ANALYSIS OF COMPONENTS PRODUCED USING WIRE ARC ADDITIVE MANUFACTURING

FATIN NAZIRAH BINTI ISMAIL

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ANALYSIS ON COMPONENTS PRODUCED USING WIRE ARC ADDITIVE MANUFACTURING

FATIN NAZIRAH BINTI ISMAIL

This report is submitted in fulfillment of the requirement for the degree of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

MAY 2019

SUPERVISOR'S DECLARATION

I hereby declare that I have read this final year report and in my opinion this final year report is sufficient in terms of scope and quality for the award of the Bachelor Degree of Mechanical Engineering with Honours.

Signature :

Name of Supervisor: ASSOC. PROF. IR. DR. MOHD RIZAL BIN ALKAHARI

Date :

STUDENT'S DECLARATION

I hereby declare that I am the sole writer of this report and the work in "Analysis On Components Produced Using Wire Arc Additive Manufacturing" report is my own except for as cited in references.

Signature :

Name : FATIN NAZIRAH BINTI ISMAIL

No. Matric : B041510172

Date : 24/5/2019

DEDICATION

To my dearest mother and father

ABSTRACT

Wire arc additive manufacturing (WAAM) is one of rapid developing technology in manufacturing industries since it has proven its capability of fulfilling demands of medium – to – large production. WAAM is one of many techniques for 3D printing where a product is produced by adding and depositing material in a layer upon layer manner. It is a combination of welding and additive manufacturing techniques as it used metal welding wire as feedstock and electric arc as the heat source. However, high temperatures in WAAM process leads to defects and quality deformations such as cracking, corrosion, poor surface roughness and more upon the product produced. This is because during WAAM process, as the wall height increases, the heat dissipation to the substrate is slowed down gradually resulting to slow solidification of the molten pool which produces variation of the bead geometry. The purpose of this study is to study on the effect of deposited metal using WAAM with and without an in – process active cooling system of thermoelectric cooling technology. Thermoelectric cooling was installed to the side of the base plate of WAAM setup to regulate the heat dissipation of each layers of deposited metal. A multi – layer with a dimension of 120 mm x 40 mm was fabricated onto a mild – steel plate. Through the tensile test, hardness test and surface roughness analysis, the mechanical properties and microstructure of the fabricated parts by WAAM were explored. Based on the result obtained, the deposited metal without thermoelectric cooling system have better surface roughness and tensile strength compared to deposited metal with thermoelectric cooling system. However, for hardness test, the deposited metal with thermoelectric cooling has proven to have better hardness compared to deposited metal without thermoelectric cooling system. Hence, the proposed method has proven to provide new insight about bead geometry produced using WAAM as it the ability to improve the quality of the fabricated metal parts.

ABSTRAK

Pembuatan tambahan wayar arka (WAAM) adalah salah satu teknologi membangun pesat dalam industri pembuatan kerana ia telah membuktikan keupayaannya memenuhi permintaan pengeluaran yang bersaiz sederhana dan besar. WAAM adalah salah satu teknik untuk percetakan 3D di mana produk dapat dihasilkan dengan menambah dan menempatkan bahan lapisan demi lapisan. Ia adalah gabungan kimpalan dan teknik penambahan bahan kerana ia menggunakan wayar kimpalan logam sebagai bahan mentah dan arka elektrik sebagai sumber haba. Walau bagaimanapun, suhu yang tinggi dalam proses WAAM membawa kepada kecacatan dan merosakkan kualiti bentuk sesuatu produk seperti keretakan, kakisan, permukaan yang kasar dan buruk. Hal ini kerana semasa proses pembuatan wayar arka tambah arka, ketinggian dinding meningkat, pelesapan haba diperlahankan secara beransur-ansur menyebabkan memperlahankan pemejalan kolam lebur yang menghasilkan variasi geometri manik. Tujuan kajian ini adalah untuk mengkaji kesan logam didepositkan menggunakan WAAM dengan dan tanpa proses pendinginan yang aktif iaitu teknologi penyejukan termoelektrik. Penyejukan termoelektrik telah dipasang ke tepi plat asas mesin WAAM untuk mengawal selia pelesapan haba bagi setiap lapisan logam didepositkan Lapisan keluli tahan karat berdimensi 120mm x 40mm telah di hasil kan di atas plat keluli ringan. Melalui ujian ketegangan and ujian kekasaran permukaan, propertis mekanikal dan mikrostrukur pada lapisan keluli tahan karat yang di hasilkan oleh WAAM telah diteroka Berdasarkan keputusan yang diperolehi, logam yang didepositkan tanpa sistem penyejukan termoelektrik mempunyai kekasaran permukaan dan kekuatan tegangan yang lebih baik berbanding logam didepositkan dengan sistem penyejukan termoelektrik. Walau bagaimanapun, bagi ujian kekerasan, logam yang didepositkan dengan penyejukan termoelektrik telah terbukti mempunyai kekerasan yang lebih baik berbanding dengan logam didepositkan tanpa sistem penyejukan termoelektrik. Oleh itu, kaedah yang dicadangkan telah terbukti memberikan wawasan baru tentang geometri manik dihasilkan menggunakan WAAM kerana ia keupayaan untuk meningkatkan kualiti bahagian-bahagian logam dibina.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor, Assoc. Prof. Ir. Dr. Mohd Rizal Bin Alkahari for giving me the opportunity to do final year with him. I really grateful for his guidance from the beginning to the end that enable me to develop an understanding of this project thoroughly. I also sincerely thankful for his time spent and patience for correcting my mistakes and gave guidance whenever I confronted any kind of problems.

