance that is measured. Impedance is a combination of two properties: resistance in the wire of the coil and the inductive reactance of the coil (this is the effect caused by the AC current lagging behind the AC voltage).

The resistance will not vary much but there are variables that can greatly affect inductive reactance:

- The number of turns of wire in a coil.
- The size of the coil.
- The amount of current in the coil.
- The frequency of the current in the coil (frequency is the number of cycles per unit time, ie sine waves per second) [8].

To summarize, if a primary coil is placed near an electrically conductive metal sample, eddy currents will be induced into the sample. The eddy currents will produce a secondary magnetic field in the sample and, if this secondary magnetic field changes (there may be an interference such as a surface crack for example), then the impedance of the coil will change. These changes in impedance can then be detected and measured.

The magnetic field that surrounds the inspection coil is at its strongest next to the coil and gets progressively weaker the further away it is; therefore, the depth of penetration of eddy currents is limited [12].

If any of these metals are alloyed, the conductivity can change dramatically. (The only exception to this is stainless steel). The depth of penetration can be increased by reducing the coil's frequency (Fig II. 3). This has the effect of changing the magnetic field more slowly and so has less opposition by secondary magnetic field (Table II. 1).
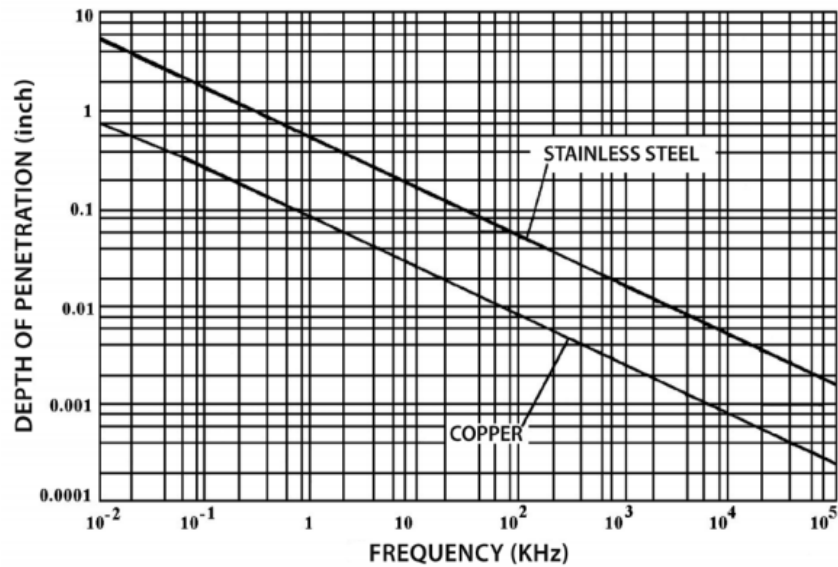
Fig II. 3. Curve representing depth of penetration of EC Vs frequency [8].

2.2.2 Common applications:

- Weld Inspection
- Conductivity Testing
- Surface Inspection
- Corrosion
- Bolt Hole Inspection
- Tubing inspection [2].

2.2.3 Eddy Current Instruments

Eddy current instruments can be purchased in a large variety of configurations. Both analog and digital instruments are available.

Instruments are commonly classified by the type of display used to present the data. The common display types are analog meter, digital readout, impedance plane and time versus signal amplitude. Some instruments are capable of presenting data in several display formats [2].
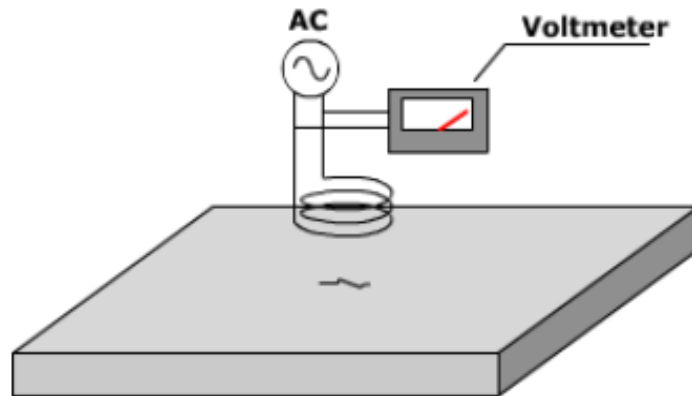
Figure II. 4. Principal system of ECT [8].

2.2.4 Display - Complex Impedance Plan. Electrical Impedance (Z), is the total opposition that a circuit presents to an alternating current. Impedance, measured in ohms, may include resistance (R), inductive reactance (XL), and capacitive reactance (XC) as shown in Equation (2.1). Eddy current circuits usually have only R and (XL) components. As discussed in the page on impedance, the resistance component and the reactance component are not in phase, so vector addition must be used to relate them with impedance. For an eddy current circuit with resistance and inductive reactance components, the total impedance is calculated using the following equation [3].

$$Z = \sqrt{R^2 + X_L^2} \qquad\qquad (2.1)$$
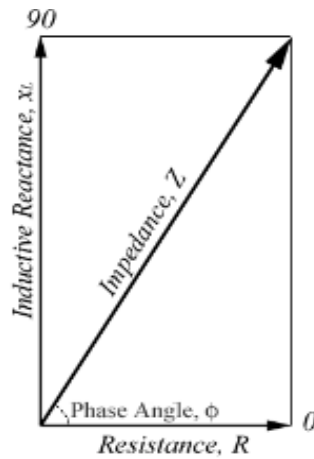
Figure II. 5. Eddy current Impedance plan responses [8].

You will recall that this can be graphically displayed using the impedance plan diagram as seen above. Impedance also has an associated angle, called the phase angle of the circuit, which can be calculated by the following equation [12].

$$\text{Tan } \emptyset = \frac{X_L}{R} \qquad (2.2)$$

The impedance plan diagram is a very useful way of displaying eddy current data. As shown in the figure below, the strength of the eddy currents and the magnetic permeability of the test material cause the eddy current signal on the impedance plan to react in a variety of different ways [3].
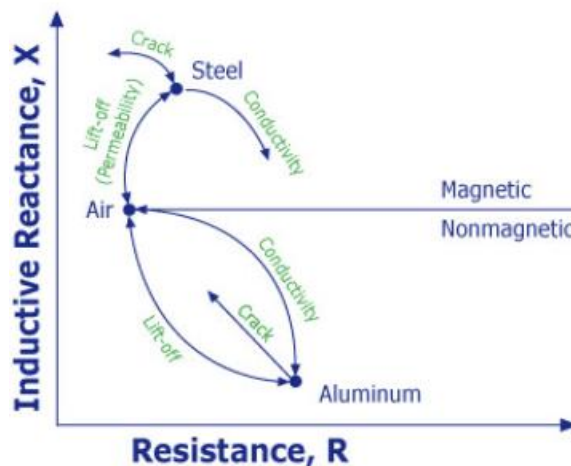
Figure II. 6. Eddy current Impedance diagram responses [8].

If the eddy current circuit is balanced in air and then placed on a piece of aluminum, the resistance component will increase (eddy currents are being generated in the aluminum and this takes energy away from the coil, which shows up as resistance) and the inductive reactance of the coil decreases (the magnetic field created by the eddy currents opposes the coil's magnetic field and the net effect is a weaker magnetic field to produce inductance). If a crack is present in the material, fewer eddy currents will be able to form, and the resistance will go back down, and the inductive reactance will go back up. Changes in conductivity will cause the eddy current signal to change in a different way [8].

2.2.5 Probes - Mode of Operation: Absolute probes generally have a single test coil that is used to generate the eddy currents and sense changes in the eddy current field. When the probe is positioned next to a conductive material, the changing magnetic field generates eddy currents within the material. The generation of the eddy currents take energy from the coil and this appears as an increase in the electrical resistance of the coil. The eddy currents generate their own magnetic field that opposes the magnetic field of the coil and this changes the inductive reactance of coil. Absolute coils can be used for flaw detection, conductivity measurements, liftoff measurements and thickness measurements. They are widely used due to their versatility (Fig II. 7) [1].
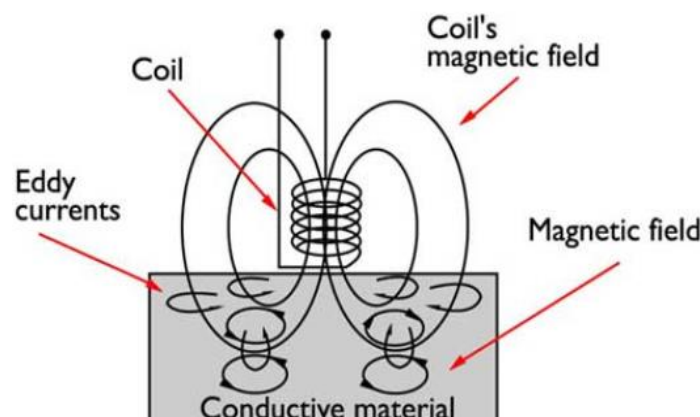
Figure II. 7. Diagram illustrating Eddy Currents created in a port [23].

2.2.6 Differential Probes: Eddy current probes are classified by the configuration and mode of operation of the test coils. The mode of operation of a probe generally falls into one of four categories as below Figures:
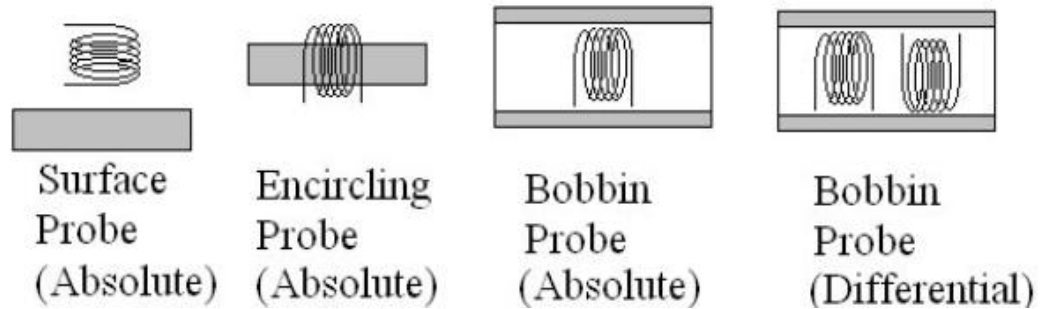
Figure II. 8. Differential eddy current probes [12].

2-3 Description and methods of Ultrasonic Testing

2-3.1 Description of the method:

Ultrasound is an ideal modality for Non-Destructive Evaluation (NDE) because it enables the interior of objects to be assessed without the safety and access issues associated with radiography. A basic ultrasonic measurement involves injecting a pulse of ultrasound into a component using a suitable transducer and then using the same transducer to record the returning echoes as a function of time, termed an A-scan [11].

2-3.2 Basic principles:

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements (Fig II. 9).

Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below will be used [1].
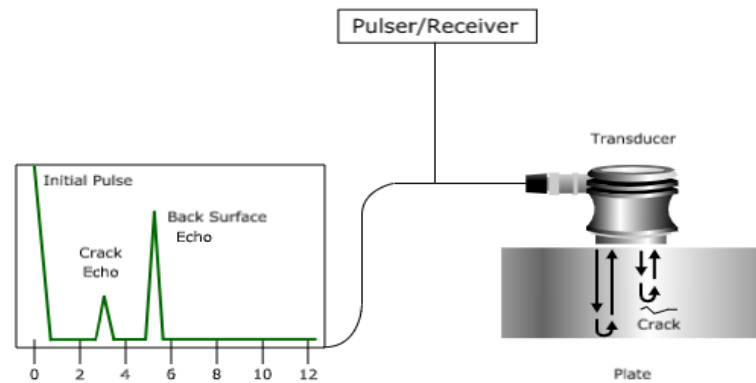
Table II. 9. Basic method of UT [22].

