

EFFECTIVENESS OF PORTABLE EDDY CURRENT INSPECTION ON WELDING PIPELINE



BACHELOR OF MECHANICAL AND MANUFACTURING ENGINEERING TECHNOLOGY (MAINTENANCE) WITH HONOURS



Faculty of Mechanical and Manufacturing Engineering Technology



Muhammad Firdaus Bin Abd Halim

Bachelor of Mechanical and Manufacturing Engineering Technology (Maintenance) with Honours

EFFECTIVENESS OF PORTABLE EDDY CURRENT INSPECTION ON WELDING PIPELINE

MUHAMMAD FIRDAUS BIN ABD HALIM



Faculty of Mechanical and Manufacturing Engineering Technology

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DECLARATION

I declare that this thesis entitled "Effectiveness Of Portable Eddy Current Inspection on Welding Pipeline" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical and Manufacturing Engineering Technology (Maintenance) with Honours.

Signature : Supervisor Name Siti Norbaya binti Sahadan : 18th January 2022 Date **TEKNIKAL MALAYSIA MELAKA** UNIVERSITI

DEDICATION

To my beloved family members and friends who have tirelessly stick and support me in an incredible journey of this 24 years of life.



ABSTRACT

Fatigue crack is one of the world oldest failure which has been studied by various researcher. Through those researcher, the humanity becomes more aware of fatigue failure which alway occurs on humans daily life. In this study, the fatigue crack in the welding has been studied throughly and the evaluation of the effectiveness of portable eddy current testing (ECT) method on welding has been inspect. However, before inspecting the weldment on the specimen, the material of the specimen must also be investigate first. The specimen selected is a pipeline removed by an industry because of it defect. The specimen material used in this study is a ferromagnetic material which has a good machinability with lower costing usage than any other materials and a conductive material in line with the use of Non-Destructive Tool (NDT) that will be used in this study. After that, the inspection on detecting the fatigue crack in the welding pipeline were inspected by using the ECT through two type of probe movement on three places on the weldment. These three place and type are right toe inspection, left toe inspection and cap inspection. The defect crack found in the welding will be recorded and analyze in three graph. Then, the next NDT inspection is Ultrasonic Testing (UT) will be used on inspecting the welding so that both of the NDT data can be comparised in order to deepen the understanding of using the portable ECT in inspecting the welding pipeline. After that, the effectiveness of portable ECT in inspecting the weldment can be evaluate.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRAK

Keretakan lesu adalah salah satu kegagalan tertua di dunia yang telah dikaji oleh pelbagai penyelidik. Melalui pengkaji tersebut, manusia lebih sedar tentang kegagalan keletihan yang selalu berlaku dalam kehidupan seharian manusia. Dalam kajian ini, keretakan lesu pada kimpalan telah dikaji secara menyeluruh dan penilaian keberkesanan kaedah ujian arus pusar mudah alih (ECT) terhadap kimpalan telah diperiksa. Walau bagaimanapun, sebelum memeriksa kimpalan pada spesimen tersebut, bahan spesimen juga mesti disiasat terlebih dahulu. Spesimen yang dipilih ialah saluran paip yang dibuang oleh industri kerana ia telah rosak.Bahan spesimen yang digunakan dalam kajian ini adalah bahan feromagnetik yang mempunyai kebolehmesinan yang baik dengan penggunaan kos yang lebih rendah berbanding bahan lain dan bahan konduktif selaras dengan penggunaan ujian tanpa musnah (NDT) yang akan digunakan dalam kajian ini. Selepas itu, pemeriksaan pengesanan retakan kelesuan pada saluran paip kimpalan diperiksa dengan menggunakan ujian arus pusar (ECT) melalui dua jenis pergerakan pengesan pada tiga tempat pada kimpalan. Tiga tempat dan jenis ini ialah pemeriksaan kanan kaki kimpalan, pemeriksaan kiri kaki kimpalan dan pemeriksaan atas kimpalan. Keretakan kecacatan yang terdapat dalam kimpalan akan direkodkan dan dianalisis di dalam tiga graf. Kemudian, pemeriksaan ujian tanpa musnah (NDT) seterusnya ialah ujian ultrasonik (UT) akan digunakan pada pemeriksaan kimpalan supaya kedua-dua data ujian tanpa musnah (NDT) dapat dibuat perbandingan bagi mendalami pemahaman penggunaan ujian arus pusar mudah alih (ECT) dalam pemeriksaan saluran paip kimpalan. Selepas itu, keberkesanan ujian arus pusar mudah alih (ECT) dalam memeriksa kimpalan boleh dinilai.

ة, تنكنك to hundo. UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

First of all, I would like thank and praise Allah, the Creater which has been giving infinite blessing and sustenance since the beginning of my life. I would also like to extend my appreciation to the Universiti Teknikal Malaysia Melaka (UTeM) for providing the education and research platform through the years of my study start in Melaka. My appreciation also goes to the lecturer in UTEM that has teach and providing knowledge tirelessly.

Next, my gratitude also goes to my project supervisor, Siti Norbaya binti Sahadan from the Faculty of Mechanical and Manufacturing Engineering, University Teknikal Malaysia Melaka (UTeM) for the supervising and her overwhelming attitude on guiding throughout the whole project from understanding topic to data collecting as well as guidance in report writing. Without all of the comments and response from her, this project will not met it completion. I sincerely thank her for the full guidance and sacrificing the time with her family members.

I would like to thank my family and friends as they gave me the colourful life while study in the university. Besides that, they also gave a lot of support both financially and emotionally throughout the university and this project.

تى تيكنيكل مليسيا ما

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

TABLE OF CONTENTS

PAGE

DECL	ARATION	
APPR	OVAL	
DEDIC	CATION	
ABSTR	PACT	i
ABSTR	2AK	ii
ACKN	OWLEDGEMENTS	iii
TABLE	E OF CONTENTS	iv
LIST O	DF TABLES	vi
LIST O	DF FIGURES	vii
LIST O	OF SYMBOLS AND ABBREVIATIONS	ix
LIST O	OF APPENDICES	xi
CHAP2 1.1 1.2 1.3 1.4	TER 1 INTRODUCTION Background Problem Statement Research Objective TI TEKNIKAL MALAYSIA MELAKA Scope of Research	1 1 3 5 6
<i>CHAP</i> 2.1 2.2 2.3 2.4	TER 2LITERATURE REVIEWIntroductionFerromagnetic materialIntroduction to fatigue failure2.3.1Cyclic loading2.3.2Fatigue failure analysis approachCrack parameterNon Destructive Testing	7 7 11 15 17 19 23 27
2.5 2.6	 2.5.1 Magnetic-based NDT 2.5.2 Eddy Current Method Summary 	27 29 31 33
CHAPT 3.1 3.2 3.3	<i>TER 3 METHODOLOGY</i> Introduction Material and specimen ECT device 3.3.1 ECT inspection method	36 36 40 42 44

3.4	UT device	45
	3.4.1 UT inspection method	48
3.5	Summary	49
CHAP	TER 4 RESULTS AND DISCUSSION	50
4.1	Results and discussion	50
4.2	Results of ECT weld inspection	50
4.3	Analysis of the ECT reading	57
4.4	Comparative data with the UT	61
4.5	Summary	72
CHAP	TER 5	73
5.1	Conclusion	73
5.2	Recommendation	74
REFEI	RENCES	75

0	2
Δ.	<u>)</u>



LIST OF TABLES

TABLE	TITLE	PAGE
Table 2.1	Curie temperature of ferum, nickel and cobalt	15
Table 3.1	Gantt Chart for PSM 1	38
Table 3.2	Gantt Chart for PSM 2	39
Table 4.1	Setting of the ECT mode	51
Table 4.2	Right toe weldment inspection	53
Table 4.3	Left toe weldment inspection	55
Table 4.4	Cap weldment inspection	56
Table 4.5	UT inspection reading based on the ECT right toe inspection	62
Table 4.6	UT inspection reading based on the ECT left toe inspection	64
	اونيومرسيتي تيكنيكل مليسيا ملاك	

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 2.1	Simple mechanism of fatigue test	8
Figure 2.2	S-N curve	9
Figure 2.3	Magnetic field created through electric current flow	10
Figure 2.4	Respond of magnetic domains to an outside magnetic field	13
Figure 2.5	Summary of fatigue failure stages	17
Figure 2.6	The schematic total strain-life curve	21
Figure 2.7	The longitudinal crack occurred in weld material	24
Figure 2.8	A simple flow of periodic inspection on any building or product	25
Figure 2.9	External crack on the surface of the pipe detected by Magnetic Particle	e
	Inspection (MPI)	26
Figure 2.10	Crack initiation near the large tips	26
Figure 2.11	Principle of ECT method IKAL MALAYSIA MELAKA	32
Figure 3.1	Flow chart of methodology	37
Figure 3.2	Ferromagnetic pipeline with weldment	40
Figure 3.3	Weldment with labeled starting point	41
Figure 3.4	(a) ECT equipment, (b) Eddy Current Mentor EM detail	42
Figure 3.5	Broadband Probe 632-134-000 (130P3)	43
Figure 3.6	ECT display	43
Figure 3.7	Toe welding inspection	44
Figure 3.8	Cap welding inspection	45
Figure 3.9	UT equipment	46

Figure 3.10 (a) UT cry	vstal probe, (b) UT crystal probe label	46		
Figure 3.11 UT couplant 47				
Figure 3.12 Sample of	Figure 3.12 Sample of test specimen48			
Figure 3.13 Expected	signal shown on UT display	49		
Figure 4.1 Welded Pi	ipe diagram (circular)	51		
Figure 4.2 (a), (b), (c), (d), (e), (f), (g) ECT crack reading for right toe inspection	53		
Figure 4.3 (a), (b), (c), (d), (e), (f), (g), (h) ECT crack reading for left toe inspection	54		
Figure 4.4 (a), (b), (c), (d) ECT crack reading for cap inspection	56		
Figure 4.5 Eddy currer	nt reading on welded pipe (Right Toe)	57		
Figure 4.6 Eddy curre	ent reading on welded pipe (Left Toe)	58		
Figure 4.7 Eddy Curr	cent reading on welded pipe (Weld Cap)	59		
Figure 4.8 (a), (b), (c), (d), (e), (f), (g) UT crack reading based on the ECT right toe			
inspection Figure 4.9 (a), (b), (c), (d), (e), (f) UT crack reading based on the ECT left toe	62		
inspection	RSITI TEKNIKAL MALAYSIA MELAKA	63		
Figure 4.10 UT Readin	ng on Welded Pipe (Right Toe)	65		
Figure 4.11 UT Readin	ng on Welded Pipe (Left Toe)	66		
Figure 4.12 Compariso	on of UT and ECT based on the ECT right toe inspection	68		
Figure 4.13 Compariso	on of UT and ECT based on the ECT left toe inspection	69		

LIST OF SYMBOLS AND ABBREVIATIONS

LIST OF SYMBOLS

N_f	-	Fatigue life
N _i	-	Crack initiation
N_p	-	Crack growth
σ_a	-	Stress amplitude
$\Delta \sigma$	-	Difference between the maximum and the minimum stress
σ_{max}	-	Maximum stress value
σ_{min}	- 14	Minimum stress
R	a de la compañía de	Ratio
P _{max}	TEK-	Maximum load
P _{min}	E	Minimum load
A	-33AT	Fatigue strength coefficient
В	14	Basquin exponent
Т	ملاك	ويور سيني بيصيب Temperature
с Е _{еа}	UNIVE	Temperature sensitivity parameter Elastic strain amplitude
ε_{pa}	-	Plastic strain amplitude
σ'_f	-	Fatigue strength coefficient
Ε	-	Young modulus
b	-	Fatigue strength exponent
${\varepsilon'}_{f}$	-	Fatigue ductility coefficient
С	-	Fatigue ductility exponent
$\frac{da}{dN}$	-	Fatigue crack growth
С	-	Material coefficients
ΔK	-	Stress intensity range
т	-	Constant/gradient in region II