I also would like to express special thanks to all staff members of the Mechanical Engineering Department, UTeM, who helped me in many ways and made the process of this project less difficult. My sincere thanks to laboratory assistant En. Hairul Niezam Bin Wahid and one of UTeM's master student., Miss Nor Ana Binti Rosli for their kindness and invaluable guidance for this project. Without their help, it would be a lot tougher to completion.

My sincere indetedness and gratitude to my parents for their love, support and sacrifice throughout my life. Their love, support and sacrifice definitely had inspired and motivated me to do my best in everything I do especially in achieving my dreams. Lastly, I would like to thanks any person who may contributes to my final year project directly or indirectly. Their comments, opinion and suggestions was crucial to me for the successful completion of this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	Three Dimensional
WAAM	Wire Arc Additive Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
SLS	Selective Laser Sintering
UV	Ultraviolet
DC	Direct Current
AC	Alternating Current
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
PAW	Plasma Arc Welding
MIG	Metal Inert Gas
MAG	Metal Active Gas
CO_2	Carbon dioxide
LOM	Laminated Object Manufacturing
FSS	Ferritic Stainless Steel

LIST OF SYMBOLS

mm	Millimetres
g	Grams
μm	Micrometre
d_{max}	Maximum diameter
d_{min}	Minimum diameter
$\langle d \rangle$	Mean of measure diameters
HV	Vickers hardness
UTS	Ultimate tensile strength
V	Voltage
W	Watt
I	Current
v	Wire feed speed
Ra	Average value of surface roughness
R	Reproducibility limit
P_{max}	Maximum tensile force
A_o	Cross – sectional area
MPa	Mega Pascal

CHAPTER 1

INTRODUCTION

1.1 Background

Three – dimensional printing, 3D printing is a new advance technology in manufacturing process. It is a process of rapid prototyping three – dimensional parts directly from computer models. This technology has been widely accessible in manufacturing process since normal manufacturing process requires a great deal of time and cost. Manual manufacturing process such as injection moulding or lost wax casting can be a complex process that takes months to complete and require human attention to detail. In industry, productivity and competitive success depend on fast, efficient product development technologies. Hence, 3D printing offers an alternative to fulfil the industry demands for rapid prototyping and low – cost production (Sachs *et al.*, 1990).

Wire arc additive manufacturing (WAAM) is one of many techniques for 3D printing. WAAM is a techniques where a product is produced by adding and depositing material in a layer upon layer manner. WAAM is a combination of welding and additive manufacturing technology where metal welding wire is used as the feedstock and electric arc as the heat source. The process steps of this technique start with designing of 3D CAD model using software such as Catia and Solidworks. The model is then saved in .stl format that represents model's geometry before transfer to Repetier software. Repetier software is a slicing software for 3D printing where the model will be slice layer by layer with a different slicer. This steps is followed by choosing suitable welding parameters in terms of travel speed, current, voltage and more. The product is then can be made by additive manufacturing where the first layer of the welding is deposited on the base plate, torch goes up for the specified layer's height to deposit the second layer onto it and the process continuous until the whole product is made (Knezovi, 2019).

The first WAAM was back on 1925s when an electric arc was used as the heat source with filler wires as feedstock material to deposit layer by layer. Now, WAAM has been popularized to industrial manufacturing sector due to its ability to create large metal parts with high deposition rate, low equipment cost, high material utilization and resulting environmental friendliness. WAAM system can reduce the fabrication time by 40 – 60% and post machining time by 15 – 20% depending on the component size which shows a great deal of change compared to traditional manufacturing process(Wu, Pan, Ding, Cuiuri, Li, Xu, *et al.*, 2018).

In recent years, both academia and industry has drawn significant interest on wire arc – based additive manufacturing (WAAM) due to its low cost and efficiency. It is low cost because of the easy to access wire material and welding technologies such as Gas Metal Arc Welding (GMAW). High efficiency of wire arc – based additive manufacturing is due to its large heat input and high wire feed rate. These advantages have made WAAM highly competitive in fabricating medium to large scale products compared with other additive manufacturing processes. (Shi *et al.*, 2018)

1.2 Problem Statement

In WAAM, high temperature input for welding leads to residual stresses, deformation, poor strength, porosity, and cracking. High residual stress can result in distortion in product. Besides that, surface oxidation can easily occur when metal is exposed to air which lead to corrosion. Surface oxidation can be seen through the colour changes on the product surface. The darker the surface, the higher the levels of surface contamination. Solidification in WAAM product can be challenging due to the high temperature that causes microstructure to contain large columnar grains. It provides lower strength and toughness compared to a fine microstructure (Cunningham *et al.*, 2018).

1.3 Objectives

The objectives of this project are as follows:

1. To study the improvement of WAAM by applying thermoelectric cooling technology.
2. To compare the mechanical structure of deposited metal produced by WAAM with and without thermoelectric cooling.
3. To analyse the mechanical properties on the parts produced using WAAM in terms of surface roughness, hardness and tensile strength.

1.4 Scope of Project

The project was mainly to study on the effect of deposited metal using WAAM with and without thermoelectric cooling. The macrostructure and mechanical properties of the deposited metal produced by WAAM was observed and analysed throughout the experiment process of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Classification of 3D Printing Processes

Three dimensional printing is an innovative technology that can manufacture three dimensional parts directly from digital model. In manufacturing industry, it is a new advance technology that can fulfil industry demands for rapid prototyping and speedy, low – cost production. Besides that, production time and material waste can be reduced as it can print models multiple time in short amount of time.