2.3.3   Ultrasonic techniques: There are several different types of ultrasonic testing, including:

▪ **Time-of-flight diffraction (TOFD):** Is an ultrasonic technique used to detect diffracted waves from crack tips and to size the cracks from the arrival times of those waves (Fig II. 10) [20].
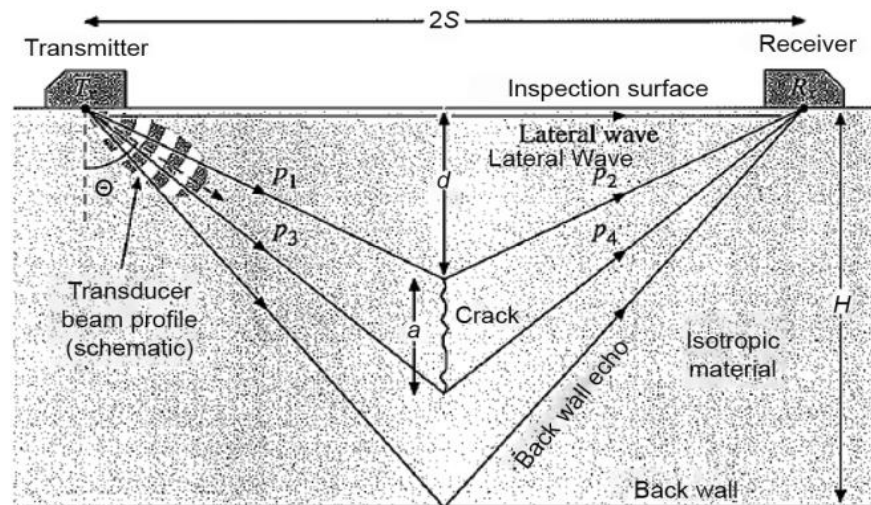
Figure II. 10. Typical arrangement for the time-of-flight diffraction technique [11].

▪ **Acoustic microscopy:** Is applied to high-resolution, high-frequency ultrasonic inspection techniques that produce images of features beneath the surface of a sample. Compared to conventional ultrasound imaging techniques, acoustic microscopes operate up to and beyond 1 GHz [10].
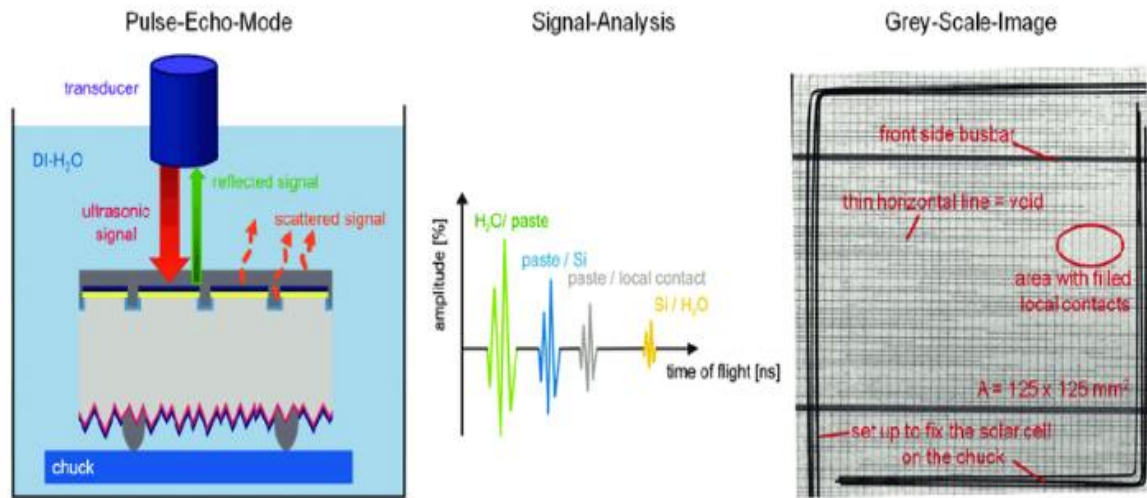
Figure I. 11. Sketch of the scanning acoustic microscopy (SAM) working principle shown on the left, the signal analysis in the center, leading to a grey-scale image shown on the right [23].

- **Automated Ultrasonic Backscatter Technique (AUBT)**: Is a UT technique developed for detecting damage from High-Temperature Hydrogen Attack (HTHA). The technique is for use in pressure vessels and piping using of high frequency, broadband UT probes and a digital oscilloscope (Fig II. 12). It's provides both an A-Scan display and frequency analysis [19].
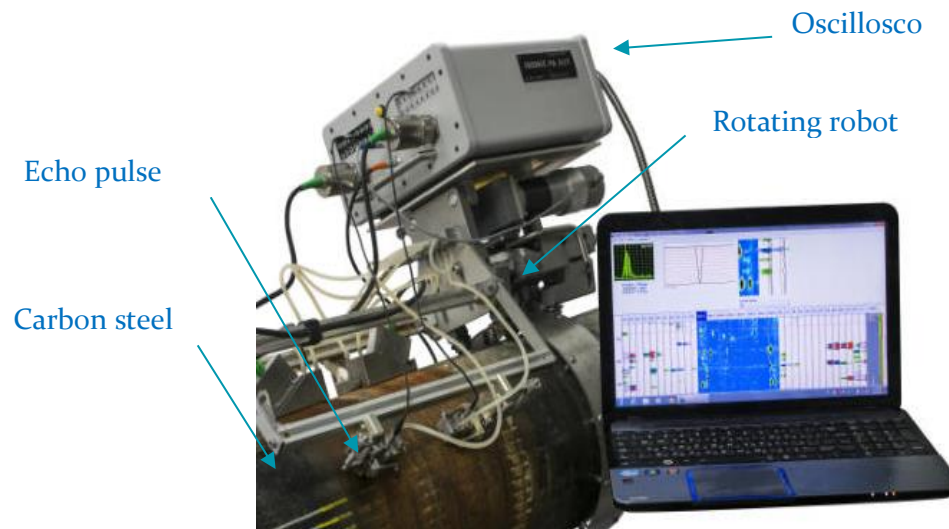
Figure I. 12 Ultrasonic Inspection (AUT) systems combining Phased Array (PA) [23].

- **Phased Array Ultrasonic Testing (PAUT):** Is a UT technique that utilizes a set of UT probes made up of numerous (anywhere from 16 to over 250) small elements (Fig II. 13). Each of the elements in a PAUT system is able to pulse individually. This is done with computer calculated timing, through a process known as phasing. This allows the system to steer focused beam through various angles and focal distances [1].
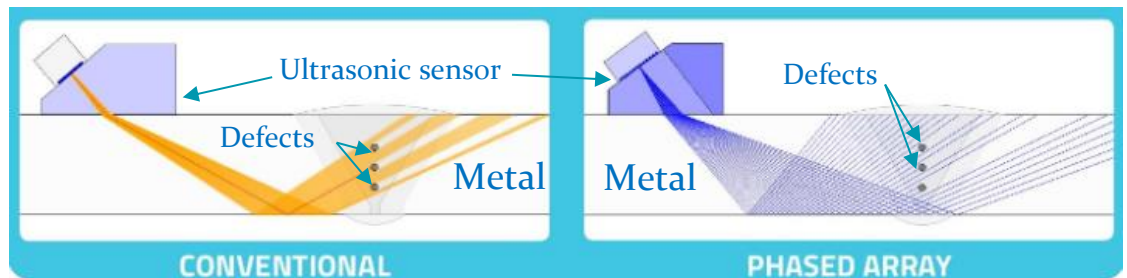
Figure I. 13. Probe of Phased Array Ultrasonic Testing Vs conventional [26].

- **Long Range Ultrasonic Testing (LRUT):** Is a UT method developed to allow for testing large volumes of material from a single test point. This method works by fix transducer rings uniformly around a pipe (Fig II. 14). These rings then generate a series of low frequency guided waves which can then propagate symmetrically along the pipe axis [2].
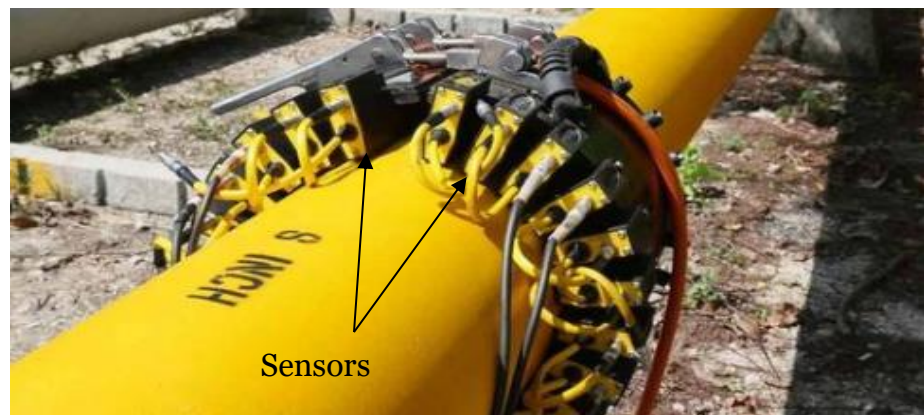
Figure II. 14 Probes of Long-Range Ultrasonic Testing (PLRUT) in oil and gas [25].

- **Internal Rotating Inspection Systems (IRIS):** Is an ultrasonic technique used to detect corrosion in piping and tubing. using an internally inserted probe that generates sound waves (Fig II. 15).
  The system works by inserting a probe into a flooded pipe [3].
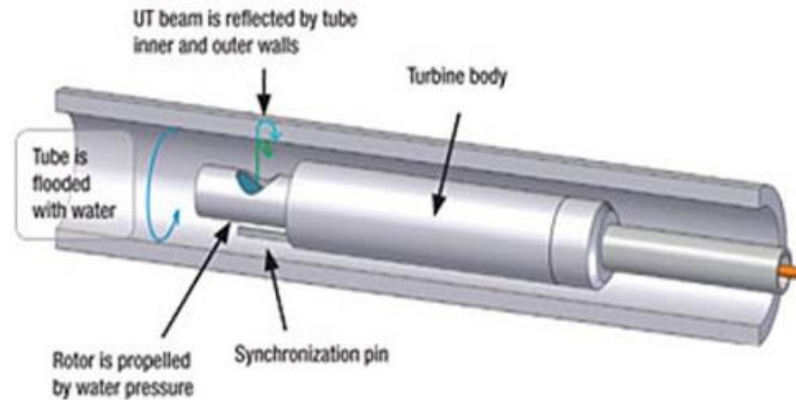
Figure II. 15. Probe of Internal Rotating Inspection System [9].