LIST OF ABREVIATION

ASTM	-	American Society For Testing Materials
NDT	-	Non-Destructive Test
QC-NDT	-	Quality Control Non-Destructive Test
UT	-	Ultrasonic Testing
RT	-	Radiographic Testing
IRT	-	Infrared Thermography Testing
THz	-	Terahertz
ECT	-	Eddy-Current Testing
EC	-	Eddy Current
Ni	- M	Nickel
Fe	and the second s	Iron
Co		Cobalt
SCC	EA	Stress Corrosion Cracking
LCF	- 4311	Low Cycle Fatigue
HCF	st.	High Cycle Fatigue
MPI	ملات	Magnetic Particle Inspection
MFL	UNIVE	Magnetic Flux Leakage MALAYSIA MELAKA
PMP	-	Permanent Magnetic Perturbation
PEC	-	Pulsed Eddy Current
ISO	-	Isometric View

LIST OF APPENDICES

APPENDIX

TITLE

PAGE

APPENDIX A

Weldscan demonstration plate drawing



CHAPTER 1

INTRODUCTION

1.1 Background

In the beginning of 19th century, the assessments of structure and material fatigue failures have been started to thrive in engineering. There are various failures on engineering components and structures such as fracture, creep, rusting, fatigue failure and others. Failure process which occurs due to repetitive stress or strain loads are known as a cracking phenomenon caused by a number of repetitive load cycles (Leuders et al., 2017). The unexpected cracking and sudden breakdown of components will occur due to the fact that tensile stresses, which can originate from various manufacture processes at different production stages, added to the in-service stress reduce the component life (Han & Yang, 2021).

Generally, fatigue cracking consists of three main stages namely (i) crack initiation,

(ii) crack propagation and (iii) final rupture. This problem of fatigue failure becomes an important issue in various fields due to the fatigue failure occurs without signal (Sánchez et al., 2021). Thus, the ability of a component that can optimally function will be affected by the damage came from those components. Deterioration of component performance can also cause by several other factors. If all the damage detected not maintained from the early stage then failure can occur more often and the components or machine will become total lost which is cannot being used at all again (Jiao et al., 2016).

According to the definition of fatigue stated in the American Society for Testing Materials (ASTM), fatigue is the process of permanently changes in the structure of a material occurs when the material is subjected to stress and strain repeatedly. This process is a progressive process that is focused on the local area where the area cracks or fractures occur when the load cycle reaches the limit on certain number of cycles (Sánchez et al., 2021). Fatigue is the condition where a material cracks or fails because of repeated (cyclic) stresses applied below the final strength of the material. The term "Fatigue Cyclic", for instance, is an analogy to cycles which will be counted on mechanisms comprising revolving axes, gears and chains, but it becomes a challenge to define what a cycle really means within the multiaxial loading context (de Lacerda et al., 2017).

Crack is a major concern in ensuring the durability, safety and serviceability of structures. This is because the presence of crack can cause the reduction in the effective loading area which lead to the increase of stress and subsequently failure of the materials or structures. Cracking seems unavoidable and appears in wide variety of structures such as concrete wall, beam and brick walls. Various types of defects also can be found in pipeline applications (Dadfarnia et al., 2019). Slit and crack are the examples of defects that commonly found especially in the ferromagnetic materials. The presence of defects will affect the reliability, safety and the consistency of materials' quality. Therefore, it is crucial to test and evaluate the materials or structure to detect cracking for the safety and health of the structure. The presence of such cracks can be detected by using various types of Non-Destructive Test (NDT).

The NDT is an engineering evolution of science for engineer to evaluate any specimen which being test without causing any destructive and it guarantee the safety, reliability and integrity of engineering structure and components. The NDT inspection was first being used for Quality Control NDT (QC-NDT) and then applicated widely because of its effectiveness in practice(Trampus et al., 2019). Thus, NDT is the most practicable for inspection the fatigue fracture test which really sensitive on any additional impact. Combination of different NDT is a good way to inspect the defect and abnormalities of the structures. In many cases, more than one NDT method is use in the process of defect inspection. To ensure the effectiveness of the inspection process, more understanding on the backgrounds, advantages and limitations of each NDT technique is necessary. Understanding one non-destructive method alone may not be enough to obtain the accurate results from the testing process (Dwivedi et al., 2018).

1.2 Problem Statement

AALAYSI

The current NDT methods used for inspection is include ultrasonic testing (UT), radiographic testing (RT), infrared thermography testing (IRT), terahertz (THz) imaging technology, and eddy-current testing (ECT). A deep understanding on the foundation, advantages and limitations of each NDT technique is necessary to ensure the effectiveness of the inspection process (Dwivedi et al., 2018). Non-destructive eddy current evaluation techniques have been globally used in the inspection of conduction structures for the diagnosis of surface and near-surface cracks. The basic eddy current (EC) is a cylindrical coil used to generate and sense the electrical current in the metallic part simultaneously. However, there are various improvement on traditional eddy current testing in previous study. (Ge et al., 2021) state that eddy current inspections are performed using a uniform eddy current probe driven with 10 kHz, and all of the fatigue cracks are detected with clear signals. (Almeida et al., 2013) propose a new type of eddy current probe with enhanced lift-off immunity and improved sensitivity and estimates a new NDT system. The inspection of

non-destructive monitoring of microstructural changes in austenitic steels under cyclic loading as well as the lifetime prediction by combining high-accuracy acoustic monitoring of elastic anisotropy and eddy current monitoring of volume fraction of the martensite. This combined approach allows estimation of fatigue life as well as the information on the past loading history (Mishakin et al., 2020).

In NDT, the eddy current testing is one of the most inspection which has a high sensitivity. Its sensitivity primary on to the surface defects and able to detect defects of 0.5mm in length under favourable conditions. Eddy current also able to observe through several layers. The ability to spot defects in multi-layer structures (up to about 14 layers), without meddle from the planar interfaces. Its accuracy on conductivity measurements also acceptable and dedicated conductivity measurement instruments operated. Eddy current also has a little pre-cleaning required. Only major soils and loose or uneven surface coatings need to be removed, reducing preparation time. However, this method is basically used for conductive materials and more difficult to determine the defects that embedded in the specimen. Theoretically, phase measured signal can be used to characterize the defect depth. However, it is complicated to evaluate the phase of signals in reality (Tong et al., 2020). Eddy current also will not detect defects parallel to surface. Without exception the flow of eddy currents will always be parallel to the surface. If a planar defect does not intercept or interfere with the current then the defect will not be easily spotted. Then, eddy current is not suitable for large areas and/or complex geometries. Although the large area scanning can be accomplished, but it needs the aid of some type of area scanning device which is usually supported by a computer it is not inexpensive. The more complex the geometry becomes, the more difficult it is to differentiate defect signals from geometry effect signals.

The simplified version of eddy current method is the portable ECT equipment that has been widely used in a lot of industry. However, the appearance of other NDT equipment significantly made the usage of eddy current method become declining depends on the advantages and the disadvantages of these NDT. Therefore, this study will be conduct on investigation the effectiveness of eddy current method in the aspect of detecting the fatigue crack in the welding pipeline compared with the UT method. The results of previous researchers found that, ECT is a popular approach for inspecting conductive materials but its complexity necessitates a strong processing unit. Remote access is an unique move in the field, since research in this area has shown to improve ECT efficiency (Rosado, 2020). Therefore, analysis on portable ECT will be expected to be less efficient.

1.3 Research Objective

The main objectives for this research are as follows:

- a) To conduct fatigue crack test for weldment of ferromagnetic materials.
- b) To collect eddy current signals in detecting crack in a welding of ferromagnetic pipeline.
- c) To confirm the crack detection of eddy current testing using ultrasonic testing.

1.4 Scope of Research

The scope of this research are as follows:

- This experiment will only be conduct in laboratory scales.
- In this experiment, the specimen that need to be observed as a sample is limited only for ferrous metal because of the inspection method that was used is magnetic flux eddy current method.
- The inspection is only using the portable or conventional eddy current testing.
- The comparison data is only by using the portable ultrasonic test.



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Essentially, this chapter will describe the literature review of the history of previous studies that have been conducted, which have a correlation between work done in this study. The samples history which are applications and advantages the use of ferromagnetic materials is discussed to reinforce the importance of the study run. Ferromagnetic materials have already infiltrated our lives with applications from the magnets in people's refrigerator to the hard drives of our computers. Ferromagnetic material beginning with their earliest usage as compass needles in China since 12th century. They were historically even more researched, but the crucial elements for Maxwell's theory of electromagnetic and quantum mechanics was not found until the last two centuries (Enya Vermeyen, 2019).

Focus on literature review and basic concepts in the approach fatigue failure is also discussed. The fatigue life approach is divided into three commonly used approaches are life-stress, life-strain and mechanical methods linear elastic fracture. Although failures related to structural integrity are not a new problem in the field of engineering, studies in this field are still very active especially involving fatigue failures on metal and alloy materials (da Costa Mattos, 2017). In addition, fatigue failure occurs in local areas where it occurs only in areas that experience high stresses or strains as a result of actions such as external loads, temperature changes and residual stresses. This process does not apply to entire components or structures (Guimaraes et al., 2016).

Germany's Julius Albert mine administrator (1829) is the first one to disclose errors because of repeated tiny loads. He is being the first one to design the equipment to test the existance of fatigue failure. As shows in (Figure 2.1), the equipment had a crank fixed to a water wheel and a chain linked the crank to a weight which was raised up and down until the chain broke (Giovanni M & Teixeira, 2017).



Source: (Giovanni M & Teixeira, 2017)

Around 1850-1870, August Wöhler conducted a fatigue test using cyclic loads to study the fatigue failure experienced by railway axles. The test conducted in a fatigue laboratory has been considered the first systematic fatigue study. Accordingly, August Wöhler was called the father of systematic fatigue testing. His research (Mlikota et al., 2018) has led to the introduction of (S-N) curves, however he does not organise the data into S-N curves as currently seeing in fatigue textbooks nowadays until the end of the 19th century which constant amplitude schemes were introduced (Giovanni M & Teixeira, 2017).



The next main approach of literature review in this paper is eddy current testing (ECT). ECT is a technique which globally used as non-destructive testing (NDT) on various type on industries. ECT is also applied on material as a quality control equipment in a lot of industries. Commonly, eddy current method is applicated on 2 type of detection. First, ECT is being used to detect and inspect the condition of sample. The sample mentioned which have flaws related to degradation, near surface crack and sub-surface flaws. Eddy current method also being used to calculate the thickness of substance on the sample which are coating or paint with a sensitivity range from the level of micrometres to millimetres. ECT

also able to detect corrosion on the sample because corrosion is a mechanism which change the thickness of coatings. The discovered of ECT methods can be related to Hans Christian Ørsted who was a Danish physicist and alchemist in 1820, which introduced that a magnetic field is created when an electric current flow through a wire as shown in figure 2.3 and discovered Oersted's Law (Ali et al., 2017a).



Figure 2.3 Magnetic field created through electric current flow

Source: (CK-12 Foundation, 2019), Christopher Auyeung, CC BY-NC 3.0

Although the electric current used was direct current from a dry cell (figure 2.3), this contribution has led the Michael Faraday (1831) to discover electromagnetic induction which is operating the principle of eddy current testing (Ali et al., 2017a). After three years, in 1834, Heinrich Lenz is introducing the theoretical foundation for ECT from another important principle that is Lenz's Law which explain the relationship between the direction of an induced current and the change in the magnetic flux. Although foundation of ECT has exist long ago, eddy currents were still not discovered until 1864, when James Maxwell derived the famous equations for electromagnetic fields. The development of ECT is progressing slowly until 1950 when Dr Friedrich Förster conduct an experiment on the eddy current phenomenon which leading to a detail research on ECT. Late 1960, the institute Förster founded made a cooperation with manufacturers to create a production by using the applications of ECT(S. Liu et al., 2017).