Since 3D printing is still evolves, there are a few processes for 3D printing such as stereolithography, selective laser sintering (SLS), laminated object manufacturing (LOM) and more. Stereolithography is a form 3D printing where a focused UV light causes chain of molecules to link and forming polymers. The polymers then form a three – dimensional solid part. However, stereolithography only can be apply to polymers that may be photopolymerized. For SLS, it uses a high – powered laser to sinter selected regions of a powder layer and binding the material together to form a solid structure. Laminated object manufacturing is a process where it cuts foils or sheets using a laser and stacks the material together using glued or weld to form a three – dimensional part (Sachs *et al.*, 1990). These processes has high potential for increasing manufacturing productivity and improve the economic feasibility of tooling and prototype fabrication.

2.2 Wire Arc Additive Manufacturing

Wire arc additive manufacturing (WAAM) is also one of 3D printing processes where metal is deposited layer by layer to form a three dimensional part. Arc welding is a type of welding that uses a welding power supply such as direct (DC) or alternating (AC) current to create an electric arc between arc and the base material to melt the metals at the welding point. In 19^{th} century, arc welding became commercially important technology during the Second World War for ship building. Today, it still an important process for manufacturing industry. This is because WAAM techniques has provides a strategic advantages in the manufacturing industry especially to create part models and prototypes.

WAAM is a combining of arc welding with wire feeding that able to give the design freedom with no constraints in size and low cycle times. These advantages make WAAM suitable for custom made, large functional components made of high value materials (Busachi *et al.*, 2015). Besides that, it is possible to automate the WAAM process from part design to fabrication in a computer aided design (CAD) or computer aided manufacturing (CAM) environment. This process can help to reduce the production time and requirement for human attention to detail on each new part (Ding *et al.*, 2015). WAAM is an innovation technology where further investigation should be conduct to improve parameters optimization, monitoring, process control, part design and heat treatment in order for better understanding and implementation of WAAM technology.

2.3 Wire Arc Additive Manufacturing (WAAM) Processes

As the welding technology evolves, there are three common types of wire arc additive manufacturing processes: Gas Metal Arc Welding (GMAW) – based, Gas Tungsten Arc Welding (GTAW) – based and Plasma Arc Welding (PAW) – based. GMAW is also known as metal inert gas (MIG) welding or metal active gas (MAG) welding which is commonly used in WAAM process. It is a welding process in which an electric arc forms between a consumable wire electrode and the workpiece metal. GTAW and PAW use a non – consumable tungsten electrode to produce the weld.

The wire feed orientation in GMAW is normally perpendicular to the substrate while in GTAW and PAW, the wire feed orientation is variable and affects the quality of the deposit which makes the process of WAAM more complicated. The rate of deposition is higher by using wire – feed additive manufacture instead of powder materials and large components could be economically produced. Besides that, metal wires are lower in cost and easily accessible than metal powder which making WAAM technology more demanding (Ding *et al.*, 2015). The rate of deposition for GMAW – based WAAM is also 2 – 3 times higher compared to GMAW – based and PAW – based methods. The typical deposition rate for GMAW is 3 – 4 kg/hour (Wu, Pan, Ding, Cuiuri, Li, Xu, *et al.*, 2018). Besides that, the wire – feed in GMAW is coaxial with the welding torch which makes it easier to generate path during welding (Knezovi, 2019). The choice of WAAM process can affect the processing conditions and production rate for a target component since each process has its own advantages and disadvantages.

2.4 Defects and Quality Deformation in WAAM

Common defects in WAAM are porosity, high residual stress, cracking and surface oxidation which must be avoided as they lead to failure modes. Poor programming strategy, unstable weld pool dynamics due to poor parameter setup, thermal deformation associated with heat accumulation, environment influence and other malfunctions are many reasons for the defects in WAAM to occur. Certain materials tend to be easily effected to specific defects as shown in Figure 2.1. For example, severe surface oxidation for titanium alloys, porosity for aluminium alloys and poor surface roughness in steel with severe deformation and cracks (Wu, Pan, Ding, Cuiuri, Li, Xu, *et al.*, 2018).