- **Dry-Coupled Ultrasonic Testing (DCUT)**: is an alternative, low-cost method that does not require a liquid couplant to inspect metallic and nonmetallic material (Fig II. 16) [21].
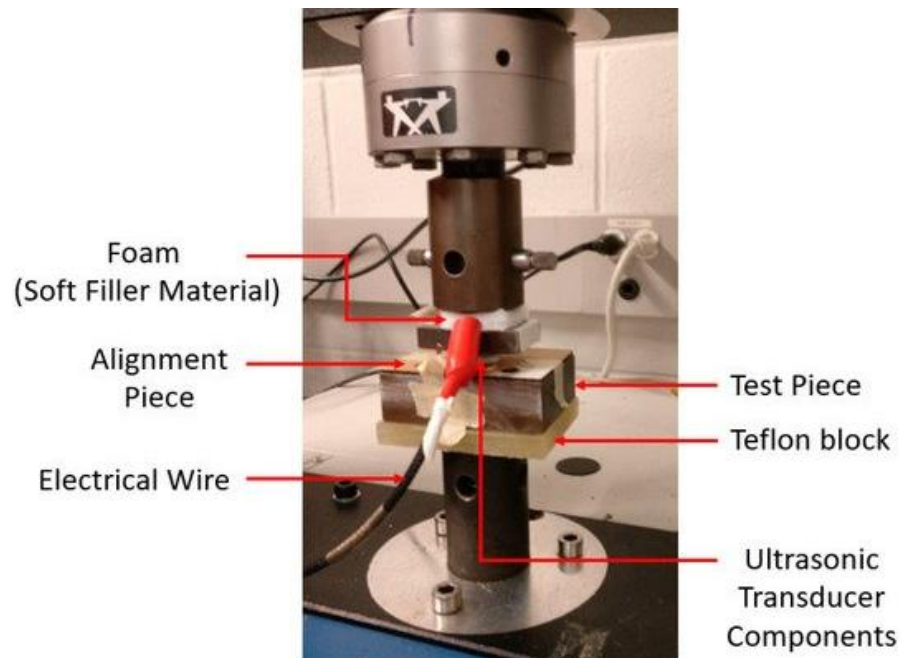
Figure II. 16. Dry Coupling of Ultrasonic Transducer Components for High Temperature Applications [20]

- **Rapid Ultrasonic Gridding (RUG):** is an NDE method of performing ultrasonic thickness in which multiple ultrasonic thickness probes are utilized, simultaneously, to rapidly gather thickness measurements in a predefined or ad hoc space (Fig II. 17) [19].
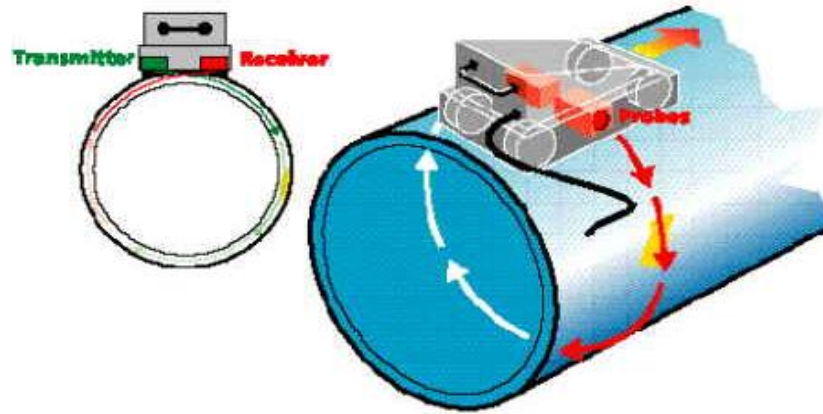
Figure II. 17 Rapid Ultrasonic Gridding of Pipe [16]

2-3.4 Advantages of ultrasonic inspection:

- Penetration of ultrasound into materials can detects the deep-lying defects.

- The method is very sensitive and can locate very small defects.

- The nature, shape and orientation of the defect can be determined.

- The entire volume is scanned from the front to the back surface [11].

2-3.5 Disadvantages of ultrasonic inspection:

- It is often difficult to interpret a defect signal.

- Single-crystal probes have a dead-zone in which defects will not be detected.

- Calibrate the equipment, reference standards is needed.

- Requires removal before further processing can occur, i.e. ainting/coating [10].

2-4 Conclusion:

In this chapter II, we discussed both NDT technic Ultrasonic Testing(UT) and Eddy Current Testing (EDT) and there methods and Materials, we can say thatUltrasonic Testingare commonly used for inspection the defects in welded joints such as: porosity, slag inclusions, lack of side-wall fusion, lack of inter-run fusion, lack of root penetration, undercutting, and longitudinal or transverse cracks. It's generally works by emitting waves into a material. By measuring these waves, the properties of the material and internal flaws can be identified. Most UT devices consist of many separate units. These can include pulsers and receivers, transducers, and display monitors. The components included depend on the type of UT that the inspector is performing.

But Eddy Current Testing Commonly used for a variety of applications such as the detection of cracks (discontinuities), measurement of metal thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness, and the measurement of electrical conductivity and magnetic permeability. Eddy current inspection is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known [1]

Chapter III

Materials and experimental procedure

3-1 Introduction

In this chapter III, I'm explaining how to experience both devices created using two techniques, Ultrasonic Testing (UT) and Eddy Current Testing (ECT) techniques.

The first technique I have chosen is UT which has the prominent role innondestructive testing with ultrasonic has won because of the application versatility, sensitivity and convenience. It has become evident that it is practical and cost effective to expand the role of the testing to include all aspects of materials and structures production and application.

The second technique is Eddy Current Test. This process requires a prior calibration procedure which I performed in the specialized center named "CRTI", this procedure must follow these steps:

    a. Building the EC probe.
    b. Test probe in air (void test).
    c. Characterization of probe with deferent metals to check the required frequency to be used while inspection.
    d. Test the probe with cracks using calibration block.

The above steps performed in the ECT laboratory, in similar conditions to the real test, to obtain databases for comparing and interpreting the signals response seeing on the part being tested and assures the test system sensitivity is sufficient to detect the required crack size. In order to improve accuracy of results out of laboratory, I added Oscilloscope to my chain of test (EDT device).

However, inspection a piece of metal with cracks and exact size can be an arduous task due to the difficulty incontrolling the dimensions. Meanwhile, using my simple equipment, I successfully assembled my tool of test to achieve an acceptable result. According to the tests which I performed during this experience, I used an artificial defect which is prevalent practice torepresent real defects in calibration procedure and creation of a database.

3-2 Development of defect detector with ultrasonic method.

3-2.1 Ultrasonic sensor HC-SR04

Ultrasonic Sensor HC-SR04 is a sensor that can detect a visible crack (or structure interruption) (Fig III. 1). It emits an ultrasound at 40 000 Hz (40kHz) which travels through the air and if there is an object or obstacle on its path it will bounce back to the module with different waves. If the object has hole (structure interruption) which bounce back the waves, considering this signal as defect.

The configuration pin of HC-SR04 is VCC (1), TRIG (2), ECHO (3), and GND (4). The supply voltage of VCC is +5V and you can attach TRIG and ECHO pin to any Digital I/O in your Arduino Board [21].
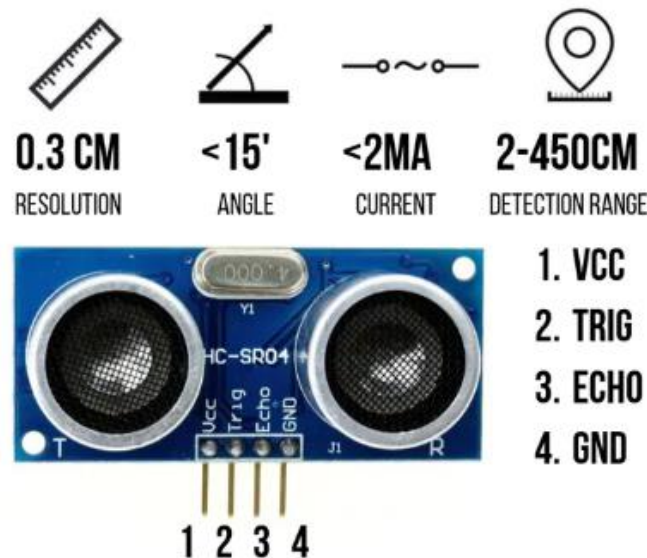
Figure III. 1. Ultrasonic sensor HC-SR04
configuration and specification [26].

3-2.2 Arduino UNO R3 CH340

a) **Introduction:** Because Arduino UNO is an essential component in my device, which is microcontroller board based on 8-bit ATmega328P microcontroller (Fig III. 2), I needs a set up program as mentioned in next step.
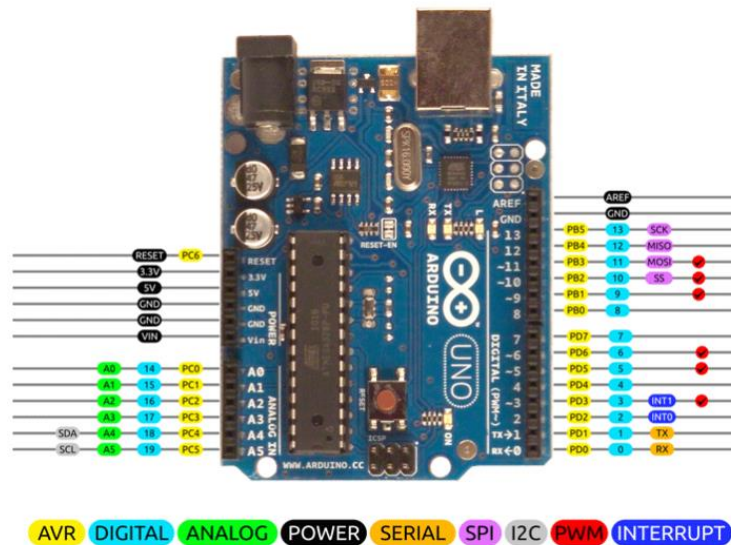
Figure III. 2. Schematic of Arduino Uno Pin [27].

b) Programing Arduino (using Sketch): A *sketch* is the name that Arduino uses for a program. It's the unit of code that is uploaded to and run on an Arduino board. For the programming code, first we need to define the Trigger Pin and Echo Pin that connected to Arduino board. In my project Echo Pin is attached to D2 and Trig Pin to D3. Then define variables for the signals (int) and duration (long).

▶ **Steps for programing Arduino:**

1. First wiring as shown in the picture (Figure III. 3).

2. Open Arduino IDE Software and write down the code.

3. Choosing Arduino Uno, by selecting Tools > Board > Arduino/Geniuno Uno (Fig III. 4).

4. Choosing COM Port (usually it appears only one existing port), Tools > Port > COM (Fig III. 5).

5. Upload the code by pressing Ctrl + U or Sketch > Upload.

6. To display the measurement data we can use Serial Monitor by pressing Ctrl + Shift + M (Baudrate speed is 9600) (Fig III. 6).

▶ The Codes used for set up Arduino per order (Fig III. 3):

Figure III. 3.Window of Sketch for set up Arduino UNO.
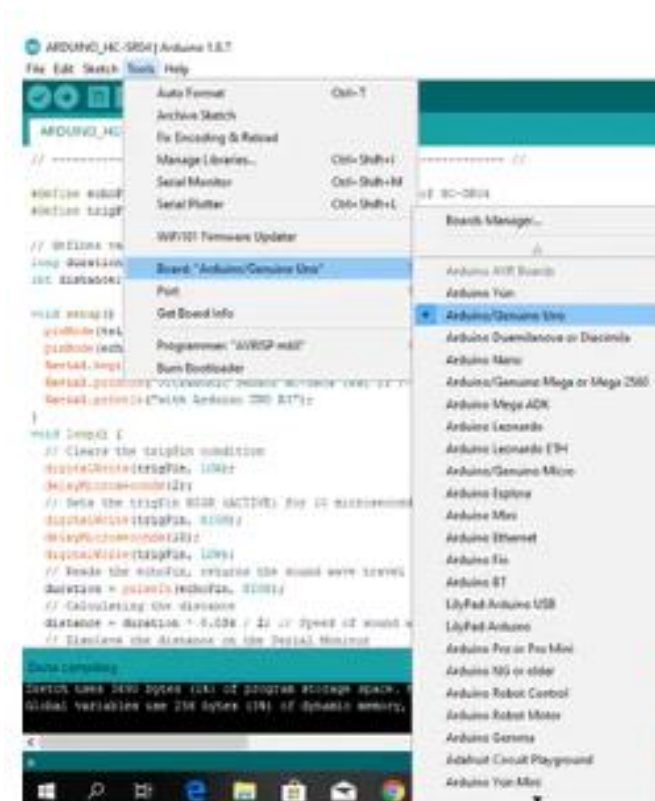
Figure III. 4.Choosing Arduino Board.

Figure III. 5. Select own Arduino COM

Figure III. 6.Uploading the code.