2.2 Ferromagnetic material

Ferromagnetic materials are the materials which exhibit a spontaneous net magnetization at the atomic level (Donati et al., 2016), even in the absence of an external magnetic field. When there is a presence of external magnetic field, ferromagnetic materials will strongly magnetize in the direction of the exposed field. Ferromagnetic materials are strongly attracted to a magnet and can become a permanent magnet (Mikhailov et al., 2020). These because the materials will retain their magnetization for some time even after the external magnetizing field is removed. This property is called hysteresis (Zou et al., 2018). A ferromagnetic material mechanical properties is made up of areas known as the magnetic domain. Magnetic domain is in reality a small region which is based upon quantum mechanical effect and has its own particular overall spin orientation (Lux et al., 2018). In his research, it describes that fresh spark of interest in the Berry Phase and the effects of transport originating in non-collinear magnetism and spinal chirality has been seen in the field of magnetism.

The characteristic of ferromagnetic materials is that their small group of atoms which the electrons have the same magnetic orientation will band together to form an area called domains. Electrons are tiny particle of magnets (Holzmann & Moroni, 2020) which has a north and a south pole (Hernández-Pajares et al., 2020) and it generally spin around an axis. This rotation produces a very small but extremely significant magnetic field. Each electron has one of two possible direction for its axis. For most materials, the atoms are arranged in that way because the magnetic orientation of an electron will cancel out the orientation of the other. Figure 2,4 below is that shows the respond of magnetic domains to an outside magnetic field.



S

N



Figure 2.4 Respond of magnetic domains to an outside magnetic field Source: 2020, April. <u>https://nationalmaglab.org/education/magnet-academy/watch-play/interactive/magnetic-domains</u>

In the ferromagnetic material on figure 2.4 above, the domains are randomly aligned (the illustration not the actual size or shape of domains). Normally invisible magnetic field lines which depicted in red are seen emanating from the poles of the bar magnet. The magnet position then slide to move the magnet closer to the ferromagnetic material so that it interacts with the field lines. As the processes repeat, it shows that the domains gradually aligning with the field of the bar magnet and with each other. By the time the magnetism process complete, the ferromagnetic material has become a permanent magnet itself which a dipole having oppositional north-south poles. A permanent magnet is just a ferromagnetic material in which all domains are aligned with each other (Shukrinov et al., 2019). There are commonly only four elements in the world which are ferromagnetic can become permanently magnetized at room temperature such as iron, nickel, cobalt and gadolinium (Na et al., 2018).

Ferromagnetic material has a behaviour named ferromagnetism. This behavior explained that when an external magnet is exposed to the ferromagnetic material, a magnetizm cause and it will become a lifelong magnet. Ferromagnetism, which is important for many electromechanical and electrical systems in the many automotive, electronic and even spatial exploration industries (Guo et al., 2017). This is because of the Ferromagnetic materials are often magnetized and it properties is made of the daily used ferrous types which are cobalt, iron, and nickel (Na et al., 2018). Ferromagnetic materials can be divided into magnetically soft materials like annealed iron, which can be magnetized but do not tend to stay magnetized, and magnetically hard materials, which are made from hard ferromagnetic materials such as alnico.

In daily life, ferromagnetic material is one of the most commonly used because all of these materials were used in may modern devices. These devices giving humanity a lot of benefit. The ferromagnetic materials have properties which can be easily magnetized and it is ideal to be a permanent magnet. However, once the temperature reaches a threshold termed the Curie temperature named curie point, ferromagnetic materials are unable to retain their spontaneous magnetization (L.-Z. Zhang et al., 2020). At the curie temperature, ferromagnetic materials transform into paramagnetic materials, which lose their magnetic characteristics (Pasquale, 2020). Although the materials' compatibility to be magnetized is lost, they still keep their ability to react paramagnetically to external magnetic fields.

This happens because the increase of temperature will unconditionally supplies the material with sufficient thermal energy to counterpart the material's internal aligning forces. Paramagnetic materials do not maintain their magnetic characteristics after being exposed to an external magnetic field and instead are somewhat attracted to the magnetic field when exposed to it. This means that paramagnetic materials can only become magnetised when they are exposed to magnetic fields from outside the body. Otherwise, there will be no

magnetic moment in the substance (Khandy & Gupta, 2016). The Curie temperature of various materials is given in the table 2.1 below.

Materials	Curie temperature (K)
Nickel, Ni	631
Iron, Fe	1043
Cobalt, Co	1395

Table 2.1 Curie temperature of ferum, nickel and cobalt

Source: (Chaturvedi & Goyal, 2020)

2.3 Introduction to fatigue failure

Fatigue is arguably the most significant and investigated mechanism of failure since start the days of the industrial revolution. The mining and railway industries long ago has greatly change the current fatigue research and are the most responsible for the terminology and methodology that currently used. Fatigue phenomenon happened solely because of a material cracks or fails because of repeated load exerted under the ultimate strength of the material. The term of fatigue cyclic is related to the cycle of load that can count on systems consist of rotating axes, gears and chains and it becomes more challenging when to define the cycle really means in context of the multi-axial loading (Giovanni M & Teixeira, 2017). Fatigue failures are the development and propagation of cracks caused by repeated or cyclic loads. Cyclic loads are usually and significantly below the load, which is leading the material to yeild produced by most fatigue failures (Charalambidi et al., 2016).

Fatigue failure has a habit to occurs suddenly with major catastrophic result (Nguyen et al., 2018). When a specimen is loaded, a crack will form a nucleus on a microscopically. This crack then grows until finally complete the failure of the specimen. The entire process

is the fatigue life of the component concerned. Fatigue prediction for an analysis can only be done when fatigue is not only seen as an engineering problem but also a material phenomenon that is involving an invisible micro scale crack initiation until a macro scale fatigue failure (Chowdhury & Sehitoglu, 2016). The fatigue failure which is causing the material or component malfunction will not have a sudden failure or unexpected breakdown if the component has been investigate earlier. The fatigue failure will take a lot of time to slowly deteriorate the particle of the metal or any other material until the sudden breakdown occurs.

Since the failure occurs due to the cyclic nature of the load, it causing the microscopic material imperfections to grow into a macroscopic crack (Chowdhury & Sehitoglu, 2016). This stage is the most complex stage of failure because the initial stage shows a very small sign and never extending for more than two to five grain around the nucleus or origin. Then, the crack can reach the propagation which is propagate to a critical size that results in structural or pressure boundary failure of the component. Fatigue cracks usually initiate at a place with concentration of load and structural discontinuities. The existing macroscopic crack such as weld defect also has a potential for the fatigue cracks to propagate (Niazi et al., 2021). Fatigue cracking can be overlaid with the corrosion process and the combination of stress and corrosion comprises the cracking of stress corrosion (SCC) (RAO et al., 2016). In this stage, the fatigue analysis has reach and ready to be identify it area of the occurrence of fatigue failure. Then, in the final rupture stage, there will be a sign of reducing the cross-sectional area of the material or specimen and eventually making the part become worst which produced a complete fatigue failure. Figure 2.5 shows a summary of fatigue failure stages.



Figure 2.5 Summary of fatigue failure stages

Source: (Beden et al., 2009)

2.3.1 Cyclic loading

In engineering components, it consists of loads which used on every mechanical part such as simple mechanism, machine components and vehicles. The structures can be divided into four categories namely static loads, workloads, vibration loads and accidental loads. Static loads are unchanging and continuous loads. A workload is a load that changes and occurs as a result of the functions performed by a component. Vibration loads are cyclic loads at high frequencies resulting from the environment or secondary effects of component function. This is often due to turbulent movement of fluids or rough solid surfaces. Accidental loads are usually loads imposed suddenly. The combined effect of workload and vibration load produces a cyclic load that can cause fatigue failure. The damage caused by cyclic loads is greater when the components also experience static loads and accidental loads. The presence of these two types of additional loads can add damage to the component and result in the component being more prone to failure (Dowling, 2013).

The fatigue life of a particular structure or component depends on the amplitude, load ratio, load regulation and frequency of load. Due to the actual nature of the load which is always changing randomly, it is difficult to take a cyclic load model for the fatigue process accurately. The fatigue life (N_f) can be count by the total number of cyclic loads needed to cause failure or by using the value of crack growth as shown at (2.1) below:

$$N_f = N_i + N_p \tag{2.1}$$

where, N_i is the crack initiation and N_p is the crack growth

By calculating the fatigue life through crack initiation and crack growth, it can be calculated with more accuracy which the value can be obtained directly. However, this situation of made the prediction of fatigue life using variable amplitude loads is more complex which using constant amplitude loads during the analysis of fatigue problems (Gates & Fatemi, 2016). The cyclic load is constant when it cycles between the same maximum and minimum load values. The basic definition of a constant amplitude cyclic load is shown in a formula expression such as eq. (2.2) and eq. (2.3) (Bandara et al., 2016). In these equations, the loads are count as stress which shown a certain amount of load pressured to a material. The stress range, $\Delta \sigma$ is the difference between the maximum stress value, σ_{max} and the minimum stress value, σ_{min} . The average values of the maximum stress and minimum stress are named as the average stress, σ_m . The value of the stress amplitude, σ_a is equal to half the value of the maximum and minimum stress ranges.

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{2.2}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{2.3}$$

Stress ratio or also called load ratio, R is the ratio between minimum stress and maximum stress or the ratio between maximum load, P_{max} and minimum load, P_{min} .

$$R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{P_{min}}{P_{max}}$$
(2.4)

2.3.2 Fatigue failure analysis approach

Structural or engineering components consisting of various materials usually undergo cyclic or variable stress in their operations. Mainly, metallic material is widely used in the manufacture of engineering structures. Thus, failure analysis and fatigue life evaluation of these materials are important especially for structures exposed to cyclic loads (Bandara et al., 2016). Most of the vehicle engine running components are at the same time subject to fatigue and excessive temperature. At high temperatures, the material behavior differs considerably from that in ambient temperatures under cyclic loading (Hussain et al., 2016). There are three main methods used to analyze the fatigue failure and fatigue life of metallic materials which are the stress-life method, the strain-life method and the fracture mechanics method. In general, stress-life method and the strain-life method are commonly used in determining the total fatigue life of a material (Bandara et al., 2016).