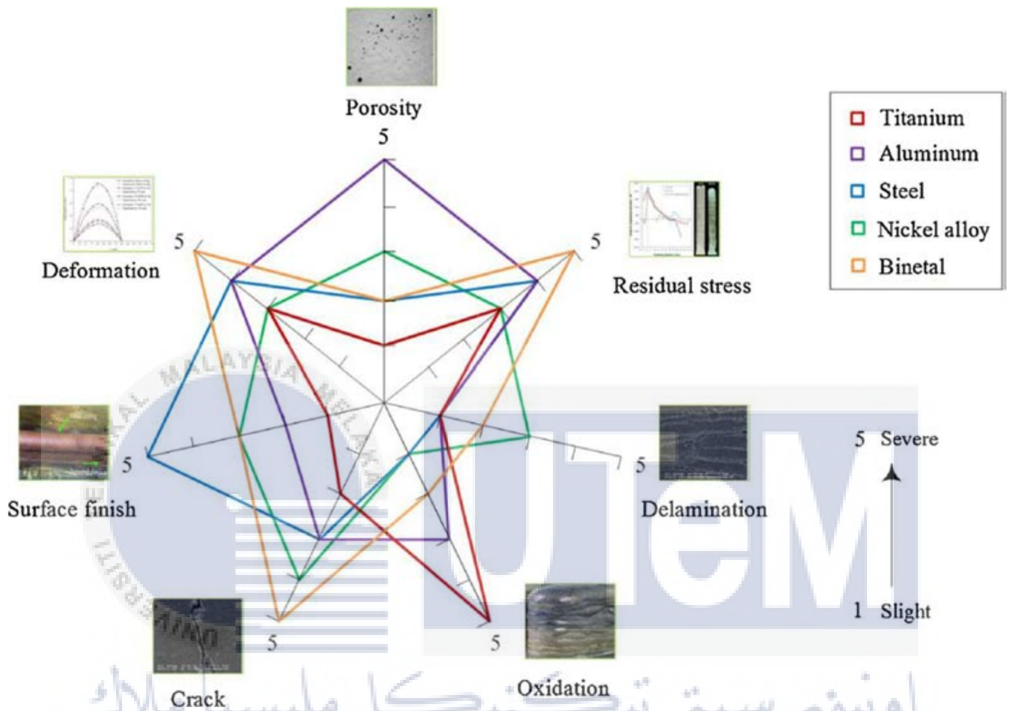


Figure 2.1 Correlation between materials and common defects in WAAM processes.

(Wu et al., 2018)

As the metal heats and expands during welding, the compressive yielding occurs around the molten zone that can cause residual stress. When the metal cool down, it create tensile residual stress particularly in the longitudinal direction as shown in Figure 2.2. The tensile residual stress can reduces the fatigue strength and toughness (Colegrove *et al.*, 2009). Besides that, residual stress also can cause distortion and cracking of the component. Although post – processing technologies can minimised residual stress, residual stresses –

induced distortions are still a major cause of loss in tolerances. Hence, a lot of researcher have been investigated on thermal stresses analysis of material deposition of multi – pass single – layer structure by altering deposition patterns, deposition sequences and preheating or interpass cooling to improve the quality of WAAM – fabricated part (Wu, Pan, Ding, Cuiuri, Li, Xu, *et al.*, 2018)

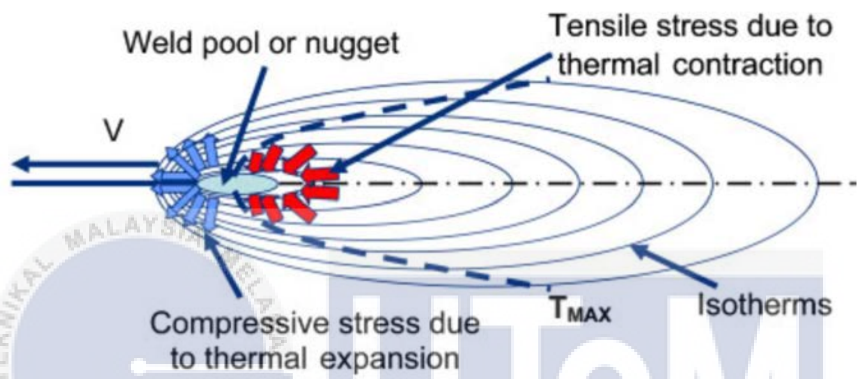


Figure 2.2 Stresses that occur on fabricated part during WAAM process.

(Colegrove et al., 2009)

2.5 Heat Accumulation on Deposited Metal in WAAM

Heat accumulation can affect the composition and oxidation of WAAM parts due to evaporation of low melting point element and absorption of atmospheric gases. The heat transfer from conduction – based heat dissipation in the change of local geometry between substrate to thin wall as shown in Figure 2.3(a) to include radiation and convection process within this wall section in Figure 2.3(b). Heat accumulate along the build direction can causes the loss of weld bead dimensional control as it can affect the transition zone of microstructural and dimensional control when the heat dissipation becomes less effective and preheat from previous layer is added to the part. The heat transfer becomes more variable in the build direction with the inclusion of adjacent weld beads in multi – layer deposition as shown in Figure 2.3(c). However, it provides less opportunity for development of steady state deposition (Cunningham *et al.*, 2018).