3-2.3 Jumper Wires

The Jumper wires are the connections between the Arduino and Ultrasonic Sensor HC-SR04 as following (Fig III. 7):
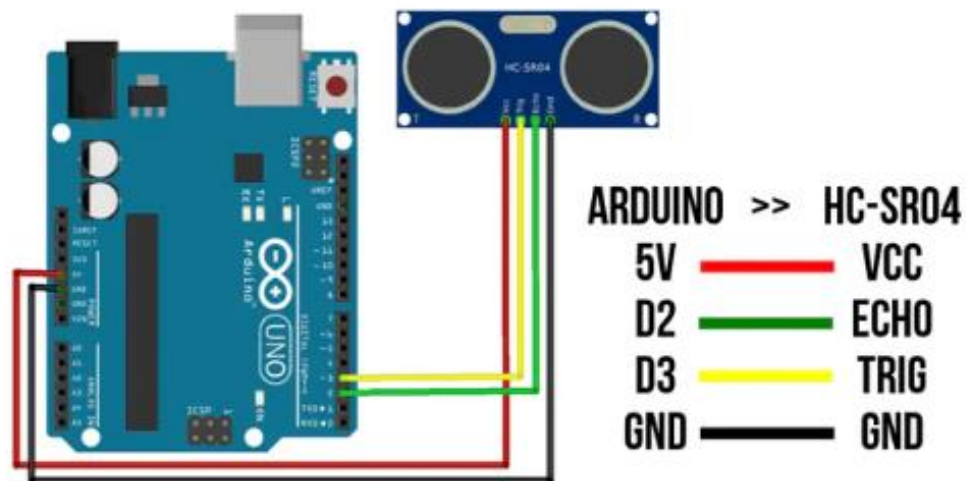
Figure III. 7. Schematic of Jumper wires.

3-2.4 Working principal.

Ultrasonic sensors use pulses of ultrasonic sound (sound above the range of human hearing) to detect the distance solid objects. The sensors consist of two main components:

- **An Ultrasonic Transmitter**: This transmits the ultrasonic sound pulses; it operates at 40 KHz (Fig III. 8).

- **An Ultrasonic Receiver:** The receiver listens for the transmitted pulses. If it receives them it produces an output pulse whose width can be used to determine the object bounced waves from object and pulse travelled (Fig III. 8).

The HC-SR04 has the following four connections:

- **VCC**: Is is the 5 Volt positive power supply.

- **Trig**:Is the "Trigger" pin, the one driven to send the ultrasonic pulses.

- **Echo**: Is the pin that produces a pulse when the reflected signal is received. The length of the pulse is proportional to the time it took for the transmitted signal to be detected.

- **GND** – This is the Ground pin.

Trig pin

10 µs Trigger pulse

Pulses from module

Eight 40 KHz sound waves generated from HC-SR

Echo pin

Time taken by pulse to leave and return back
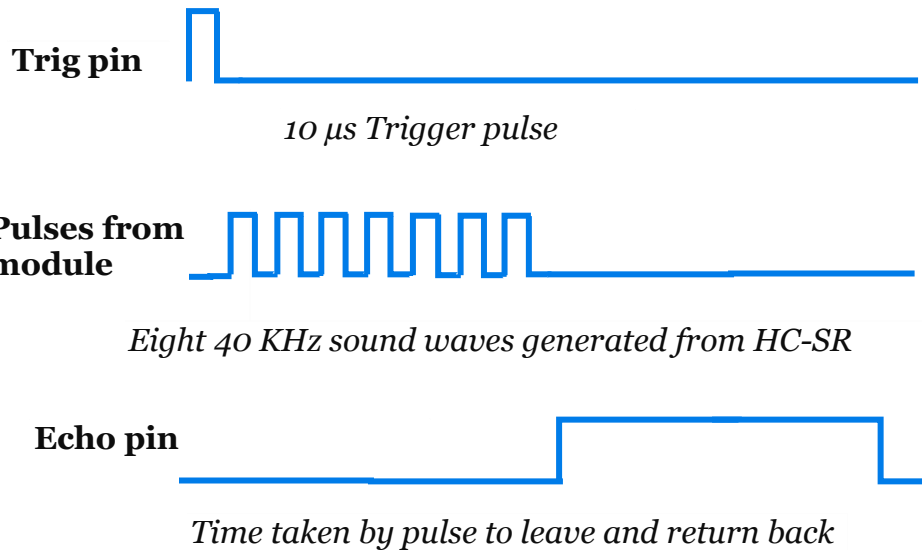
Figure III. 8. Ultrasonic HC-SR04 Timing diagrams.

▶ **In case defect:**

For example, in case of defect (hole) encountered in the material, if the object including a surface defect in front of ultrasonic sensor, the waves hits the object with speed of the sound is 340 m/s or 0.034 cm/µs the sound wave will need to travel about 588 microseconds thru the structure of object, if the discontinuity observed, a second wave generate due to change of structure changed. Which will be received accordingly. But when approach the sensor to the object, you will need to press reset button that's allow us to get the forwarded waves which bounce backward before the initial waves. So, in order to get the defect sign (visual and sound alert) must keep the distance between the sensor and object constant while sweeping sensor on surface (Fig III. 9).
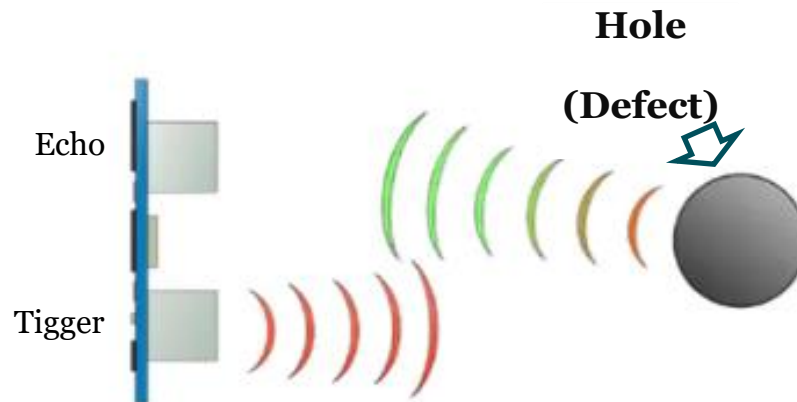
Figure III. 9. Ultrasonic HC-SR04 reflecting defect signal.

3-2.5 Set up and Code forRanging Test.

I wrote the Arduino IDE Software, saved it. Selected the port (COM5) and I chosemy Arduino board type (i.e. Arduino Uno) then compile it to my Arduino.

Figure III. 10. Ultrasonic HC-SR04with Arduino code.

3-2.6 Results

After uploading the code, display the data with Serial Monitor. Now we put an object in front of the sensor and see the measurement.
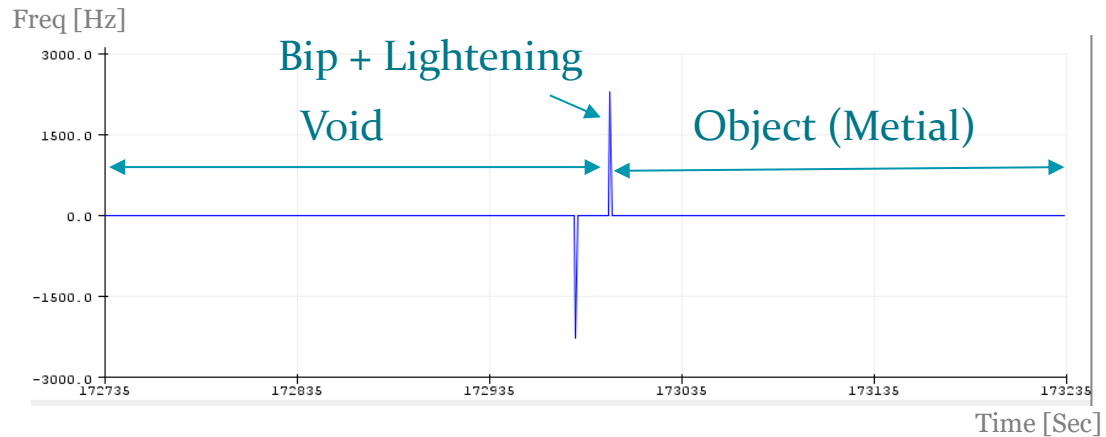
Figure III. 11. Ultrasonic HC-SR04 waves chart after swept
over piece of material (shot screen of Arduino program).
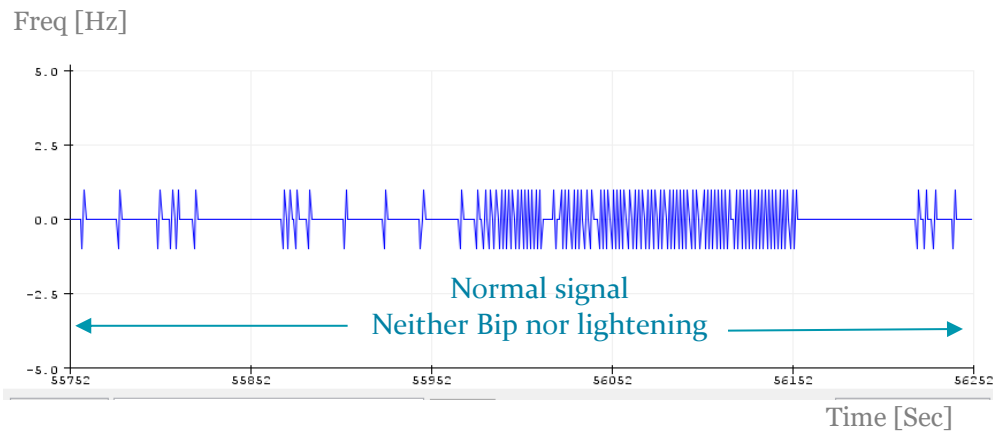
Figure III. 12. Ultrasonic HC-SR04 waves chart while
sweeping over piece of material.

Freq [Hz]

Hole in Material
(Bip + lightening)

Ampletude

3000.0

1500.0

0.0

-1500.0

-3000.0

11119   11219   11319   11419   11519   11619

Time [Sec]
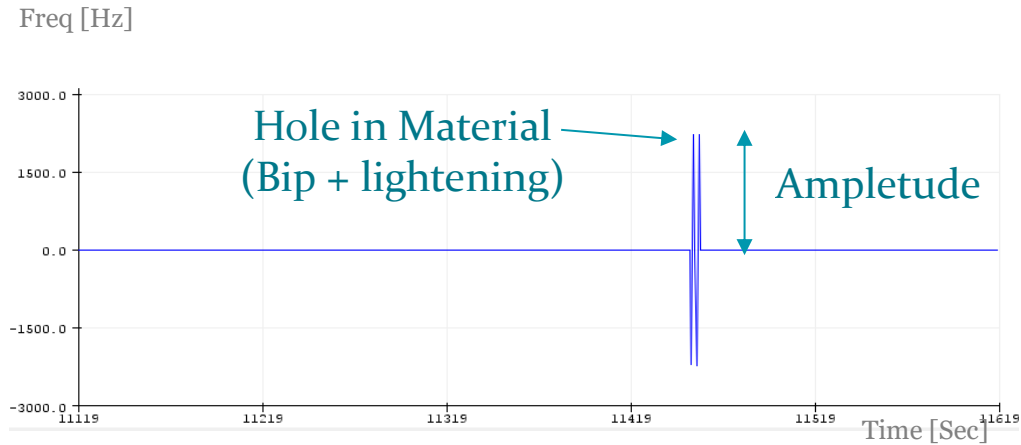
Figure III. 13. Ultrasonic HC-SR04 signal while detecting hole
at surface of material (shot screen of Arduino program).

3-2.7 Partial conclusion.

Visual Inspection and defect detection, it has a great impact in the industry of metallurgy which helping the chain productions of metals to be a very large sensitive to surface defects. Strengthen the primary product material with UT inspection is very useful, like in deep production of pipes. Because it can check defects very quickly.

3-3 Development of Eddy Current defect detector

3-3.1 Development of probe (sensor)

3-3.1.1 Principal of probe

The sensitivity to defects and other parameters of the parts control can be modified by the design of the probes. Eddy Current sensors are electrical windings which generate a magnetic field when powered by avariable signal. In non-destructive testing by eddy currents, we meet:

a) The coils, for the external control of tubes (or solid bars).
b) The probes for the internal control of tubes, or the control of flat parts.