For the calculation of the number of cycles in which the material failures to a specific amount of applied stress, the stress-life curve is helpful. For constant loading of amplitude, the stress-life curve is shown on the semi-log or log-log scale. The S-N curves have been created to fit the tabular data by using the Basquin equation (Hussain et al., 2016) which is the equation (2.5) shows:

$$\sigma_a = A(N_f)^B \tag{2.5}$$

where, σ_a is the stress amplitude, *A* is the fatigue strength coefficient, N_f is the number of fatigue cycles, and *B* is the Basquin exponent.
The Basquin equation was used to obtain a general mathematical relationship to study the stress-life behaviour at elevated temperatures (Hussain et al., 2016). The equation (2.6) can be stated as follows:

$$\sigma_a = A(N_f)^B T^c \tag{2.6}$$

where, T is the absolute temperature in kelvin, and c is the temperature sensitivity parameter

The next method is a strain-based approach called strain-life (\mathcal{E} -N) which is approach while considering plastic deformations that occur in local areas that undergo stress concentration during applied cyclic loads (Dowling, 2013). The strain-life analysis method provides better fatigue behaviour analysis at low cycles compared to analysis using the stress control test method. In this method, the life of a component is related to the number of cycles that cause the onset of cracks in small structures of the same component. Through the strainlife method, it may be described by the Coffin-Manson relationship (2.7), based on the compilation of Morrow's proposal and Basquin eeuation (Gu & Ma, 2018) that determination of the fatigue-life cycle for crack start for most metallic materials:

$$\varepsilon_a = \varepsilon_{ea} + \varepsilon_{pa} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c$$
(2.7)

where, ε_{ea} is the elastic strain amplitude, ε_{pa} is the plastic strain amplitude, σ'_f is the fatigue strength coefficient, E is the young modulus, N_f is the number of cycles to failure $(2N_f$ reversals), b is an empirical constant known as the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, c is also an empirical constant of the fatigue ductility exponent of the material. This is the fundamental equation of the fatigue life analysis strain-based approach. At the intersection of the elastic line and the plastic lines a transition point can be located. The point of crossing known as $2N_t$, is the transition fatigue life that marks the cut-off point of the low cycle fatigue (LCF) and high cycle fatigue (HCF). In other words, with the rise fatigue life the proportion of elastic strain and plastic strain changes in total strain. Specifically, the plastic lines are above the elastic lines meaning that in the assessment of fatigue life, plastic strain is of more significance when fatigue life is less than transition life. Thus, the elastic line is above the plastic line. Which means, the elastic strain is playing a major role in evaluating fatigue life when fatigue life is higher than transition fatigue life (Gu & Ma, 2018). Figure 2.6 below shows a schematic total strain-life curve.



Figure 2.6 The schematic total strain-life curve

Source: (Gu & Ma, 2018)

The last method is the fatigue life evaluation method based on linear elastic fracture mechanics in which the concept of fracture mechanics is used to evaluate the strength of the structures or components that have cracks. This method is used to evaluate the growth of fatigue cracks on a material with the assumption that the material is always in an elastic state along the fatigue process occurs. Through this method, the fatigue crack growth behavior is shown through the log plot of the fatigue crack growth rate, da/dN against the log of the stress intensity factor range, ΔK whose behavior can be divided into three parts namely crack onset (region I), stable crack growth (region II) and final failure (region III). The plot of region II, which is generally a line or gradient of steady crack development, is represented a termed of the equation Paris law (2.8). This Paris law equation can be used to predict the fatigue life of specimens undergoing a fatigue crack growth process (Ancona et al., 2016).

$$\frac{da}{dN} = C\Delta K^m \qquad (2.8)$$

where, *a* is the crack length and $\frac{da}{dN}$ is the fatigue crack growth for a load cycle *N*. *C* is the **UNIVERSITI TEKNIKAL MALAYSIA MELAKA** material coefficients, ΔK is the stress intensity range seen in a load cycle and *m* are acquired experimentally through the gradient of the straight line in region II. These two constants are constants for materials whose values change on different materials. The value of the constant *m* is important because this value indicates the sensitivity to the crack growth rate (Ancona et al., 2016).

2.4 Crack parameter

Crack is a term that refers to a material failure that may be readily defined as the breakdown of a material or component without full separation of its actual size body of the components. Therefore, it is critical for the safety such like a building that fractures. If it is detected early, prevention will succesfully able to avoid or eradicate different kinds of cracks and effectively provide effective information for structural disaster (L. Zhang et al., 2018). Without any action is taken to curb the spread of cracks, it will eventually resulting worsting the fracture and may ultimately end in system collapse. Flexural fractures are often seen in areas with low shear and strong bending loads These bending and shear stresses are the primary drivers of fracture propagation, which ultimately resulting in material failure (Eisenhut et al., 2017).

Cracks are usually considered to be faults or flaws that occur as a result of material deformation. External pressures exerted on the material produce deformation, which may result in cracking. Parallel to the applied force is the compressive crack, whereas the tensile crack is perpendicular to it(Ronevich et al., 2016). Cracks in welding are caused by a variety of reasons, including the material being welded, the welding environment, and the welding process itself. This kind of fracture occurs as a result of the thermal strains generated during the welding process. It is because when any material which under thermal stresses, this simple insolation will unconditionally lead it to cause the growth of crack propagation (Eppes et al., 2016). The longitudinal fracture that is often present in the welding material is seen in Figure 2.7.



material and directly causing the material's or system's effectiveness. Additionally, material flaws may be more hazardous, resulting in loss of life, economic damage and also affecting the loss of goods or services. As a result, it is critical to use a systematic method to fracture detection in order to reduce and eradicate the occurrence of cracks in the material. Cracks may also develop in industries during production, testing, or usage since it is difficult to create a crack-proof product. Which is why a systematic maintenance should be done in according to the building through time. Figure 2.8 below shows a simple flow of periodic inspection on any building or product from the day it created.



Figure 2.8 A simple flow of periodic inspection on any building or product

Target/critical limit is set in advance using performance index or deterioration state, depending on the performance requirement.

The ability to detect cracks that are caused by fatigue, thermal shocks and stress corrosion is important to ensure safety of materials and components. For example, many incidents that occur in nuclear fuel road in nuclear reactor which is the main safety barrier of the system are due to the cracks and ruptures in these parts (Hoseyni et al., 2019). In addition, crack can lead to the early initiation of corrosion in steel because it provides easy access to the ingress of chlorides that can cause corrosion. Apart from that, the width, length and cracking frequency of the crack are all can influence the corrosion of the steel. The formation of cracks will adversely affect its durability properties (Shaikh et al., 2018).

The cyclic load is also related to pressure changing during the pipeline operations. The details of this type of crack is called corrosion fatigue which were found to be responsible for the cracking in near-neutral pH environments (Yu et al., 2016). Figure 2.9 shows the external crack in pipeline detected by Magnetic Particle Inspection and figure 2.10 shows a crack initiation at the tip of the main crack.



Figure 2.9 External crack on the surface of the pipe detected by Magnetic Particle



Figure 2.10 Crack initiation near the large tips

Source: (Niazi et al., 2021)

2.5 Non-Destructive Testing

Non-destructive testing (NDT) is examining or inspecting objects without destroying them, in order to detect local adverse imperfections generated in a device that belong to the objects. These adverse imperfections are thus referred as defects. The main objectives of conducting NDT techniques are to make sure the quality of a surface or a part according to criteria and specifications depends on each type of NDT. Many types of NDT techniques are effective in testing surface components. Radiography, eddy current testing, ultrasonic testing, acoustic emission, dry penetrant testing, and magnetic particle testing are widely used and standardized. Each of these techniques is needed to be used based on the physical principles, which can detect any defects on the surface of a part or a whole body more effectively. This is because the NDT technique with various types will have more performance and applicability if it being used through the advantages on NDT types based on the physical, geometry, and material properties (Chauveau, 2018).

Through the development of the NDT method, this test method is currently used in several applications covering a range of industrial activities. These methods are being utilised for various applications such as production, piping and inspection of products, and maintaining a uniform material quality standard (Usarek & Warnke, 2017). Furthermore, it can reduce the risk of any failure particularly in the construction of structures and piping, that would cause significant risks. There most common types of NDT techniques being used for the inspection or testing are eddy current testing, magnetic flux leakage, ultrasonic test, and dye penetrant test.

Despite NDT, there is a test that has destructive in nature which is applied on the finite number of samples rather than applied directly to the materials. Destructive testing is commonly used to evaluate the physical properties of materials, for example, testing the toughness, fracture toughness, and fatigue strength. Destructive testing is usually easier and produces more information when analyzing than NDT. However, when comparing with the NDT, NDT seem to be more efficient and accurate if it see from the other aspect such as the limitation on the multiple time the specimen can be inspected and other characteristic. The destructive test is thus not feasible enough in applying it on the machine which still in running because it needs to interrupt the service or system operation, and the parts are needing to disamble from the service (Aire & Chimezie, 2016). The differences between destructive testing and non-destructive testing are as shown in Table 2.2.

Destructive Testing	Non-Destructive Testing
To measure the material properties	To measure defects found in the material
Apply load to the material	Does not apply load to the specimen
The load cause damage onto the material	No load to cause damage to the material
Not convenient to be apply on parts while	Usually apply to parts in-service without
in-service	interruption
Examples: Eddy current testing, ultrasonic	Examples: Hardness test, compression test,
testing, magnetic flux leakage	tensile test

Table 2.2 Differences of destructive testing and NDT

Source: (Aire & Chimezie, 2016)

2.5.1 Magnetic-based NDT

Magnetic-based NDT is an inspection of materials by using a magnetic field through external or electrical methods. The inspection is a test on material and observing the distorted magnetic field response when there are presences of defects on the test materials. This inspection method can be performed without applying damage to the test materials. Because of magnetic-based NDT is a direct and contact-free inspection method for recognizing defects, it is suitable for automated inspection and then used for the inspection of metallic materials. Magnetic NDT serves a role for safety and production quality that is increasingly significant. Nowadays, there are various types of magnetic-based NDT methods, including eddy current testing (ECT), magnetic flux leakage (MFL), permanent magnetic perturbation (PMP), pulsed eddy current testing (PEC), and else (S. Liu et al., 2017).

ECT is commonly used to detect surface cracks and corrosion in metallic objects, such as surface pipes and aircraft, and building structures. MFL is commonly used for the NDT of steel pipes and tubes. PMP is a method that commonly used to test ferrous materials. PEC testing is used on detection of metal loss in metallic pipes from a considerable distance which allowing the pipes to be tested without removing insulation (S. Liu et al., 2017).

Through all the various type of magnetic-based NDT mention above, there are three main types of inspection which have been through major discussion among other researcher and become the most dominant magnetic-based NDT (Meng et al., 2021). Although these three representative NDT methods are the inspection operate on magnetic-based principles, their core principles and application differ. A comparison of these magnetic-based methods, including their core principles, advantages, and disadvantages, is clearly explained in Table 2.3.

Method	MFL method	ECT method	PMP method		
Comparison					
Principles	Magnetic refraction	Eddying effect	Perturbations in the		
			magnetic field		
Advantages	Powerful penetrant,	Suitable for	applicable in		
	valid for external and	automatic detection,	installation and		
	internal defect, not	applicable in	carrying, light		
	disturbed by non-	installation and	sensor weigh, not		
	ferromagnetic	carrying, light	limited to insulator		
	material	sensor weight			
Disadvantages	Limited to	Only for surfaces	Limited to		
	ferromagnetic	and subsurface	ferromagnetic		
Alt M	material, heavy	detection, sensitive	material, sensitive		
	detection device	to sensor liff-off	to sensor lift-off		

Table 2.3 Comparison of MFL, ECT and PMP

Source: (S. Liu et al., 2017)

MFL is majorly based on an increase in leakage from magnetic refraction, which is a peak on test signal appear. Next, ECT is then based on a disturbance in the secondary magnetic field of an eddy current signal when the fault is detected. PMP working principle is operated by a permanent magnet and if the presence of flaws in the specimen is detectable, it will produces a distorted test signal if the testing material has defective elements. Therefore, when these NDT methods thoroughly analyzed from a new perspective, it can explain the differences in development, physical mechanisms, defect features, testing procedures, and test equipment test, signal features (S. Liu et al., 2017).

2.5.2 Eddy Current Method

ECT is an NDT method that works based on the electromagnetic principle whenever it is performing inspections. On the other hand, the term electromagnetic testing is often referred to as eddy current method inspection. ECT is one of the oldest NDT methods which its principle is based on the eddy current effect. The real importance of ECT has not been completely realized until later, which theory of ECT has been more understood and implemented in the NDT community. However, with the development of electromagnetic and magnetic testing methods that are increasing over time which made the electromagnetic testing is classified as one that called electromagnetic NDT methods, and ECT is one of these classification types (S. Liu et al., 2017).