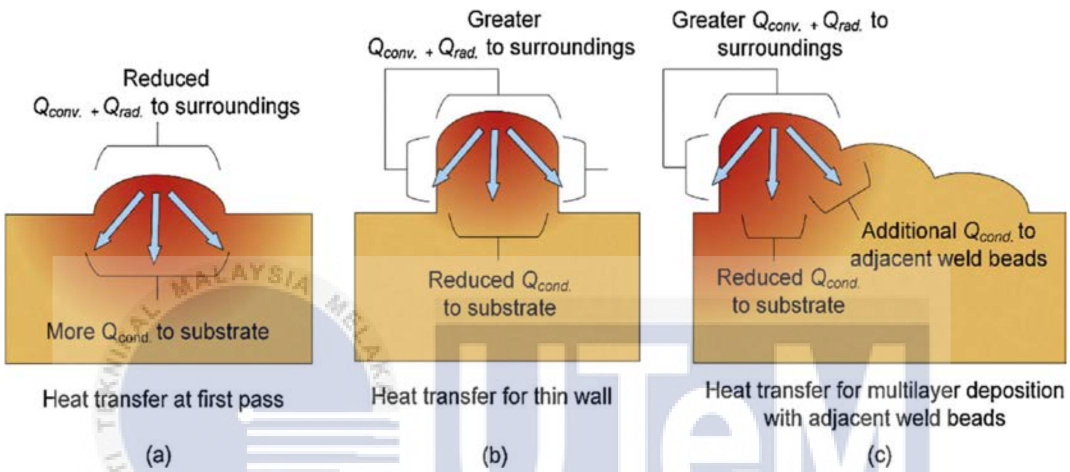
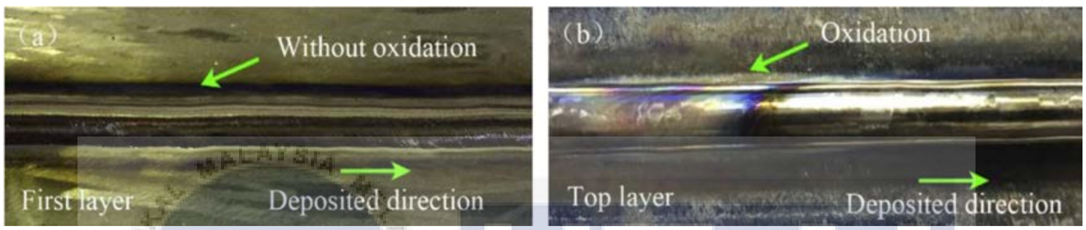


Figure 2.3 Schematic diagram of the heat dissipation process, conduction convection and radiation. (Cunningham et al., 2018)

Based on the fabrication of Fe-Al materials using similar WAAM process experiment, poorly controlled interpass temperature is more likely to produce longitudinal cracking and high residual stress in the first few layers of deposited metal (Cheng *et al.*, 2003). The stability of WAAM process such as geometrical accuracy, deposition defects, microstructural evolution and material properties of fabricated parts can be easily affected by heat accumulation on deposited metal. In Figure 2.4 shows the appearances comparison between the first layer and top layer of deposited metal. The surface layer of the first layer in Figure 2.4(a) shows a clean surface with no sign of oxidation. The surface of the top layer in Figure 2.4(b) shows obvious oxidation as the colour changes on the surface product. The range of surface discoloration start from silver, light straw through dark straw, light blue, dark blue to grey and powdery. The darker the surface, the higher the levels of surface contamination. This comparison indicates that interpass temperature has increased with increasing build height due to the heat accumulation (Wu *et al.*, 2017). Since heat accumulation is still a major influences the stability of the WAAM – fabricated part, further research are required for better understanding of WAAM process and to reduce heat accumulation occur on WAAM parts.



(a) First layer appearance of deposited metal (b) Top layer appearance of deposited metal

Figure 2.4 The appearances comparison between (a) first layer and (b) top layer of deposited metal (Wu et al., 2017)

2.6 Effect of Process Parameters on Weld Bead Geometry for WAAM Process

In WAAM, GMAW process is a continuous and consumable wire electrode where the electrode melts due to the heat and falls onto the substrate base to form weld bead. The weld and bead geometry plays an important role in determining the mechanical properties of the weld. Hence, a suitable parameter such as welding voltage, welding current, welding speed and welding angle are required to predict and optimize weld bead geometry for WAAM process. In 2015, R.Sakthivel, P.Venkadeshwaran, R.Sridevi, R.Ahamed Meeran and K.Chandrasekaran conduct an experiment where ER4043 solid wire having 1.2 mm diameter was used as an electrode in GMAW process with an argon gas employed as shielding gas. The result for the experiment indicated as the welding current and voltage increases, the depth penetration is constant, the bead width and height increased (R.Sakthivel, 2015).

Besides that, there is also an experiment where the effect of GMAW process parameters on the bead geometry and heat – affected - zone (HAZ) area on 6 mm thick plate through bead on plate was investigated. For this experiment, Taguchi orthogonal array design and analysis of variance (ANOVA) was apply in the experiment to find the most significant parameters that influence in the bead geometry and HAZ area. The result for this experiment also indicated the depth of penetration, HAZ area, bead width and height are strongly influenced by the welding parameters such as welding voltage, speed and wire feed. Therefore, set up the correct welding parameters is important before printing as they can affect the mechanical properties and quality of the WAAM fabricated part (Anbarasan N, 2015).

2.7 Effect of Heat Input in WAAM Process

Heat input in WAAM process has a significant influences on solidification mode and secondary metallurgical transformations where both facts can affect the microstructure of the part at different welding zones. High heat input can increase the solidification time and reduce the cooling time (Luisa Quintino, 2013). Besides that, weld bead geometry also influenced by heat input. In 2016, Ajit Mondal, Manas Kumar Saha, Ritesh Hazra and Santanu Das conducted an experiment where duplex stainless steel E2209 T01 is deposited on E250 low alloy steel specimens with pure carbon dioxide gas as shielding medium at different heats. According to the experiment, higher heat input can produce larger quantity of molten weld material and increase in weld bead due to the more spread of weld material onto the substrate base as the filler wire was easily melted. Hence, proper heat input is required to provide greater penetration, favourable fusion and strong bead reinforcement (Ajit Mondal, 2016).