A sensor consists of an open magnetic circuit of high permeability, on which are wound one or more windings traversed by a variable current. The approach of a conductive part changes the distribution of the field lines and results by a variation in reluctance and the appearance of electromagnetic losses due to the penetration of the field inside the Metal [21].

3-3.1.2 Main parameters influencing on construction of sensors

The characterization of the material depends on the electrical conductivity [σ] and the magnetic permeability [μ] which must be considered. It also depends on the distance between the sensor and the part to be inspected. The frequency of excitation of the coil will be chosen taking into account the depths adequate penetration. The operating point on the impedance diagram allowsgood discrimination of the different parameters [23].

In conclusion; when designing eddy current probes, has the following parameters:

• The position of the operating point on the impedance diagram.

• The inductance and resistance of the probe.

• The detection area.

•The variation in sensitivity in the presence of a core (ferrite) [2].

3-3.1.3   Choice of probe shape

We assimilate the resulting magnetic field to a material point, we minimize the lateral field, hence the choice of circular shape for the construction of the probes (Fig III. 15). The diameter of the winding wire was chosen so as to increase the inductance clean sensors (increase in the number of turns) and decrease the value of the resistance (heating by Joule effect). The use of ferrite as a core (support) sensor enabled:

- Increase the magnetic inductance (magnetic permeabilityimportant).
- To increase the magnetic flux (very low reluctance).
- To reduce the contact surface [1].

3-3.1.4   Realization of the sensor (Probe)

We opted for the control of flat parts, hence the need to use sensors. The realization of sensors is very important in the field of Non-Destructive by eddy currents. It allows both creating currents and collecting the signal, in our case we keep the contact surface constant, the induction is proportional to:

- Relative permeability (high, ferrite).

- The current (no accessibility).

- The number of turns (allowing significant tension).

In order to build a reliable sensor, we took the piece of Ferrite which has cylindrical shape (Φ = 8mm) and we have chosen 400 number of turns with 4 layers, by taking a wire of very small section 0.132 mm. the wire used is made with cupper coated with very thin isolator (Fig III. 15).
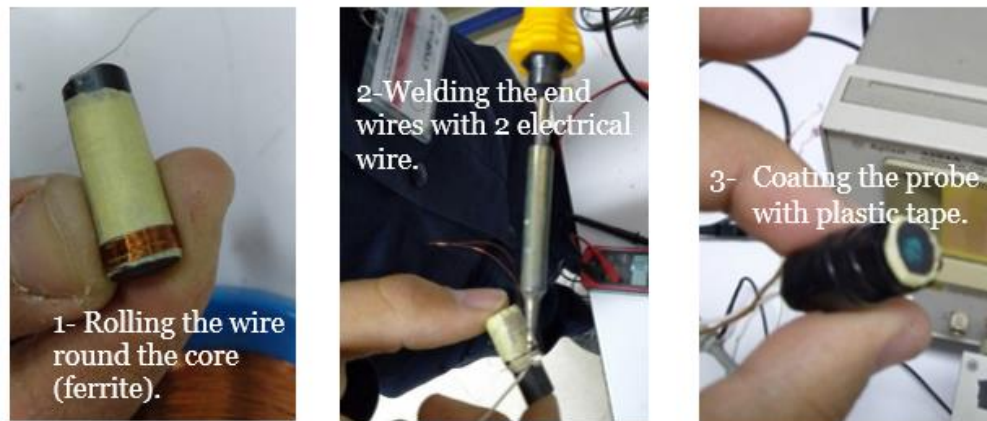
Figure III. 14. Steps of realize the probe.
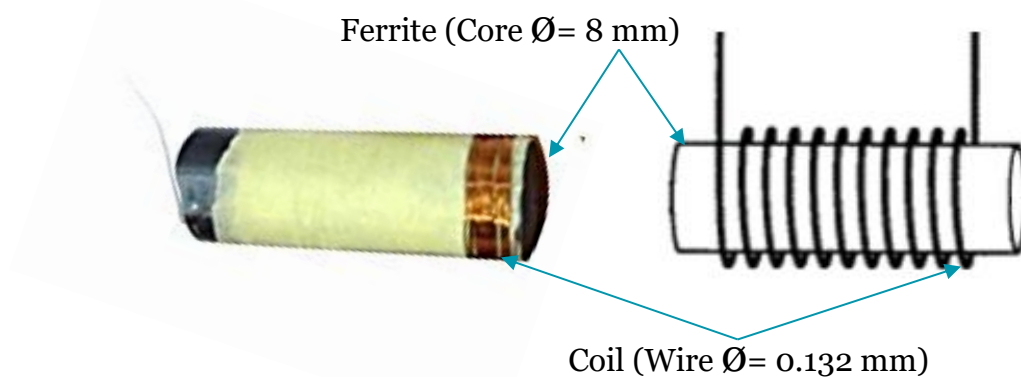
Figure III. 15. Form of Eddy current probe.

3-3.1.5 Partial conclusion

The realization of sensors is very important in the field of Non-Destructive Testing by eddy currents. It allows both to create currents and collect the signal, in our case we kept the contact surface constant, the induction is proportional to the relative permeability, the currents and the number of turns.

We increase the sensitivity and the field generated in the sensor by choosing specific geometry (Cylindric) and highly magnetic material by using (ferrite) section.

3-3.2   Choice of metal sample (specimen)

We have chosen two samples of metals to perform our Non-Destructive Tests which are widely used in industry as follows:

a) Steel duplex 2205

Grade 2205 stainless steel is a duplex stainless steel whose design enables combining improved resistance to pitting, high strength, stress corrosion, crevice corrosion and cracking. Grade 2205 stainless steel resists sulfide stress corrosion and chloride environments. [4].

Duplex steels are also magnetic, a property that can be used to easily differentiate them from common austenitic grades of stainless [21].

- **Applications:** Duplex stainless steels are typically used in:
  - ~ Chemical processing, transport and storage
  - ~ Oil and gas exploration and offshore rigs
  - ~ Oil and gas refining
  - ~ Marine environments
  - ~ Pollution control equipment
  - ~ Pulp & paper manufacturing
  - ~ Chemical process plant [24].

b) 7075 Aluminum Alloy

7075 Aluminum alloy is a very high strength aerospace aluminum and is commonly used in applications where the strength of the material is critical and where the need for good corrosion resistance is not important.Offering superior stress corrosion resistance, 7075 provides very high yield and tensile strengths which is dictated by the chosen temper [19].

- **Applications:** 7075 Aluminum alloy is commonly used in:
  - ~ Aerospace applications. often used in aircraft wings and fuselages.
  - ~ Commonly used to extrude aluminum bars, pipes, rods, and tubes
  - ~ Bicycle frames.
  - ~ Electrical fittings
  - ~ Heat sinks.

3-3.3   Characterization of probe (Sensor)

The characterization of each new probe is based on route of resistive and inductive parameters as a function of frequency (Fig. III. 16 and 17) of the probe chosen confirms our choice in the stability of the probe for a wide frequency domain while layout of the impedance diagrams of the different parts produced (Fig III. 18) allows to locate the operating point where the energy transfer between the probe and thesamples is maximum.
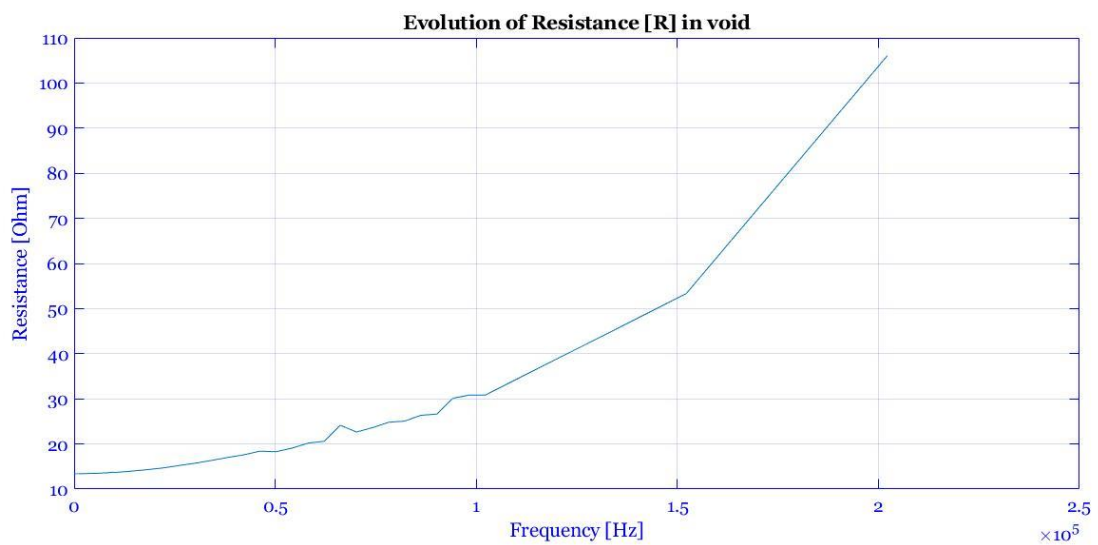
Figure III. 16. Development diagram of resistance (R_0) in air (void).
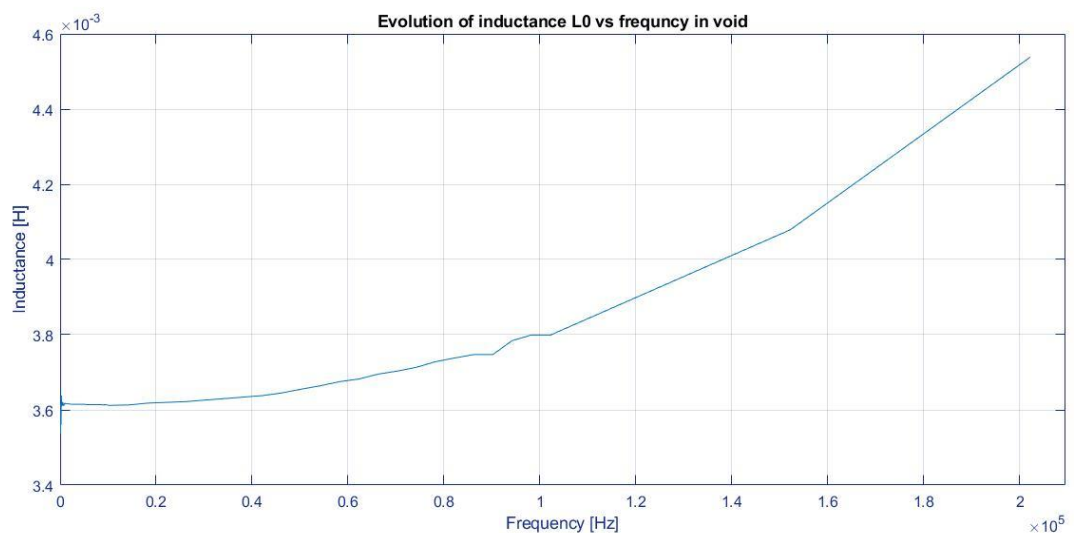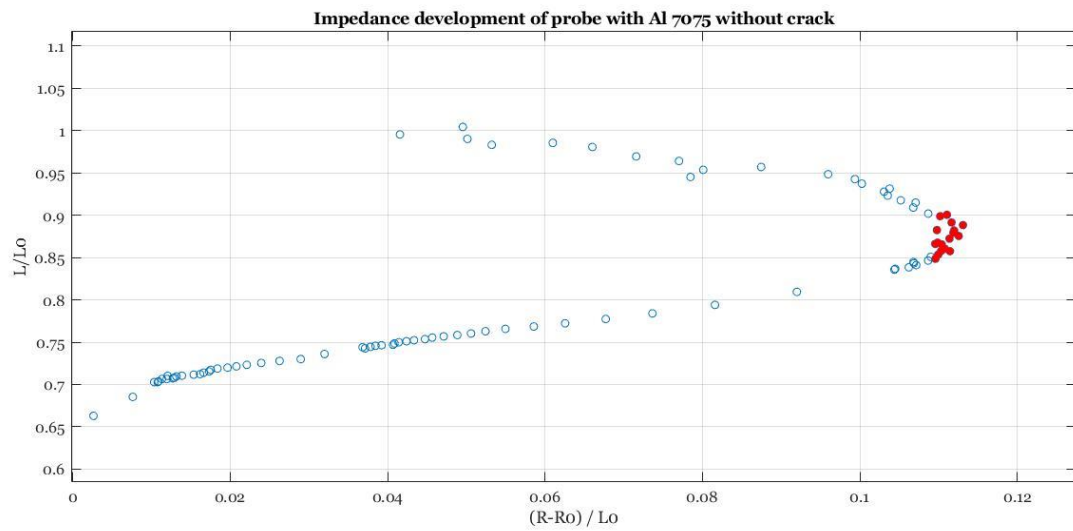
Figure III. 18. The Impedance diagram of probe with Al 7075.
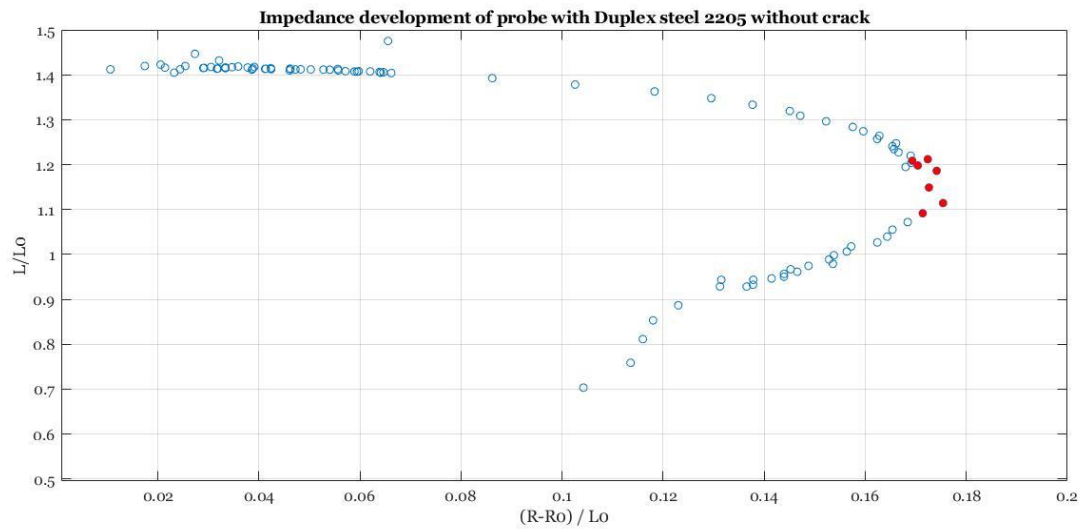
Figure III. 19. The Impedance diagram of probe with Duplex steel 2205.