Remote field testing and magnetic flux leakage are also methods based on electromagnetic theory. ECT is a foundation from Faraday's law principle of electromagnetic induction. The ECT application is widely used for an inspection to the material that involved in deficiency measurement. Furthermore, the most priority when using the eddy current method is for defect detection, especially on the surface flaws. It is also a technique with advantages in inspecting the tiny spaces. Therefore, before using the ECT as an NDT for an inspection, the probe style, parameter, spacing, and type of defect need to be deeply studied and understood since ECT advantages are majorly only being used onto the material surface. So, the detection of defects is mostly discovered only along the surfaces of the material (Ali et al., 2017a).

Surface defect detection of NDT methods for ECT is when the high electrical conductivity supply to the probe then to the material. These working principles is a step to measure the decrease in the magnetic field created by eddy current distortion in the test

material caused by faults. The presence of fault or defect on the material will be detected by the magnetic permeability, which caused an eddy current flow shift and a corresponding phase change, and the measured current amplitude. This mechanical principle is the basis of the flat coil used in the eddy current inspection method, which is ECT's main working principle. For further detail of ECT, as shown in the figure 2.11, a circular coil carrying an AC current is placed near a ferromagnetic material which generates an eddy current on the material (S. Liu et al., 2017).



Figure 2.11 Principle of ECT method

Source: (S. Liu et al., 2017)

2.6 Summary

Overall, this chapter explained briefly the ferromagnetic material, the fatigue failure, and the ECT. The history and theory of fatigue failure and eddy current testing ECT are described as an introduction. Meanwhile, the mechanism of ferromagnetic material is also explained in this chapter. Other than that, there are three stages of fatigue failure which cause by cyclic loading that influence the growth of fatigue cracks. Then, the three method of predicting fatigue life by numerical integration is described. The equations required when predicting fatigue life based on the concept stress-life, strain-life and mechanic fracture. Next, the ECT is one of the magnetic-based NDT which being discussed.

In the next section, the discussion of the experimental work will start from identifying the material of the specimen. Then, the portable ECT inspection equipment and probe which has been used in this study and the type of probe movement. Then, the portable UT inspection will be used and the data of both NDT will be compared in order to study the ECT inspection effectiveness on weldment.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain the methodology that is being used to ensure this project is well completed. It compasses tools and techniques to conduct a particular research or finding. While conducting this project, it is vital to select an accurate and proper method that suits the project objective to collect all the necessary information. In order to identify all the information and data, planning must be done in the proper manner.

The project started from planning where flow chart and Gantt chart are created. Then, it follows the methods that being used to achieve the target of the study are shown in Figure 3.1. The study methodology begins with the selection of appropriate test materials to be used as test specimens. The material of the specimen used is ferromagnetic material. The NDT of this inspection need this type of material in order to fully function in detecting the crack. The specimen which is weldment of pipeline is obtain from an actual source from a company from Johor. This pipeline has been cut out because of crack form in the welding. The specimen will be clean before the study will be conduct. The starting point is a point where the inspection will be started circularly the weldment pipeline.

The study of the portable ECT inspection was conduct through two type of probe movement which are toe inspection and cap inspection. Both of these methods are carried out on specimens designed according to set standards. The data crack detected from the inspection will be study and analysed in a form of graph. Then, the UT inspection has been conducted in order to compare both portable ECT and UT data and the evaluate the effectiveness of portable ECT on welding inspection.



Figure 3.1 Flow chart of methodology

Gantt Chart for PSM 1

Task W13 W14 W1 W2 W3 W4 W5 W6 W7 **W8** W9 W10 W11 W12 Discussion with the supervisor **Determination of the topic and** YS1, A Pala 145 objectives of the project Literature review **Report chapter 1 Preparation on progress report Report chapter 2** Selection of material and specimen 12 13.6 preparation **Report chapter 3** Submission of draft final report **PSM 1 seminar**

Table 3.1 Gantt Chart for PSM 1

Gantt Chart for PSM 2

Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Discussion with the supervisor														
Laboratory session	AT 51,	Me												
Data analysis		N N	n. Vi											
Comparative study			A											
Preparation on progress report							-		V					
Results and discussion							1	-						
Report chapter 4 and chapter 5	_				/									
Final report writing	·····	Jo,	2	R		R	° is	للعب	فير	ود				
Submission of final report		_					-							
PSM 2 seminar UNIVEF	SII	IE	KN	KA	_ M.	ALA	YSI	AM	EL/	AKA				

Table 3.2 Gantt Chart for PSM 2

3.2 Material and specimen

Ferromagnetic materials are the materials which exhibit a spontaneous net magnetization at the atomic level (Donati et al., 2016), even in the absence of an external magnetic field. When there is a presence of external magnetic field, ferromagnetic materials will strongly magnetize in the direction of the exposed field. Ferromagnetism is avital in modern industry and technology as it is fundamental for many electromechanical and electrical system which used on various industries automobiles, collaborative robots, and even space exploration (Guo et al., 2017). Therefore, these electromechanical and electrical system need a proper maintenance in order to elongate the materials life expectancy. One of the most preferable maintenance inspections on ferromagnetic material is ECT which is it using the electromagnetic field in the material selected. Thus, the defect and crack detected in the materials can be analysis and make a proper guess of time for the material or the equipment will be totally broken.

In this thesis, the material which will be inspect is ferromagnetic material pipes that has been discarded for a certain factory because of the leakage form from it. This leakage happened because of the crack form in the weldment from this ferromagnetic pipe. Figure 3.2 below shows the specimen which has been obtain from a factory because of it defect.



Figure 3.2 Ferromagnetic pipeline with weldment 40

The specimen is made of a ferromagnetic material which is suitable for the inspection by using the ECT inspection and later will be inspect again by using the UT inspection. This pipe has 3 weldments and each weldment contain 1 layer of welding. In this thesis, the inspection will only investigate one weldment which is a weldment on the straight lines pipe. This is because the inspection on the join of pipe will be a bit complex and hard to inspect by UT inspection later. The UT inspection need a bigger flat surface in order to inspect the welding properly. Figure 3.3 below is the weldment that will be inspect by both ECT and UT inspection.



Figure 3.3 Weldment with labeled starting point

The inspection of the weld on this pipe will be begin on the starting point as shown in figure 3.3. The inspection process will continue incircle the specimen pipe by follow the arrow until it reaches the starting point again. The inspection processes will also be the same on the other side of the weldment that is start from starting line until it fully incircle the pipe.

3.3 ECT device

ECT is an NDT method that works based on the electromagnetic principle whenever it is performing inspections (S. Liu et al., 2017). The Eddy Current Weld Probes are specifically intended for non-ferrous weld examination on a ferromagnetic material inspection. They can detect surface cracks on a weld with a non-conductive surface layer up to 2mm. The Weld Probe's application specific design allows it to check welds with uneven surfaces and coatings, which can make inspection more difficult when using protable ECT methods. So, the detection of defects is mostly disturbed along the surfaces of the material if the method of inspection is by using the portable ECT methods (Ali et al., 2017). Figure 3.4 (a) is the ECT probe and kit that has been used in order to inspect the welding on the pipe for this thesis. The figure 3.4 (b) is a detail of the ECT equipment and the Eddy Current Mentor EM that display the crack defect in the welding.



Figure 3.4 (a) ECT equipment, (b) Eddy Current Mentor EM detail

Before the inspection of the ECT begin, the ECT probe and setting must be set in order to gain a more accurate reading while inspecting the welding. Then, the welding of the pipe will need to do a coating calibration so that the effectiveness of the reading will not inaccurately inspect. The coating inspection is important to determine the thickness of the coating layer on the welding before the examination in order to compensate for it. If this is not done, wrong sensitivity levels may be chosen, and potential problems may be ignored. The probe used to check the coating thick is as shown in figure 3.5



Figure 3.5 Broadband Probe 632-134-000 (130P3)

Broadband Probe 632-134-000 (130P3) figure 3.5 will detect the thickness layer of the non-ferrous on the weldment and the thickness will be recoded for further analysis. After that, the probe and the mode of the ECT can be change into the welding inspection which then start the inspection processes. Figure 3.6 is the display and the settings of the welding inspection mode.



Figure 3.6 ECT display 43

3.3.1 ECT inspection method

The ECT inspection method can be divided into two types which are the toe welding inspection and the cap welding inspection. For both of the method, their pattern in moving the probe is like producing a 'Z' shape continuously on the toe of the welding and the cap of the welding. Figure 3.7 below shows scanning and inspecting pattern for the toe welding inspection and figure 3.8 is the scanning and inspecting pattern for the cap welding inspection.



Figure 3.7 Toe welding inspection



3.4 UT device

The UT method is an NDT that employs mechanical vibrations that are similar to sound waves but have a greater frequency. Ultrasonic testing inspects objects by using high-frequency sound waves that are above the human hearing range (Sharma & Sinha, 2018). An ultrasonic energy beam is focused towards the thing which is weldment to be evaluated. The UT method capable of detecting faults on the surface and subsurface of discontinuities created during welding activity (Abd. Rahman et al., 2015). Except when intercepted and reflected by a discontinuity, this beam goes through the object with no loss. After that, the technique of ultrasonic contact pulse reflection is applied. A transducer is used in this system to convert electrical energy into mechanical energy. A high-frequency voltage excites the transducer, causing a crystal to vibrate mechanically. The figure 3.9 is the UT equipment that has been used in this comparative data.



Figure 3.10 (a) UT crystal probe, (b) UT crystal probe label

The crystal probe figure 3.10 (a) becomes a source of ultrasonic mechanical vibration. These vibrations are conveyed into the welded pipe via a couplant figure 3.11, which is typically a thin film of oil. When an ultrasonic wave pulse strikes a discontinuity in the test piece, it is reflected back to its place of origin. As a result, the energy returns to the transducer. The transducer now acts as a receiver for the reflected energy.



A trace on the screen of a cathode-ray oscilloscope displays the initial signal or main bang which is the returning echoes from the discontinuities, and the echo of the test piece's rear surface. Because the velocity of sound through a particular material is virtually constant, distance measurement is achievable, and discontinuities can be technically detected, located, and evaluated. Figure 3.12 is the sample of test specimen which is has been undergoing the UT inspection according to the method follows.

	<u> </u>		T
And			
	sonas	spection	
1 March	NDE INSPI	ECTION REPORT TRASONIC	
AS PORT	Webl Spectrum Cross Section(s)	Date 25/02/16 Specimen Type Phin mm Acceptance Spec. St/16/38	
the solution			
1 Mps			
	To Scrie	The length Disates from J Street The Indian	and the second
	1 Centre Lines (Seek	20 47 -4 60	11
ALAYSIA	Commuts		
SET M	[hspector Cury Stor Signal]		
E			
Figure	3.12 Sample of te	st specimen	

3.4.1 UT inspection method

Crack can be detected at various angles of orientation using probes with variable beam angles. A defect aligned normal to a beam angle will provide a strong detector signal, however with a beam angle 20 or 30 degrees away from the normal, the reflected signal may be very modest, or non-existent. Only when the defect and crack surface area in the welding equals the weld area does the deflected signal reach its maximum amplitude. As a result, the magnitude of the reflected signal can only provide a poor indicator of the defect's true size. In this thesis the crystal probe that has been used is 60 degree as shown in figure 3.10 (b). The expected succession of crystal probes as a 60 degree is passed across a specimen block with a defect or crack is shown in Figure 3.13. As the signal reach the crack in the welding,

A.

اوىيۇم

the return signal will be disturbed while then display on the screen as defect signal. The defect signal becomes evident as the probe goes over the defect's edge.



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Overall, the research methods described in this chapter are implemented to achieve the objectives that have been outlined and the results required to lead to the contribution of knowledge. The fatigue crack behavior in the welding has been detected on NDT inspection. The selected NDT method, ECT will used to detect the eddy current signal released from the specimen during the fatigue crack inspection. Then, the UT inspection will be made so that the observations of the fatigue crack is determined and compared for both ECT and UT.