2.8 Mechanical Properties of WAAM

2.8.1 Surface Roughness

Surface roughness is one of many important factors that can influence the product quality in terms of hardness, tensile strength and metal fatigue. The surface roughness of WAAM can be affected by various factors from pre – processing, processing and post – processing stages. These factors are material properties, layer thickness, part orientation, post – treatment and more. In 2008, Mercedes Pérez, Gustavo Medina-Sánchez, Alberto García – Collado, Munish Gupta and Diego Carou conducted two different types of experiment to analyse five printing parameters which are layer height, printing path, printing speed, temperature and wall thickness. The result is then analyse by using Analysis of Variance, graphical methods, and non – parametric tests. The authors concluded that the layer height and wall thickness are the most influence parameter that can control surface roughness while printing path, printing speed and temperature do not have impact on surface roughness. As the layer height and wall thickness increases, the quality of the surface decreases (Mercedes, Medina-s and Carou, 2018).

2.8.2 Hardness

The resistance of material to plastic deformation is known as hardness. An accurate bead geometry can be difficult to achieve due to excessive heat accumulation during WAAM process. Thus, this leads to differences in mechanical properties such as hardness. Besides that, low heat dissipation during WAAM generates coarse grain in the welds which can contribute to poor hardness. In 2012, M.O.H. Amuda and S. Mridha conducted an analysing to study cryogenically cooled ferritic stainless steel (FSS) welds in terms of grain distribution and hardness distribution. Based on the result obtained, the authors concluded that cryogenic cooling helps to reduces more than 30% of the weld dimensions with better grain refinement compared to conventional weld. For hardness distribution, the thickness direction of weld has slightly higher profile due to decreased grain growth by rapid cooling effect of cryogenic liquid.

Besides that, Bintao Wua, Zengxi Pan, Donghong Ding, Dominic Cuiuri, Huijun Li and Zhenyu Fei also conducted an experiment to study the effect of forced cooling gas on deposition geometry, surface oxidation, microstructural evolution and mechanical properties of WAAM product. According to the experiment, with the aid of forced cooling gas, the geometric accuracy of each deposited layer more stable which contributed to better surface finish with less surface oxidation, more refine microstructure, improved hardness and stronger strength (Wu, Pan, Ding, Cuiuri, Li and Fei, 2018). Hence, low heat accumulation can contributed to better hardness with better grain refinement and surface finish.

2.8.3 Tensile Strength

In 2016, Zhuqing Wang, Todd A. Palmer and Allison M. Beese conducted an experiement where the authors studied the effect of processing parameter on the mechanical properties of AISI304L stainless steel fabricated by laser – based deposition directed energy deposition. Tensile test were performed on samples from the walls in longitudinal and transverse directions. Based on the result obtained, the authors found that the yield strength, ultimate tensile strength and ductility were higher in low heat input compared to high heat input. However, the ductility in the transverse direction is higher than in the longitudinal directions. Hence, the samples with different build direction and heat input have different mechanical strength and elongation (Wang, Palmer and Beese, 2016).

2.9 Thermoelectric Cooling

During WAAM process, the heat is dissipated partly to the substrate onto the previously deposited layers and partly to the surrounding via convection and radiation. However, as the heat dissipation becomes less effective and preheat from the previously deposited layers, heat can accumulate along the build direction which can slows down the solidification of the molten pool that can lead to a wider and lower weld bead. In 2018, Fang Li, Shujun Chen, Junbiao Shi, Yun Zhao and Hongyu Tian conducted an experiement where they introduced for the first time an in – process active cooling system based on thermoelectric cooling technology into WAAM process. The aims for this research is to eliminate the difference in heat dissipation between upper and lower layers which can improve the capabilities of WAAM in fabricating in terms of geometric accuracy, productivity and microstructure. This study used thermoelectric cooling technology because its benefits such no circulating liquid, invulnerability to leak, small in size, flexible shape, controllable cooling rate and long. It is a solid – state active heat pump and it operates by the Peltier effect where it transfers heat from one side of the device to the other with consumption of electrical energy. In the experiment, two thermoelectric coolers were placed side by side as shown in Figure 2.5 to make sure the cold from thermoelectric coolers were distributed symmetrically on the two sides of the wall. The result of experiment shows that the bead width error is reduced by 56.8%, the total time for fabrication is reduced by 60.9% and the average grain is refined by 25% with the aid of thermoelectric cooling (Shi *et al.*, 2018).

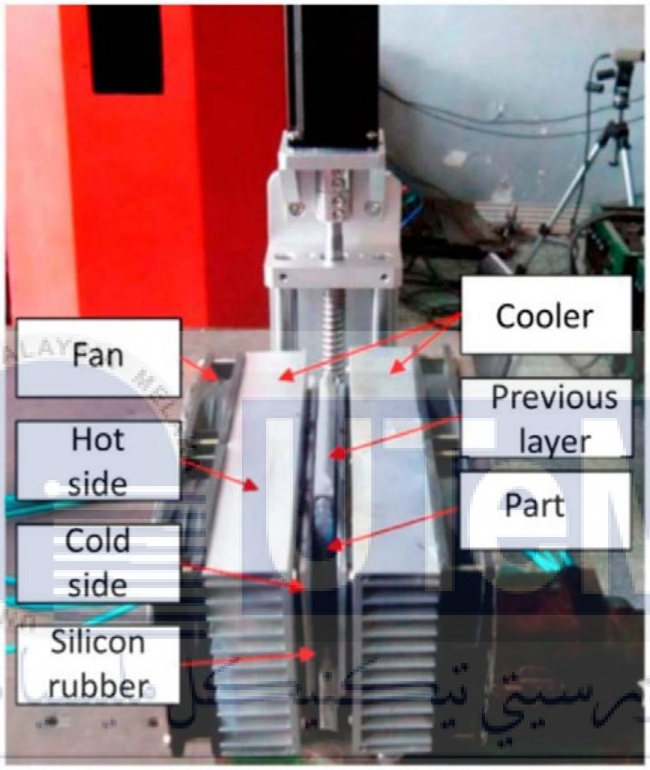


Figure 2.5 Experimental setup: Enlarged view of the thermoelectric cooling system