3-3.3.1 Interpretation of graphs

The above graphs which have been generated with MATLAB, representing the results of the Characterization of probe.

In Fig II 18 & 19 the **Impedance** of sensor (probe) part, collected during the inspection operation with both calibration blocks (Al 7075 and Duplex steel 2205).

___

We found that the maximum exchangeof energy occurs in the middle of the curve, where the ratio of reactive parts tends towards the unit, it is equivalent to a frequency of 1Khz, if we use the theoretical formulas developed in chapter III (3.9) as well as those giving the working frequency based onpractice, where we consider that the penetration depth is the thickness of the part toinspect are identical we find the frequency that oscillates between 1 KHz to2.2 KHz for the Duplex steel, but the transfer of energy for the alloy of Al 7075 is between 520 Hz to 680 Hz only.

3-3.3.2 Partial Conclusion

As mentioned previously in this chapter III, the parameters influencing on the construction of probe. So, the Ideal frequency to inspect Duplex steel 2205 with this probe is the interval of (1.0 KHz to 2.2 KHz). And between interval (520 Hz to 680 Hz) for the Alloy of Al 7075.

3-3.3.3 Calculation of the different parameters.

- Ohm's law now simply states that the current (I), in amperes, is proportional to the voltage (V), in volts, divided by the impedance (Z), in Ohms.

$$I = V/Z \qquad (3.1)$$

I: The current [Amp].

V: The voltage [V].

Z:impedance[Ω]

- The impedance (Z) of an eddy current probe is given by:

$$|Z| = \sqrt{R^2 + iLw^2} \qquad (3.2)$$

- The real part of the R probe is given by ohm's law:

$$R = (\rho L)/S \qquad (3.3)$$

ρ: Electrical resistivity [Ω/m].

L: Wire length [m]

S: Section of wire[m²].

The diameter of the probe is one of the important parameters of the probe,

Hence: $R = (\rho \, \pi D N)/S$ (3.4)

D: Diameter [m].

N: Number of coils.

The impedance calculation is done for vacuum probes, in order to consider the losses in the nucleus which are very difficult to assess, for ferrite cores.

The reactive part is then calculated by assumi ng only the inductive effect.

$$L = 4\pi \, S \, 10^{7-} / l \qquad (3.5)$$

S: section [m²]

l: wire length [m].

If the length of the coil is not large compared to its diameter, a parameter corrector "k" is introduced called the coefficient of "Nagaoka" obtained according to the formula of "Nagaoka" or according to tables depending on the ratio (r / l).

Eddy current probes are generally manufactured in section rectangular, short, multilayer.

The Eddy current probes are generally manufactured with a cross section rectangular, short, multilayer

a) Calculate magnetic field created by one coil.

The current element $I.(\overrightarrow{dl})$ creates an elementary magnetic field $(\overrightarrow{dB})$. Characteristics of the vector.

$$\begin{cases} \textit{Direction: } \perp \text{ to } I\,\overrightarrow{dl} \text{ and } \overrightarrow{\mu_r} \\ \textit{Sense: right hand } 3 \textit{ finger rule.} \\ \textit{Norme: } dB = \dfrac{\mu_0}{4\pi} \dfrac{I \, dl \sin\left(I\,\overrightarrow{dl}\overrightarrow{u_r}\right)}{r^2} = \dfrac{\mu_0}{4\pi} \dfrac{I \, dl \sin\left(\frac{\pi}{2}\right)}{r^2} = \dfrac{\mu_0}{4\pi} \dfrac{I \, dl}{r^2} \end{cases}$$

$$B = \int dB_\perp = \int dB. \sin\theta = \int \frac{\mu_0}{4\pi} \frac{I.dl}{r^2} \sin\theta$$

$$\Rightarrow B = \frac{\mu_0}{4\pi} \frac{I.dl}{r^2} \sin\theta \int dl = \frac{\mu_0}{4\pi} \frac{I}{r^2} \sin\theta [2\pi R]$$

$$\left| \begin{array}{l} \sin\theta = \dfrac{R}{r} \\ r^2 = x^2 + R^2 \end{array} \right. \quad \Rightarrow B = \frac{\mu_0}{2} R \frac{I}{r^2} \frac{R}{r} = \frac{\mu_0 I}{2} \frac{R^2}{r^3} = \frac{\mu_0 I}{2} \frac{R^2}{\left(x^2 + R^2\right)^{\frac{3}{2}}}$$

The magnetic field created by a circular turn of radius R at distance X from the axis of the turn has the expression:

$$B = \frac{\mu_0 I}{2} \frac{R^2}{\left(x^2 + R^2\right)^{\frac{3}{2}}} \qquad (3.6)$$

The following representation simulates a turn; it makes it possible to assess behavior eddy currents in a material; as well as the influence of the impedance of the coil exciter on the material.
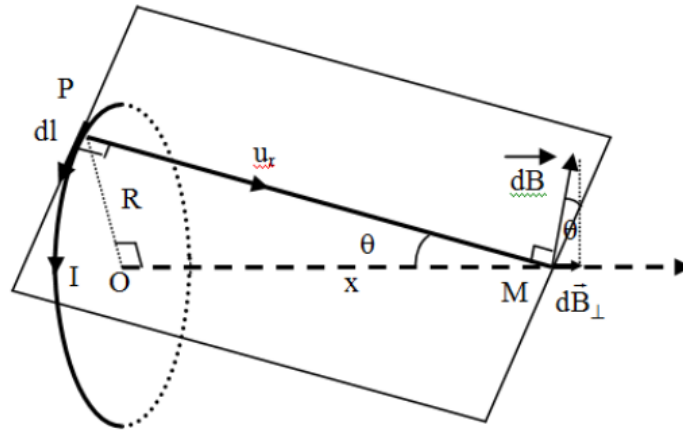
Figure III. 20. Magnetic field created by coil.

b) Calculation of resistance of coil.

The value of the resistance R of the probe is calculated by Ohm law:

$$R = \rho\, L/S \qquad (3.7)$$

L: Wire length [m],

P: Wire resistivity [Ω / m],

S: Wire section [m²],

R: Resistance value in ohm [Ω].

d) Calculate Inductance.

The value of the inductance L is calculated by the approximate formula of NAGAOKA:

$$L = (N . \Phi)/I \qquad L = \mu \frac{N^2 S}{l} \qquad (3.8)$$

μ: is the magnetic permeability.

    N: Number of turns.

    S: Solenoid section [mm].

    l: Solenoid length [mm].

    Φ: Magnetic field [Weber].

    L: Value of the inductance in Henry [H].

e) Calculate Standard penetration depth:

Standard penetration depth is the depth at which the density of eddy currents decreases by 37% of their value on the surface figure 2.4, it depends on the resistivity of the material, its permeability, and frequency.

$$\delta = 50 . \sqrt{\frac{\rho}{f . \mu_r}} \qquad (3.9)$$

$$\begin{cases} f : Frequency \ of \ the \ signal \ passing \ through \ the \ sensor \ in \ Hertz. \\ \mu_r : Relative \ magnetic \ permeability \ (without \ units). \\ \rho : Electrical \ resistivity \ in \ microhm - centimeters. \\ \delta : Stndard \ depth \ with \ millimeter. \end{cases}$$

3-3.4 Development of Eddy Current system

In CRTI we used the Laboratory of Eddy Current Testing, in the computer a program allowing to characterize the probes carried out and in parallel the data acquisition during thecontrol consists of below schematic diagram:
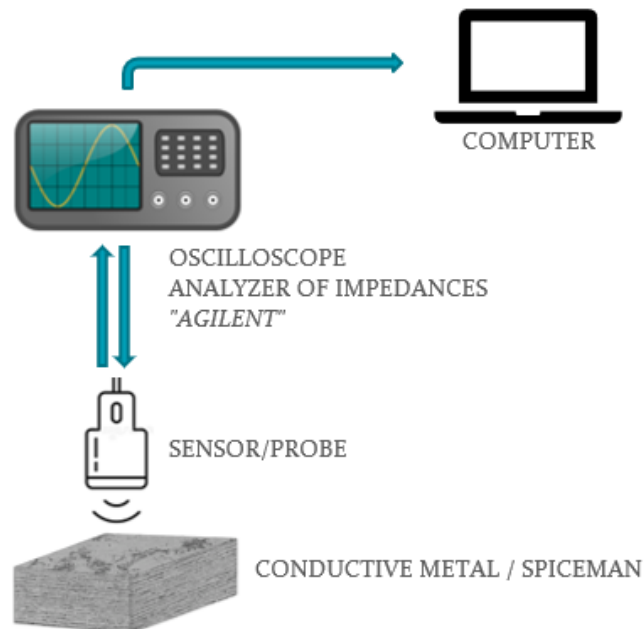
Figure III. 21. Schematic diagram of an eddy current measurement chain using Oscilloscope in laboratory.