The results obtained through the research method are described and analyzed in the next chapter. The data collected from eddy current signal and ultrasonic signal will be compared to evaluate the effectiveness of portable ECT on weldment inspection.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 **Results and discussion**

This chapter will be discussing the results of the eddy current testing which contain the defect detected in the weldment of the steel pipe. The results of the defect detected by using the eddy current testing is collect in form of eddy current display. The picture then has been simplified into visual diagram, specific length and depth which contain the rough assumption of the defect in the weldment. The data then tabulated into a scatter line graph in order to further understand the detection in the weldment of the steel pipe.

This chapter is divided into three parts and sub-section. The first section is explaining about the specific ECT settings for the weld inspection and the rough data collected from the ECT. Then, the result of the ECT will be further describe into an analysis which tabulated and graphically presented in the next section. Lastly, the section 4.3 will be discussing the comparative data collected which is conducted by using the Ultrasonic Testing based on the defect found and display in a form of graph.

4.2 **Results of ECT weld inspection**

Eddy current reading is a method of inspection using the electromagnetic wave which being conduct through the ferromagnetic material. In this case, the inspection of the ECT is done on the weldment of an actual steel pipe which has been dispose because of a lot of defect detected in the weldment. By using the ECT instrument, there are various type of setting that need to be done and in order to get a more specific and fixed calibration, the setting of the ECT mode has been finalize which are as has shown in the table 4.1 below.

Settings	Value of the settings			
Gain	40.0 40.0dB			
Phase	75 deg			
Persistence	0.5sec			
Scan Time	10.0sec			
LP Filter	100.0Hz			
Drive voltage	8.0V			
Drive percentage	100%			
Receiver Gain	22dB			
HP Filter	0.0Hz			

Table 4.1 Setting of the ECT mode

ECT inspection on the weldment has been divided into three type which are inspection on the both side of toe and the cap of the weldment. Therefore, the data collected from the ECT inspection is being divided into three as according to the methods mentioned above. The figure 4.1 below shows the weldment of pipe labeled with the position of the inspection of the ECT. Since the weldment on the steel pipe is in circular form, the figure 4.1 below is a simplified picture of the weldment that has been categorized into a straight line with the labeled on it which specify the location of the ECT inspection.





Left toe weldment inspection



The figure 4.2 (a), (b), (c), (d), (e), (f), (g) below is presenting about the location which is right toe of the weldment inspection that will be further elaborate in form of the display reading that has been scanned by using the ECT. There are seven defects located on the right toe of the weld. The figures below show the ECT reading of the defect.









(g)

Figure 4.2 (a), (b), (c), (d), (e), (f), (g) ECT crack reading for right toe inspection

The figure 4.2 above is presenting about the location of the weldment inspection that will be further explain in the table 4.2 below which describing the position and the depth of the defect detected on ECT reading based on the location of the weldment inspection.

AST TE	Table 4.2 Right toe w	eldment inspection
	Depth (mm)	Position (cm)
上	في السياما	اونيوم 11.5ق نيڪ
UNI	VERSITI 7.5KNIKAL	MALAY 97.7-18.3 LAKA
	0.3	28-28.15
	0.3	29.8-32.8
	0.25	39.7-41
	0.2	48.9-49.1
	0.35	50.6-52.8

The next ECT reading is which been scanned is the left toe of the weldment. In the scanned operation of ECT on the left toe, there are eight defect which has been detected. The figures 4.3 (a), (b), (c), (d), (e), (f), (g), (h) below show all the displays of ECT reading.





(b)



(e)





Figure 4.3 (a), (b), (c), (d), (e), (f), (g), (h) ECT crack reading for left toe inspection

The figure 4.3 above is presenting about the defect of the weldment inspection on the left toe that will be further explain in the table 4.3 below. It is also describing about the position and the depth of the defect detected on ECT reading based on the location of the weldment inspection.

Depth (mm)	Position (cm)
1.0	0-3.25
0.5	7.4-11.5-12.2
0.35	14.6-15.2
0.6	19.1-25.4
0.3	28-28.15
⁰ ////n 0.2	38.95-39.05
كل مادميا ملاك	ويبوم 52.8-53.55
INIVERSI ^{2.0} TEKNIKA	L MALA45555.5MELAKA

Table 4.3 Left toe weldment inspection

Lastly is the figure 4.4 (a), (b), (c), (d) below is presenting about weldment inspection on the cap of the weldment that will be further elaborate in form of the display reading that has been scanned by using the ECT. There are four defects located on the cap of the weld. The figures below show the ECT reading of the defect.





The table 4.4 below shows a data which has been recorded into a table that describing the defect detected by scanning the cap of the weldment.

Depth (mm)	Position (cm)
1.5	17.7-18.3
0.3	28-28.15
0.25	39.7-41
2.0	54.5-55.5

Table 4.4 Cap weld	dment inspection
--------------------	------------------

4.3 Analysis of the ECT reading



Figure 4.5 Eddy current reading on welded pipe (Right Toe)


Figure 4.6 Eddy current reading on welded pipe (Left Toe)



Figure 4.7 Eddy Current reading on welded pipe (Weld Cap)

In the ECT reading on the pipe weldment, the effectiveness of the ECT is very sensitive because the defect and crack found in the weldment are very fast. The signals are indicating from the center of the display viewing the point moving relatively to any direction which depends on the type of the crack in the welding. While there is a crack found, the point will move to the edge of the ECT display causing the red line viewed on it. This length of the red line can be used as an estimation of the crack length found in the welding. Based on the figure 4.5 shows above, the graph has been indicated that there are 7 defects and cracks which has been detected through the right toe inspection using the ECT. The highest length of the crack found is at the position 29.8cm until 32.8cm with a 0.3mm depth. On the other hand, at the position 17.7cm until 18.3cm the highest crack depth is 1.5mm was found on this right toe ECT inspection.

The graph on the figure 4.6 shows above has been indicated that there are 8 defects and cracks which has been detected through the left toe inspection using the ECT. The longest crack found is from the position 19.1cm until 25.4cm while the highest depth crack found in the welding is 2.0mm which is from the position 54.5cm until 55.5cm that is the end of the pipe circle. Next, based on the figure 4.7 shows above, the graph has been indicated that there are 4 defects and cracks which has been detected through the cap weldment inspection using the ECT. The crack found by the cap weldment inspection is overlapping with the right toe and left toe inspection. The right toe inspection which are overlapping on the cap weldment inspection which is overlapping on the cap weldment inspection which is overlapping on the cap weldment inspection is on the position 54.5cm until 55.5cm. On the position of 28cm until 28.15cm, this case shows that the crack reading is shown on both right toe and left toe inspection. So, it shows that the crack found on this position proved that the crack is formed perpendicularly to the weldment.

4.4 Comparative data with the UT

Ultrasonic testing is an NDT method that testing by employs mechanical vibrations that are similar to sound waves but have a greater frequency. An ultrasonic energy beam is focused towards the thing to be evaluated. Based on the actual pipe, the inspection of the pipe using the UT is quite challenging because the surfaces of the pipe on one side is large and on the other side is narrow which complexing the inspection processes. However, the inspection is successfully recorded through multiple times of test conducted. The following are all the defect or crack that has been detected by using the UT testing. The UT a-scan display recorded then has been classified based on the toe side inspection of ECT so that the comparison of the data can be tabulated and compared easier.

The figure 4.7 (a), (b), (c), (d), (e), (f), (g) below shows the UT display of the pipe which has been classified based on the right toe reading from the ECT display reading. For the right toe data collected, it shows that there 7 defect or crack that has been detected same as ECT reading.



(a)

(b)





(d)



Figure 4.8 (a), (b), (c), (d), (e), (f), (g) UT crack reading based on the ECT right toe inspection

The figure 4.8 above is presenting about the location of the weldment inspection that will be further explain in the table 4.5 below which describing the position and the depth of the defect detected on UT reading based on the location of the weldment inspection for the right toe defect.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Depth (mm)	Position (cm)
0.3	10-11.5
1.5	17.7-18.3
1	28-28.15
5	32.7-33.3
0.5	39.7-41
0.5	48.9-49.1
1	50.6-51.4

Table 4.5 UT inspection reading based on the ECT right toe inspection

Lastly, the figure 4.9 (a), (b), (c), (d), (e), (f) below is presenting about weldment inspection on the left toe inspection that will be further elaborate in form of the display reading that has been scanned by using the UT. There are six defects located on the welding that is different compared to the ECT reading.



Figure 4.9 (a), (b), (c), (d), (e), (f) UT crack reading based on the ECT left toe inspection

The figure 4.9 above is presenting about the location of the weldment inspection that will be further explain in the table 4.6 below which describing the position and the depth of the defect detected on UT reading based on the location of the weldment inspection for the left toe defect.

Depth (mm)	Position (cm)	
1.0	0-2.5	
0.5	11.5-12.2	
1	28-28.15	
2 ALAYSIA	38.95-39.05	
12	52.8-53.55	
2.5	54.5-55.5	
كنيكل مليسيا ملاك	اونيۆمرسىتى تيڭ	
UNIVERSITI TEKNIKAL MALAYSIA MELAKA		

Table 4.6 UT inspection reading based on the ECT left toe inspection



Figure 4.10 UT Reading on Welded Pipe (Right Toe)



Figure 4.11 UT Reading on Welded Pipe (Left Toe)

In the UT reading on the pipe weldment, the effectiveness of the UT is not as sensitive ECT reading because the defect and crack found in the weldment are need higher concentration while the inspection process is running. The signals frequency is indicating any crack form in the welding based on the display showed. While there is a crack found, the frequency on the display will fluctuated which cause of the disturbance of the frequency going back to the detector. Every fluctuated frequency show that there are cracks form in the welding. Based on the figure 4.10 shows above, the graph has been indicated that there are 7 defects and cracks which has been detected through the UT inspection based on the right toe inspection using the ECT. The highest length of the crack found is at the position 10cm until 11.5cm with a 0.3mm depth. On the other hand, at the position 32.7cm until 33.3cm the highest crack depth is 5mm was found on this UT inspection. Because of the depth of crack is exactly 5mm which is same as the thickness of the welded pipe, it proved that the pipe has a leakage on this position.

The graph on the figure 4.11 shows above has been indicated that there are 6 defects and cracks which has been detected through the UT inspection based on the left toe inspection using the ECT. The longest crack found in the welding pipe based on the left toe ECT inspection is 2.5 cm long from the position 0cm until 2.5cm. While the highest depth crack found in the welding is 2.5mm which is from the position 54.5cm until 55.5cm that is the end of the pipe circle.



Figure 4.12 Comparison of UT and ECT based on the ECT right toe inspection



Figure 4.13 Comparison of UT and ECT based on the ECT left toe inspection

The tabulated graph of ECT and UT will then be combined based on the ECT inspection types that are right toe inspection and left toe inspection. The differences of the line graph will indicate the effectiveness of the ECT compared to the UT data. Based on the combination of the data for the ECT right toe inspection on figure 4.12, it shows that the number of defect and crack detected are same for both of them. However, there are 2 cracks on ECT reading detected that has a different position compared to the UT reading that are from the position 29.8cm until 32.8cm and 50.6cm until 52.8cm. the depth found for both of these cracks was also different which are 5mm and 1mm. there are three more defects and crack which has been detected that has a different depth of crack, however the position on the defect and crack detected are same on both ECT and UT reading.