(Shi et al., 2018)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This project mainly focused on the effect on WAAM fabricated part with and without the thermoelectric cooling. This project started by identifying the common defect and quality deformation on fabricated part using WAAM process. This followed by studying journals, articles or any materials regarding to this project for better understanding and gain comprehensive knowledge about wire arc additive manufacturing. Next, conduct an experiment using WAAM process to validate the common defects and quality deformation occur on fabricated component. If the results are significant, thermoelectric cooling is introduced to resolve the problem. Modelling is prepared using CATIA software and measurement of the WAAM fabricated parts are taken as result in this project.

3.2 Development Process

Since WAAM originated from welding, their heat dissipation conditions exhibit obvious differences on deposited metal where less effective heat dissipation mechanism to the substrate can result in slow solidification of the molten pool and produce a wider and lower weld bead. Wider and lower weld bead can leads to common defects of WAAM product such as low hardness, porosity, cracking and more since bead geometry is a critical parameter for WAAM. Therefore, an alternative solution in order to heat dissipation during WAAM process, an in – process active cooling system based on the thermoelectric cooling is developed in this study.

Thermoelectric cooler is a solid – state energy converter that operated by Peltier effect where it transfers heat from one side of the device to the other with consumption of electrical energy as shown in Figure 3.1 below. The hot side of each cooler is attached to external fans to make sure it could remain at ambient temperature. The cold side is facing to the WAAM product to regulate heat dissipation. Thermoelectric cooling method is used in this study because of its benefits such as no circulating liquid, invulnerability to leak, small in size, flexible shape, controllable cooling and long life.

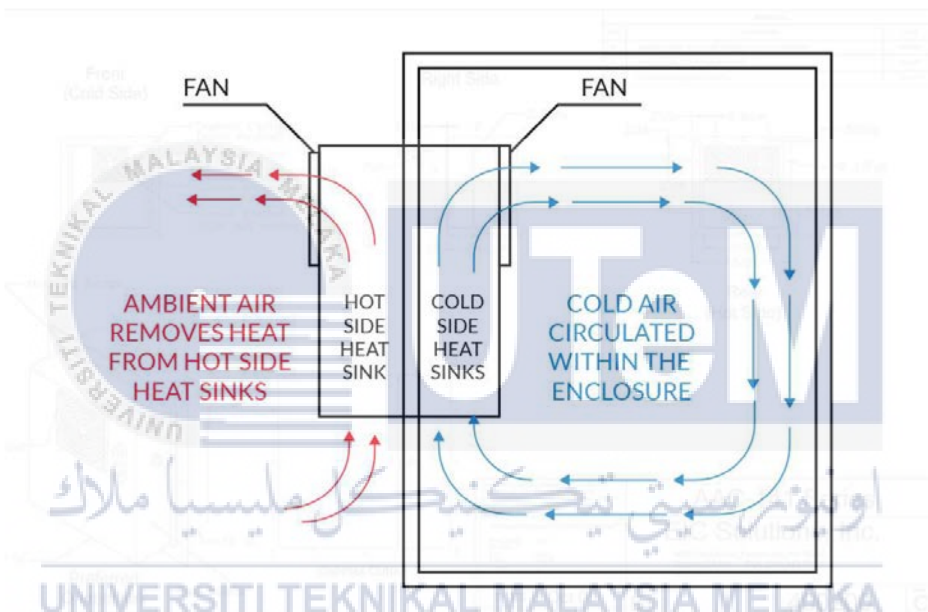


Figure 3.1The Peltier effect of thermoelectric cooling

For this experiment, the thermoelectric cooling with double fan is used as shown in Figure 3.2. The rated input voltage of thermoelectric cooling is 12 V and the cooling power is 120 W.

Figure 3.2 Thermoelectric cooling with double fan

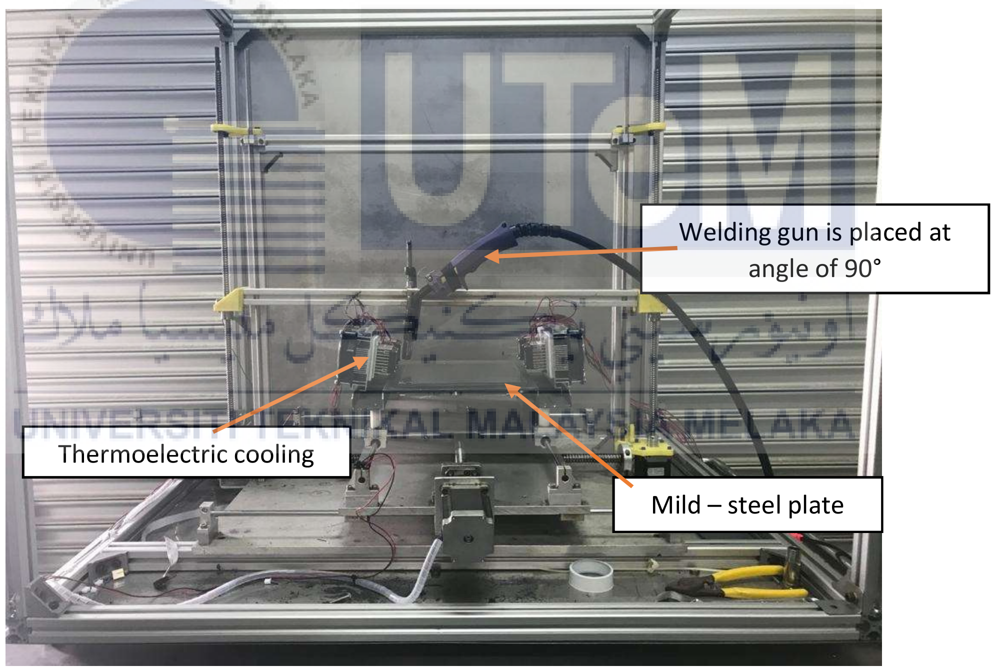
It is powered by 12 V fixed - voltage power supply that also capable of delivering up to 8.4 A of current as shown in Figure 3.3. The size and weight of thermoelectric cooling is approximately 200 x 120 x 90 mm and 816 g respectively.