But to develop my EDT system I chose the below components where I replaced the Oscilloscope by new smaller USB Oscilloscope including a function generator as showing in Fig III. 23.

3-3.4.1 Description of the Voltage Controlled Oscillator (VCO).

The ICL8038 waveform generator is a monolithic integrated circuit capable of producing high accuracy sine, square, triangular, sawtooth and pulse waveforms with a minimum of external components. The frequency (or repetition rate) can be selected externally from 0.001Hz to more than 300kHz using either resistors or capacitors, and frequency modulation and sweeping can be accomplished with an external voltage.
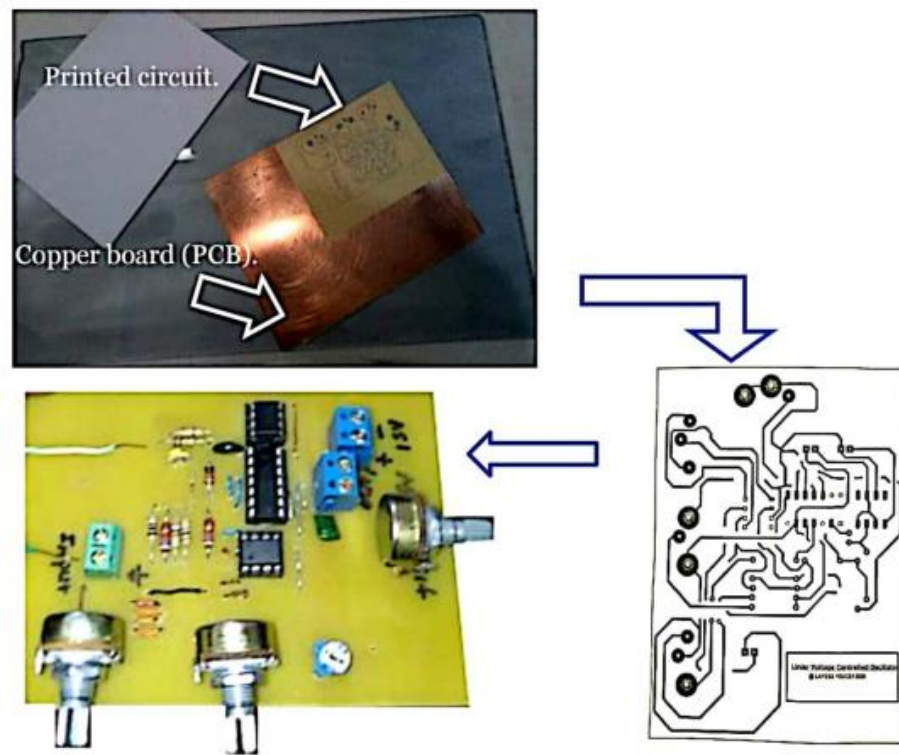
Figure III. 22. Schematic presenting the steps while prepare VCO circuit.
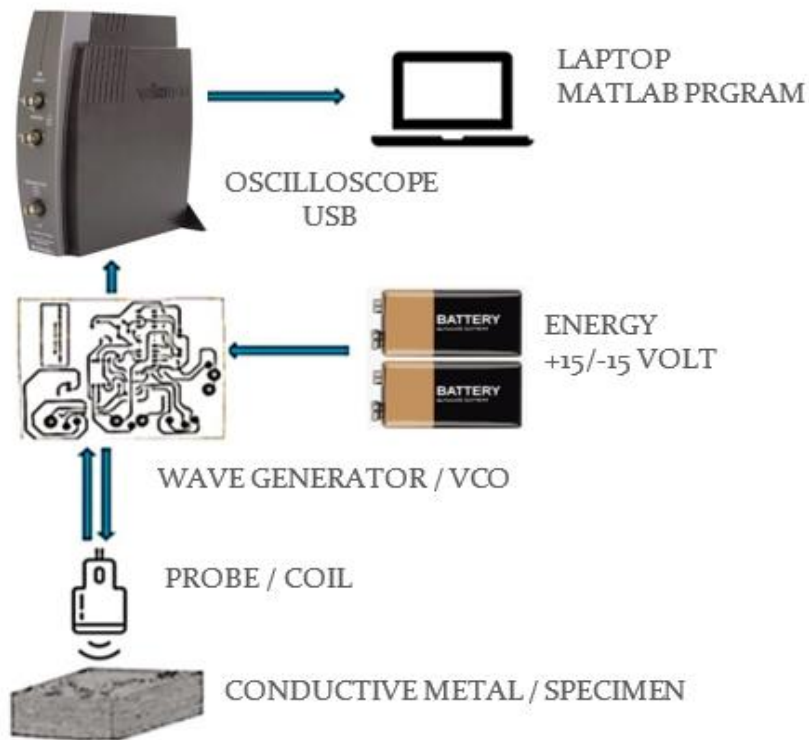
Figure III. 23. Schematic of Eddy Current Testing (ECT) system.

3-3.4.2 Description of the Oscilloscope USB Velleman

A complete USB-powered lab-in-a-box Feature-packed PcLab2000-LT having software for two channel oscilloscope, spectrum analyzer, recorder, function generator and bode plotter. With the generator, we can create own waveforms using the integrated signal wave editor. For automated measurements, it is even possible to generate wave sequences, using file or computer RS232 input.

b) Features.

- Function generator:
- Oscilloscope.
- Transient recorder.
- Bode plotter:
- Spectrum analyzer.

c) Specification

Function generator:

- Amplitude range: 100 mvpp to 10 Vpp @ 1 KHz// 600 Ohm load.
- Offset: from 0 to -5 V or +5 V max. (resolution 0.4% of full scale)
- Vertical resolution: 8 bits
- Square wave rise/fall time: 0.2μs
- Sample rate: 12.5 MHz
- Typical sine wave distortion (THD): < 1%
- Output impedance: 50 Ohm
- Frequency range: from 0.005 Hz to 500 KHz

Oscilloscope:

- Bandwidth: two channels DC to 12 mhz ± <1 db
- Input impedance: 1 MOhm / 30 pf
- Maximum input voltage: 30 V (AC + DC)
- Time base: 0.1μs to 500 ms per division
- Input range: 10 mv to 3 V/division

- Input sensitivity: 0.3 mv display resolution
- Record length: 4 K samples / channel
- Sampling frequency: 250 Hz to 25 MHz.

3.3.5   Representation of results and discussion

Complying with Eddy Current standard, we took the **Calibration block** for both metals (Duplex steel 2205 and Al 7075) contains (3) surface notches at depths of 0.08mm, 0.020mm and 0.040mm. Notch width typically 0.1mm to 0.13mm.
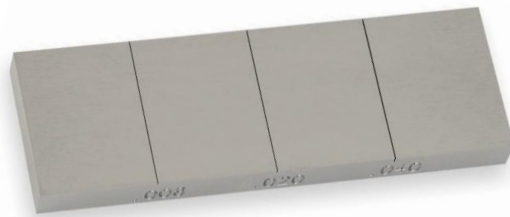
Figure III. 24. Standard calibration block of Eddy Current Testing.

 After scanned the first notch, we recorded the below impedance graph:
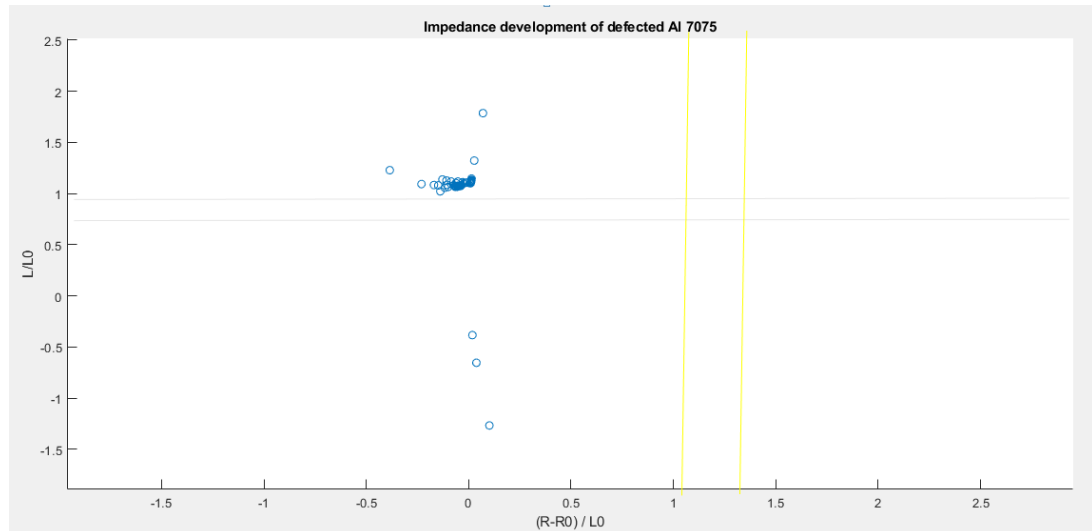
Figure III. 25. Impedance development on notch (0.08mm) in Al 7075.

3.3.6 Interpretation of graphs

According to the Fig II. 5 in Chapter II, the impedance graph presenting declination at Axe X (R-R0)/L0 below 0.5 value, and big increase also at Axe Y (L/L0) above 1 value.

That explain the presence of defect in the in Al 7075 metal. After zoom out the interval (-2; 4) on the Axe Y (L/L0) and (-1; 1.4) on Axe X (R-R0)/L0, we see the below graph.
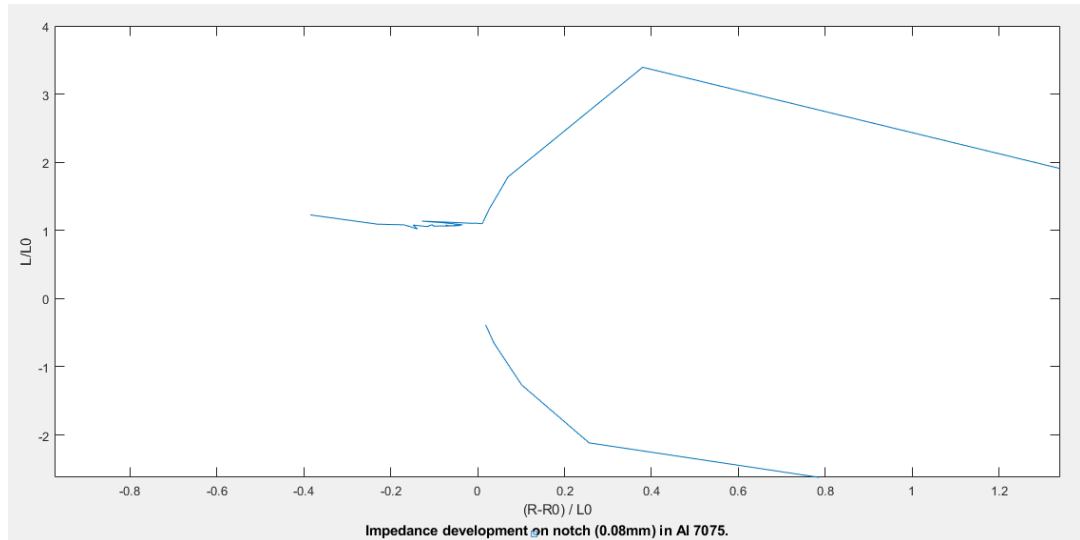
Figure III. 26. Impedance development on notch (0.08mm) in Al 7075.
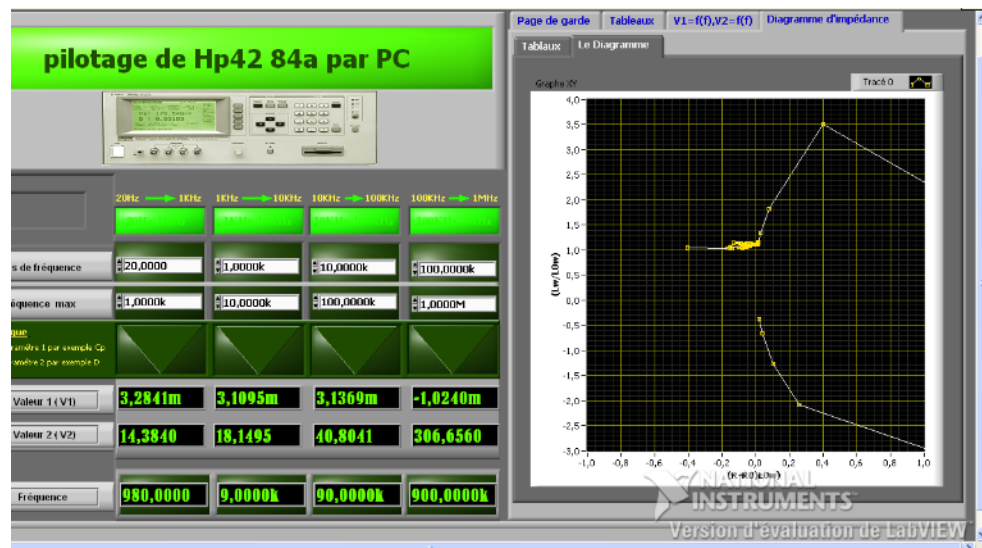
Figure III. 27. Shot screen of impedance development generated by program in laboratory of CRTI for same Al 7075 notch (Crack).