On the figure 4.13, the graph is presenting about the comparison of the data summarized on both of ECT and UT reading based on the ECT left toe inspection method. It can be observed that there are six defect and crack are match for both ECT and UT inspection. For the position 0cm until 3.25cm and 7.4cm until 12.2cm crack both have the same depth of cracks. However, the length of these two cracks are not same that UT reading shows a shorter reading compared to the ECT reading. There are four other detected cracks which has the same length detected for both ECT and UT inspection but the depth of ECT reading is lower compared to UT reading. Other than that, there are two defect and crack that has not been detected by using the UT inspection compared to the ECT inspection. This issue happened most likely because of the uneven surfaces of the pipe which is cause the ECT display detecting the gap of the uneven surfaces as a crack detected.

It shows that the sensitivity of the ECT is really good which help the inexperience inspector to learn the differences of the crack in welding and the uneven surfaces. Although by using the UT is very accurate, the preparation to begin the inspection will take a couple more times compare to the ECT inspection. Furthermore, UT inspection also need a lot more focus which the movement while the inspection in processes. However, the portable inspection for both NDT are troublesome which because of the defect and crack that has been detected will need to be recorded and marked manually on the specimen.

ECT excels in inspecting welds subjected to cyclical loading, which can cause cracks. This description includes many of the welds used in infrastructure and aircraft where a rapid expansion of cracks would almost certainly result in catastrophic failure, loss of life, and environmental damage. One of the best approaches for verifying the integrity and safety of these high-value and highly important assets is eddy current array testing for weld inspection (Ali et al., 2017). These inspections are best carried out with a tough and portable eddy current device that can be conveniently employed in the outdoor situations where many of these welds are found.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The flexibility and speed of portable and conventional eddy current equipment for weld inspection are advantages. Complex geometries certainly provide a difficulty when utilizing eddy current for weld inspection, however producing a flexible eddy current array probe that encompasses all of these zones is quite straightforward. This enables for a more thorough examination of the weld and defects in the uneven surface. Eddy current array for weld inspection can also be used to inspect welds in a wide range of surface conditions, but sufficient training is required. The signals caused by defects and the signals caused by uneven surface are jumbled together, especially when the magnitudes of the two signals are extremely similar in value, therefore identification of such surface defects on ECT is very likely hard to differentiate (Gao et al., 2015).

4.5 Summary

Overall, this chapter presenting the steps to conduct this study. First, conducting the ECT inspection on weldment of the cut industrial pipeline which been made of ferromagnetic material. Through this data, the presence of crack in the welding detected and the sensitivity of crack detection got calculated and the characteristic of the crack has been investigated.

In the next session, the study is presenting the conclusion for the whole observastion of this thesis and explain the effectiveness of portable ECT being used to evaluate the crack in welding pipeline. Then, the recommendation for improvement in the study on this topic

in the future.



CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Through all the observed and proven results, it is proved that the weldment inspection can be made by using the ECT on ferromagnetic materials. The pipeline that made of ferromagnetic has been give good responds on inspection by using the ECT. The weldment inspections that has been conduct were also successfully study when the inspection by using the ECT. The portable ECT despite its small cost, the development of ECT systems are capable of detecting fatigue and crack faults form in welding. However, the deficiency of the equipment will always occur when the simplified version of equipment has been constructed. Through this study, it shows that the sensitivity of portable ECT when detecting the flaws in welding is really high which because of the main function of the ECT inspection is specialize in detecting the surface flaws and crack. The ECT inspection on welding able to detect the presence of crack more easily and efficiently compare to the UT that need a high focus on every stroke of detection probe. The portable ECT has high detection rate but it cannot accurately inspect the real depth of crack in the welding and its data is also mixed between the irregular surface on welding and cracks in the welding. So, portable ECT need an inspector which has a lot of experiences of managing the portable ECT equipment in order to familiarize them to differentiate the crack in welding or the welding surfaces flaws.

5.2 Recommendation

Through this study, the effectiveness of ECT inspection on the crack in the weldment is partially same as the UT inspection. Therefore, there is a lot of room that can still be improved to ensure that the crack inspection on the pipeline welding by using the ECT. With this, some suggestions are listed as follows as further study in the future:

- In this study, the inspection specimen which is the ferromagnetic pipeline does not have a welding with a continuous flat and clean surface. So, in the next study, the specimen which obtain from any industry must have a better condition so that the data obtain will be more accurate.
- 2. It is recommended that the next study will do an analysis on multiple more software which that elaborate more on the data collected from portable ECT.
- Through this study, the comparison data has been made only with the portable UT equipment. For further improve this study, it is suggested that the comparison data will be made with another type of portable inspection which is Radiographic Testing (RT)

REFERENCES

- Abd. Rahman, N. A., Nor Ayob, N. M., Pusppanathan, J., Yunus, F., Fazalul Rahiman, M. H., Ahmad, N., Ahmad, A., Md Yunus, M. A., Abas, K. hamimah, Leow, P. L., & Zakaria, Z. (2015). Inspection by ultrasonic tomography (UT) leading trend in welding joint monitoring. *Jurnal Teknologi*, 77. https://doi.org/10.11113/jt.v77.6416
- Aire, G. E., & Chimezie, H. N. (2016). Comparison of Non-Destructive and Destructive Examinations in Today's Inspection Practices. http://creativecommons.org/licenses/by/3.0/
- Ali, K. bin, Abdalla, A. N., Rifai, D., & Faraj, M. A. (2017a). Review on system development in eddy current testing and technique for defect classification and characterization. *IET Circuits, Devices & Systems*, 11(4). https://doi.org/10.1049/ietcds.2016.0327
- Ali, K., Abdalla, A., Rifai, D., & Faraj, M. (2017b). A Review on System Development in Eddy Current Testing and Technique for Defect Classification and Characterization. *IET Circuits, Devices & Systems, 11*. https://doi.org/10.1049/iet-cds.2016.0327
- Almeida, G., Gonzalez, J., Rosado, L., Vilaça, P., & Santos, T. G. (2013). Advances in NDT and materials characterization by eddy currents. *Procedia CIRP*, 7, 359–364. https://doi.org/10.1016/j.procir.2013.05.061
- Ancona, F., Palumbo, D., de Finis, R., Demelio, G. P., & Galietti, U. (2016). Automatic procedure for evaluating the Paris Law of martensitic and austenitic stainless steels by means of thermal methods. *Engineering Fracture Mechanics*, 163, 206–219. https://doi.org/10.1016/j.engfracmech.2016.06.016
- Bandara, C. S., Siriwardane, S. C., Dissanayake, U. I., & Dissanayake, R. (2016). Full range S-N curves for fatigue life evaluation of steels using hardness measurements. *International Journal of Fatigue*, 82, 325–331. https://doi.org/10.1016/j.ijfatigue.2015.03.021
- Beden, S. M., Ariffin, A. K., Beden, S. M., Abdullah, S., & Ariffin, A. K. (2009). Review of Fatigue Crack Propagation Models for Metallic Components View project Review

of Fatigue Crack Propagation Models for Metallic Components (Vol. 28, Issue 3). http://www.eurojournals.com/ejsr.htm

- Charalambidi, B. G., Rousakis, T. C., & Karabinis, A. I. (2016). Analysis of the fatigue behavior of reinforced concrete beams strengthened in flexure with fiber reinforced polymer laminates. *Composites Part B: Engineering*, 96, 69–78. https://doi.org/10.1016/j.compositesb.2016.04.014
- Chaturvedi, P., & Goyal, M. (2020). Size and shape effect on Curie temperature in nanomaterials. *Materials Today: Proceedings*, 43, 1348–1351. https://doi.org/10.1016/j.matpr.2020.09.168
- Chauveau, D. (2018). Review of NDT and process monitoring techniques usable to produce high-quality parts by welding or additive manufacturing. *Welding in the World*, 62(5), 1097–1118. https://doi.org/10.1007/s40194-018-0609-3______
- Chowdhury, P., & Sehitoglu, H. (2016). Mechanisms of fatigue crack growth a critical digest of theoretical developments. *Fatigue & Fracture of Engineering Materials & Structures*, 39(6). https://doi.org/10.1111/ffe.12392
- da Costa Mattos, H. S. (2017). Modelling low-cycle fatigue tests using a gradient-enhanced continuum damage model. *International Journal of Damage Mechanics*, 26(8). https://doi.org/10.1177/1056789516653244
- Dadfarnia, M., Sofronis, P., Brouwer, J., & Sosa, S. (2019). Assessment of resistance to fatigue crack growth of natural gas line pipe steels carrying gas mixed with hydrogen. *International Journal of Hydrogen Energy*, 44(21), 10808–10822. https://doi.org/10.1016/j.ijhydene.2019.02.216
- de Lacerda, J. C., Martins, G. D., Signoretti, V. T., & Teixeira, R. L. P. (2017). Evolution of the surface roughness of a low carbon steel subjected to fatigue. *International Journal of Fatigue*, 102, 143–148. https://doi.org/10.1016/j.ijfatigue.2017.05.010
- Donati, F., Rusponi, S., Stepanow, S., Wackerlin, C., Singha, A., Persichetti, L., Baltic, R.,
 Diller, K., Patthey, F., Fernandes, E., Dreiser, J., ljivan anin, ., Kummer, K., Nistor,
 C., Gambardella, P., & Brune, H. (2016). Magnetic remanence in single atoms. *Science*, 352(6283). https://doi.org/10.1126/science.aad9898

- Dowling, N. E. (2013). *Mechanical behavior of materials : engineering methods for deformation, fracture, and fatigue*. Pearson.
- Dwivedi, S. K., Vishwakarma, M., & Soni, A. (2018). Advances and Researches on Non Destructive Testing: A Review. In *Materials Today: Proceedings* (Vol. 5). www.sciencedirect.comwww.materialstoday.com/proceedings
- Eisenhut, L., Schaefer, F., Gruenewald, P., Weiter, L., Marx, M., & Motz, C. (2017).
 Effect of a dislocation pile-up at the neutral axis on trans-crystalline crack growth for micro-bending fatigue. *International Journal of Fatigue*, *94*, 131–139.
 https://doi.org/10.1016/j.ijfatigue.2016.09.015

Enya Vermeyen. (2019). Probing itinerant ferromagnetism with ultracold quantum gases.

- Eppes, M. C., Magi, B., Hallet, B., Delmelle, E., Mackenzie-Helnwein, P., Warren, K., & Swami, S. (2016). Deciphering the role of solar-induced thermal stresses in rock weathering. *Geological Society of America Bulletin*, 128(9–10). https://doi.org/10.1130/B31422.1
- Gao, P., Wang, C., Li, Y., & Cong, Z. (2015). Electromagnetic and eddy current NDT in weld inspection: A review. *Insight - Non-Destructive Testing and Condition Monitoring*, 57. https://doi.org/10.1784/insi.2015.57.6.337
- Gates, N., & Fatemi, A. (2016). Multiaxial variable amplitude fatigue life analysis including notch effects. *International Journal of Fatigue*, 91, 337–351. https://doi.org/10.1016/j.ijfatigue.2015.12.011
- Ge, J., Yusa, N., & Fan, M. (2021). Frequency component mixing of pulsed or multifrequency eddy current testing for nonferromagnetic plate thickness measurement using a multi-gene genetic programming algorithm. *NDT and E International*, 120. https://doi.org/10.1016/j.ndteint.2021.102423
- G. Giller, & v. Khomenko. (2000). Technologies and Hardware of Ultrasonic Testing of welded Joints of Steel and Polyethylene Pipelines. JSC VNIIEF-VOLGOGAZ Ltd., Moscow, Russia, 2000–11.

- Giovanni M, & Teixeira. (2017). Fatigue of Metals: Failure and Success. *Research and Development, Dassault Systemes Simulia, Sheffield, UK.*
- Guimaraes, A. v., Brasileiro, P. C., Giovanni, G. C., Costa, L. R. O., & Araujo, L. S.
 (2016). Failure analysis of a half-shaft of a formula SAE racing car. *Case Studies in Engineering Failure Analysis*, 7, 17–23. https://doi.org/10.1016/j.csefa.2016.05.002
- Guo, Y., Deng, Y., & Wang, S. X. (2017). Multilayer anisotropic magnetoresistive angle sensor. Sensors and Actuators, A: Physical, 263, 159–165. https://doi.org/10.1016/j.sna.2017.06.001
- Gu, Z., & Ma, X. (2018). A feasible method for the estimation of the interval bounds based on limited strain-life fatigue data. *International Journal of Fatigue*, *116*, 172–179. https://doi.org/10.1016/j.ijfatigue.2018.06.024
- Han, D., & Yang, H. (2021). Effects of tensile stresses on wave propagation across stylolitic rock joints. *International Journal of Rock Mechanics and Mining Sciences*, 139. https://doi.org/10.1016/j.ijrmms.2021.104617

ALAYSIA

- Hernández-Pajares, M., Lyu, H., Aragón-Àngel, À., Monte-Moreno, E., Liu, J., An, J., & Jiang, H. (2020). Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology. *Journal of Geophysical Research: Space Physics*, 125(6). https://doi.org/10.1029/2019JA027677
- Holzmann, M., & Moroni, S. (2020). Itinerant-Electron Magnetism: The Importance of Many-Body Correlations. *Physical Review Letters*, 124(20). https://doi.org/10.1103/PhysRevLett.124.206404
- Hoseyni, S. M., di Maio, F., & Zio, E. (2019). Condition-based probabilistic safety assessment for maintenance decision making regarding a nuclear power plant steam generator undergoing multiple degradation mechanisms. *Reliability Engineering and System Safety*, 191. https://doi.org/10.1016/j.ress.2019.106583
- Hussain, F., Abdullah, S., & Nuawi, M. Z. (2016). Effect of temperature on fatigue life behaviour of aluminium alloy AA6061 using analytical approach. *Journal of Mechanical Engineering and Sciences*, 10(3), 2324–2335. https://doi.org/10.15282/jmes.10.3.2016.10.0216

- Jiao, S., Cheng, L., Li, X., Li, P., & Ding, H. (2016). Monitoring fatigue cracks of a metal structure using an eddy current sensor. *Eurasip Journal on Wireless Communications* and Networking, 2016(1). https://doi.org/10.1186/s13638-016-0689-y
- Khandy, S. A., & Gupta, D. C. (2016). Structural, elastic and thermo-electronic properties of paramagnetic perovskite PbTaO 3. *RSC Advances*, 6(53). https://doi.org/10.1039/C6RA10468A
- Leuders, S., Meiners, S., Wu, L., Taube, A., Tröster, T., & Niendorf, T. (2017). Structural components manufactured by Selective Laser Melting and Investment Casting—
 Impact of the process route on the damage mechanism under cyclic loading. *Journal of Materials Processing Technology*, 248, 130–142.
 https://doi.org/10.1016/j.jmatprotec.2017.04.026
- Liu, Q., Yu, H., Zhu, G. chuan, Tong, K., Wang, P. bo, & Song, S. yin. (2021).
 Investigation of weld cracking of a BOG booster pipeline in an LNG receiving station. *Engineering Failure Analysis*, *122*.
 https://doi.org/10.1016/j.engfailanal.2021.105247
- Liu, S., Sun, Y., Gu, M., Liu, C., He, L., & Kang, Y. (2017). Review and analysis of three representative electromagnetic NDT methods. In *Insight: Non-Destructive Testing* and Condition Monitoring (Vol. 59, Issue 4, pp. 176–183). British Institute of Non-Destructive Testing. https://doi.org/10.1784/insi.2017.59.4.176
- Lux, F. R., Freimuth, F., Blügel, S., & Mokrousov, Y. (2018). Engineering chiral and topological orbital magnetism of domain walls and skyrmions. *Communications Physics*, 1(1). https://doi.org/10.1038/s42005-018-0055-y
- Meng, X., Lu, M., Yin, W., Bennecer, A., & Kirk, K. J. (2021). Inversion of Lift-Off Distance and Thickness for Nonmagnetic Metal Using Eddy Current Testing. *IEEE Transactions on Instrumentation and Measurement*, 70. https://doi.org/10.1109/TIM.2020.3038289
- Mikhailov, A. v., Gobov, Yu. L., Smorodinskii, Ya. G., & Simonov, N. A. (2020). EMA testing system with a small force of magnetic attraction to the surface of ferromagnetic objects. https://doi.org/10.1063/5.0035288

- Mishakin, V., Gonchar, A., Kurashkin, K., & Kachanov, M. (2020). Prediction of fatigue life of metastable austenitic steel by a combination of acoustic and eddy current data. *International Journal of Fatigue*, 141. https://doi.org/10.1016/j.ijfatigue.2020.105846
- Mlikota, M., Schmauder, S., & Božić. (2018). Calculation of the Wöhler (S-N) curve using a two-scale model. *International Journal of Fatigue*, 114, 289–297. https://doi.org/10.1016/j.ijfatigue.2018.03.018
- Na, S. M., Yoo, J. H., Lambert, P. K., & Jones, N. J. (2018). Room-temperature ferromagnetic transitions and the temperature dependence of magnetic behaviors in FeCoNiCr-based high-entropy alloys. *AIP Advances*, 8(5). https://doi.org/10.1063/1.5007073
- Nguyen, H. P., Liu, J., & Zio, E. (2018). Dynamic-weighted ensemble for fatigue crack degradation state prediction. *Engineering Fracture Mechanics*, 194, 212–223. https://doi.org/10.1016/j.engfracmech.2018.03.013
- Niazi, H., Eadie, R., Chen, W., & Zhang, H. (2021). High pH stress corrosion cracking initiation and crack evolution in buried steel pipelines: A review. In *Engineering Failure Analysis* (Vol. 120). Elsevier Ltd. https://doi.org/10.1016/j.engfailanal.2020.105013
- Pasquale, V. (2020). *Curie Temperature*. https://doi.org/10.1007/978-3-030-10475-7_109-1
- RAO, A. C. U., VASU, V., GOVINDARAJU, M., & SRINADH, K. V. S. (2016). Stress corrosion cracking behaviour of 7xxx aluminum alloys: A literature review. *Transactions of Nonferrous Metals Society of China (English Edition)*, 26(6), 1447– 1471. https://doi.org/10.1016/S1003-6326(16)64220-6
- Ronevich, J. A., Somerday, B. P., & San Marchi, C. W. (2016). Effects of microstructure banding on hydrogen assisted fatigue crack growth in X65 pipeline steels. *International Journal of Fatigue*, 82, 497–504. https://doi.org/10.1016/j.ijfatigue.2015.09.004
- Rosado, L. (2020). Eddy Current Testing Instrument for Online Industrial Quality Control. https://doi.org/10.13140/RG.2.2.25537.89449

- Sánchez, M., Mallor, C., Canales, M., Calvo, S., & Núñez, J. L. (2021). Digital Image Correlation parameters optimized for the characterization of fatigue crack growth life. *Measurement: Journal of the International Measurement Confederation*, 174. https://doi.org/10.1016/j.measurement.2021.109082
- Shaikh, F. U. A., Fairchild, A., & Zammar, R. (2018). Comparative strain and deflection hardening behaviour of polyethylene fibre reinforced ambient air and heat cured geopolymer composites. *Construction and Building Materials*, *163*, 890–900. https://doi.org/10.1016/j.conbuildmat.2017.12.175
- Sharma, A., & Sinha, A. (2018). Ultrasonic Testing for Mechanical Engineering Domain: Present and Future Perspective. In *International Journal of Research in Industrial Engineering* (Vol. 7). https://doi.org/10.22105/riej.2018.100730.1018
- Shukrinov, Y. M., Rahmonov, I. R., & Sengupta, K. (2019). Ferromagnetic resonance and magnetic precessions in φ0 junctions. *Physical Review B*, 99(22). https://doi.org/10.1103/PhysRevB.99.224513
- Tong, Z., Xie, S., Liu, H., Zhang, W., Pei, C., Li, Y., Chen, Z., Uchimoto, T., & Takagi, T. (2020). An efficient electromagnetic and thermal modelling of eddy current pulsed thermography for quantitative evaluation of blade fatigue cracks in heavy-duty gas turbines. *Mechanical Systems and Signal Processing*, 142. https://doi.org/10.1016/j.ymssp.2020.106781
- Trampus, P., Krstelj, V., & Nardoni, G. (2019). NDT integrity engineering A new discipline. *Procedia Structural Integrity*, 17, 262–267. https://doi.org/10.1016/j.prostr.2019.08.035
- Usarek, Z., & Warnke, K. (2017). Inspection of Gas Pipelines Using Magnetic Flux Leakage Technology. Advances in Materials Science, 17(3), 37–45. https://doi.org/10.1515/adms-2017-0014
- Yu, M., Chen, W., Kania, R., van Boven, G., & Been, J. (2016). Crack propagation of pipeline steel exposed to a near-neutral pH environment under variable pressure fluctuations. *International Journal of Fatigue*, 82, 658–666. https://doi.org/10.1016/j.ijfatigue.2015.09.024

- Zhang, L.-Z., He, X.-D., Zhang, A.-L., Xiao, Q.-L., Lu, W.-L., Chen, F., Feng, Z., Cao, S., Zhang, J., & Ge, J.-Y. (2020). Tunable Curie temperature in layered ferromagnetic Cr 5+x Te 8 single crystals. *APL Materials*, 8(3). https://doi.org/10.1063/1.5143387
- Zhang, L., Zhou, G., Han, Y., Lin, H., & Wu, Y. (2018). Application of Internet of Things Technology and Convolutional Neural Network Model in Bridge Crack Detection. *IEEE Access*, 6. https://doi.org/10.1109/ACCESS.2018.2855144
- Zou, C. L., Guo, D. Q., Zhang, F., Meng, J., Miao, H. L., & Jiang, W. (2018).
 Magnetization, the susceptibilities and the hysteresis loops of a borophene structure. *Physica E: Low-Dimensional Systems and Nanostructures*, 104, 138–145.
 https://doi.org/10.1016/j.physe.2018.07.028



APPENDICES



APPENDIX A Weldscan demonstration plate drawing

MALAYSIA MEL TEKNIKAL



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA

TAJUK: EFFECTIVENESS OF PORTABLE EDDY CURRENT INSPECTION ON WELDING PIPELINE

SESI PENGAJIAN: 2021/22 Semester 1

Saya Muhammad Firdaus bin Abd Halim

mengaku membenarkan tesis ini disimpan di Perpustakaan Universiti Teknikal Malaysia Melaka (UTeM) dengan syarat-syarat kegunaan seperti berikut:

- 1. Tesis adalah hak milik Universiti Teknikal Malaysia Melaka dan penulis.
- 2. Perpustakaan Universiti Teknikal Malaysia Melaka dibenarkan membuat salinan untuk tujuan pengajian sahaja dengan izin penulis.
- 3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
- 4. **Sila tandakan (✓)

SULIT

(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia sebagaimana yang termaktub dalam AKTA RAHSIA RASMI 1972)

(Mengandungi maklumat TERHAD yang telah ditentukan TERHAD UNIVERSIT oleh organisasi/badan di mana penyelidikan dijalankan)

TIDAK TERHAD

Alamat Tetap:

No.1 Lorong Madrasah Kampung

Mak Teh,

35400 Tapah Road, Perak

Tarikh: 17 Januari 2022

Disahkan oleh:

Cop Rasmi:

SITI NORBAYA SAHADAN Pensyarah Jabatan Teknologi Kejuruteraan Mekanikal Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan Universiti Teknikal Malaysia Melaka

Tarikh: 18 /1/2022

Scanned with CamSca

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan PSM ini perlu dikelaskan sebagai SULIT atau TERHAD.