3.3.7 Analyze Duplex steel defects with ECT device
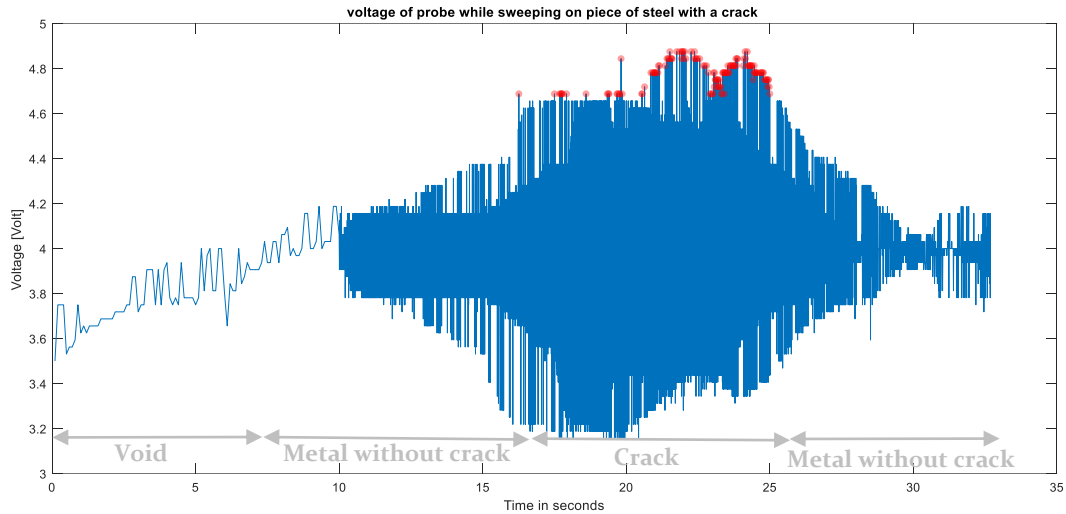
Figure III. 28. Graph generated in MATLAB representing the voltage in Oscilloscope while sweeping over steel notch (Crack).
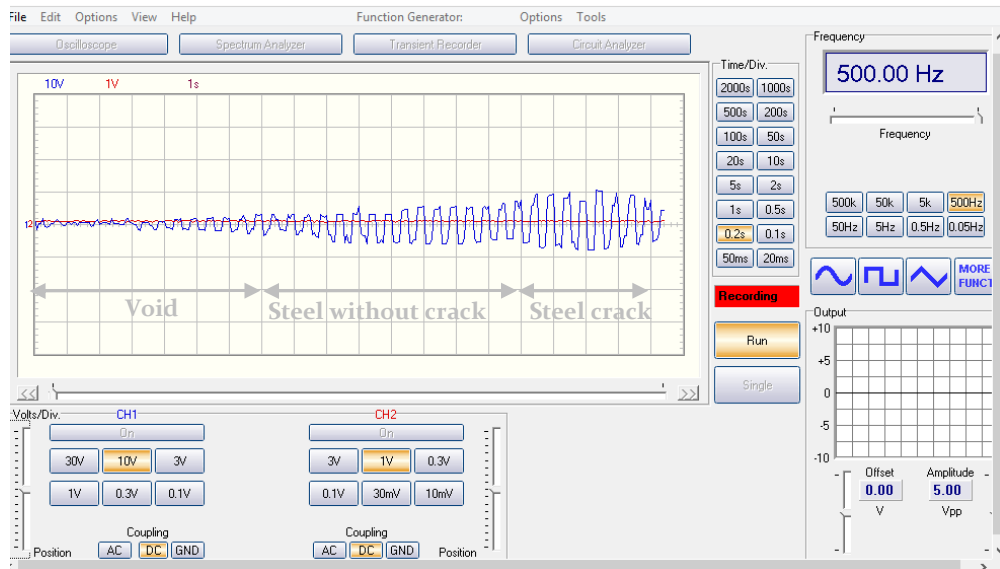
Figure III. 29. Shot screen representing the voltage [V] in Oscilloscope while scanning the steel notch (Crack).

3.3.8 Analyze Aluminum defects with ECT device.
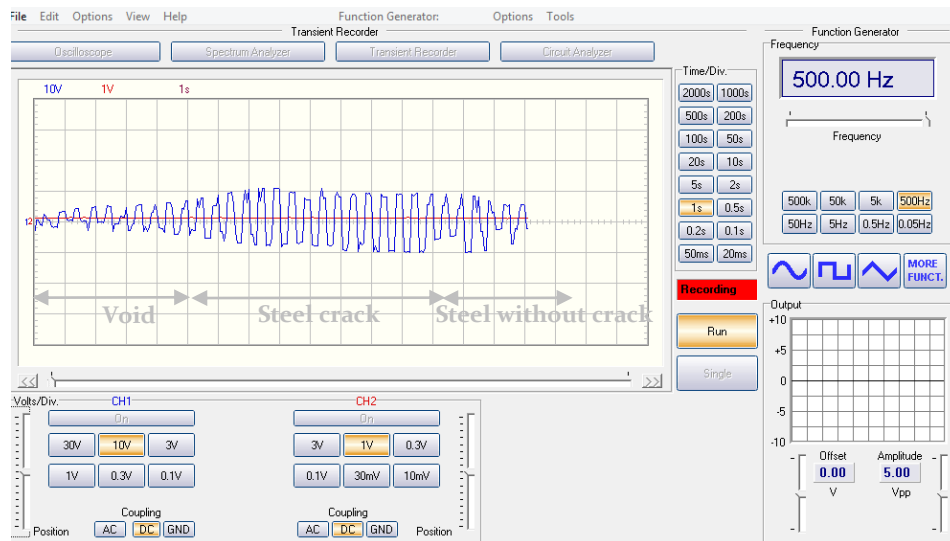
Figure III. 30. Shot screen representing the voltage [V] in Oscilloscope while scanning the Aluminum notch (Crack).

The above picture taken using the Program of USB Oscilloscope, while scanning the piece of Al 7075, the probe was sweeping over the specimen (Al) the VCO devise was generating 1000 KHz frequency then goes thru our probe (coil) the magnetic field influenced on the piece of Al gives changes in the voltage in which oscillated by the Oscilloscope.

3.3.9 Interpretations of results.

The last two Figures (29 and 30) shows the plots of the voltage diagram of the probe chosen on both the specimens Al 7075 and Duplex Steel produced; we find that the maximum change of voltage occurs on the crack area of the graph, where the amplitude of signal waves tends maximum, while using contestant frequency 1Khz, if we use the theoretical formulas developed in chapter III (3.1) as well as those giving the working frequency based onpractice, where we consider that the penetration depth is the thickness of the part toinspect are identical we find the frequency which oscillates between 750 and 1000Hz.

3-5 General conclusion.

To find defects in a material, it requires one of the techniques of Non-Destructive Testing, which includes many techniques, Eddy Current Testing (EDT) and Ultrasonic Testing (UT) are widely used technologies. throughout the industry, sometimes they are complementary to each other's, for example the UT can more thoroughly inspect the material, Although the ECT used only for subsurface and surface defects.

The goal of this Master thesis was to realize two NDT systems to detect defects in materials. The first to realize UT device and second is ECT device which is use the electromagnet field.

To achieve our purpose, a significant research in specialized in NDT companies such as "Eddyfi technology" and bibliographic search has been successfully achieved to understand these processes and also to have an idea on the principle of operation of this type of NDT technology.

The efforts while studying allows us to realize these two devices:

- Device for detecting defects using an ultrasonic sensor.
- Device for detecting defects in conductive metals using an eddy current probe.

We Note that most advances of these devices are, mobile, easy to use them, but the Eddy Current Testing (ECT) only could be scanning the conductive metals such as Aluminum and steel.

Welds are also carried out with Eddy Current testing to visualize the flaw, which have weld defect on metals, we can say the NDT with ECT is very useful because is not require preparation of surface.

Eddy Current usually the best technique when inspecting tubing materials, thinner welds and surface flaws, whereas ultrasonic technology is a good choice when assessing corrosion, wall sizing and thicker forms of welding that may harbor deviation on a volumetric level.

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Abstract:

The Non-Destructive Testing (NDT) of metals worldwide experienced a significant change in the last half of the twentieth century. During the 1950s, the NDT of metals dominated the proportion of NDT carried out by engineers and users and totaled as much as all the other industrial sectors put together (i.e. aerospace, utilities, petrochemical, automotive, and other sectors). However, at the end of my study I succeed to experience two small tools using UT and EDT to exanimate materials, both of them need sensor and analyze system. Although EDT is more complicated because it needs characterization of probe as per the norms, contrarily to UT which is able to inspect metals without pre characterization in general. But all NDT technics needs calibration.

ملخص:

شهدت الاختبارات غير المدمرة (NDT) للمعادن في جميع أنحاء العالم قدرًا كبيرًا التغيير في النصف الأخير من القرن العشرين. خلال الخمسينيات من القرن الماضي ، تم إجراء اختبار NDT للمعادن سيطر على نسبة الاختبارات غير التدميرية التي نفذها المستخدمون و المهندسون بلغ مجموعها مثل جميع القطاعات الصناعية الأخرى مجتمعة (مثل قطاعات الطيران والمرافق والبتروكيماويات والسيارات وغيرها). ومع ذلك ، في نهاية دراستي نجحت في تجربة أداتين صغيرتين باستخدام UT و EDT لفحص المواد ، وكلاهما يحتاج إلى جهاز استشعار وتحليل. على الرغم من أن EDT أكثر تعقيدًا لأنه يحتاج إلى توصيف المجسات وفقًا للمعايير ، على عكس UT القادر على فحص المعادن دون التوصيف المسبق بشكل عام. لكن جميع تقنيات الاختبار غير التدميري تحتاج إلى معايرة

Résumé :

Les essais non destructifs (CND) des métaux dans le monde ont connu un changement dans la dernière moitié du XXe siècle. Au cours des années 1950, le CND des métauxa dominé la proportion des CND réalisés par les utilisateurs et les ingénieurs et a atteint autant que tous les autres secteurs industriels réunis (c'est-à-dire l'aérospatiale, les services publics, la pétrochimie, l'automobile et d'autres secteurs). Cependant, à la fin de mon étude, je réussis à expérimenter deux petits outils utilisant UT et EDT pour examiner des matériaux, tous deux nécessitant un capteur et un système d'analyse. Bien que l'EDT soit plus compliqué car il nécessite une caractérisation de la sonde selon les normes, contrairement à l'UT qui est capable d'inspecter les métaux sans pré-caractérisation en général. Mais touts les techniques NDT nécessitent un étalonnage.