Figure 3.3 12V fixed – voltage power supply

3.3 Experimental Setup

In Figure 3.4(a) shows the general experimental setup for wire arc additive manufacturing (WAAM) process without thermoelectric cooling. Metal inert gas welding is used in gas metal arc welding (GMAW) process. The basic necessary equipment need to prepare in order to perform gas metal arc welding are a welding gun, a wire feed unit, a welding power supply and a shielding gas supply. The welding gun is placed at angle 90° and connected to the welding power source through the cable that transmits the electrical energy to the electrode and directing it to the weld area. Direct current (DC) is used as welding power supply in this experiment. Carbon dioxide is employed in this experiment as shielding gas to protect the welding area from atmospheric gases such as nitrogen and oxygen that can cause defects, porosity and brittle of weld metal. Two set of thermoelectric cooling was attached to the side of the base plate as shown in Figure 3.4(b) to regulate the heat dissipation of each layers during WAAM more effective and improve the mechanical properties produced by WAAM.

(a) WAAM experiment setup without thermoelectric cooling system



(b) WAAM experiment setup with thermoelectric cooling system

Figure 3.4 3D metal printing using WAAM

3.4 Experiment Process

The experiment is designed to study the effect of fabricated metal part using WAAM process with and without thermoelectric cooling. The experiment started from a 3D modelling using Catia software and save it as STL file before being transfer to Repetier. Repetier is a slicing software for 3D printing where the model will be slice layer by layer with different slicer and set the suitable parameter for printing as shown in Figure 3.5.

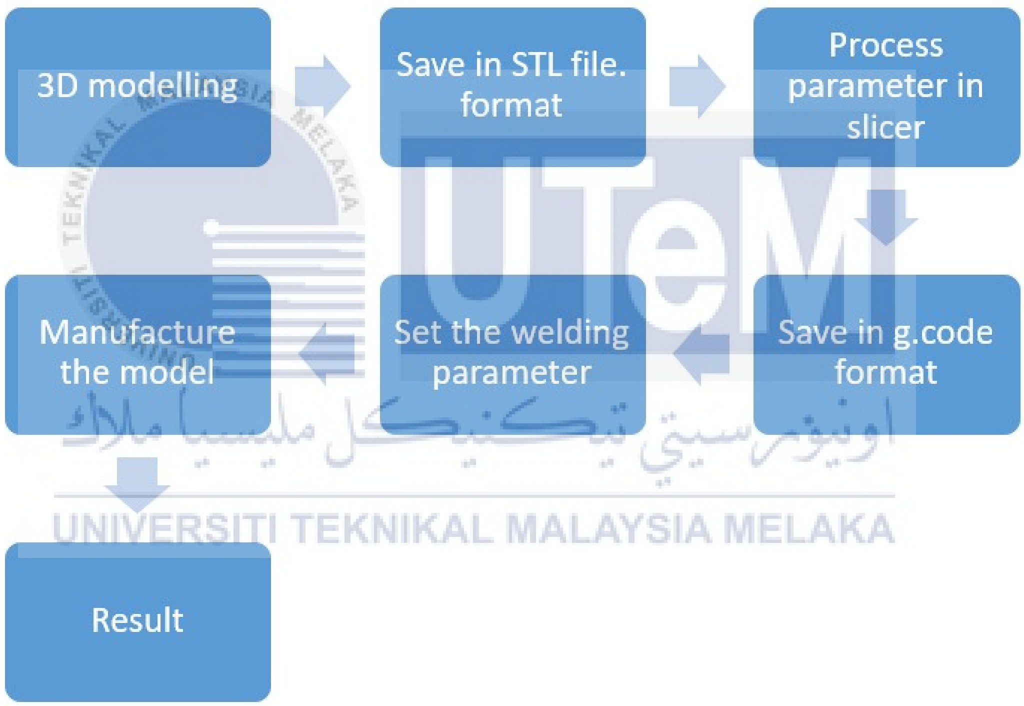


Figure 3.5 Experiment process of WAAM system

In this experiment, mild – steel plate is used as substrate base where it acts as a support for fabricated part and as heat dissipation system for the heat generated during the process by conduction transfer through the work table. The welding gun using stainless steel wire of 0.8 mm in diameter and pure carbon dioxide, CO_2 were applied. The distance of welding gun and the substrate base was 5 mm. A multi - layer with a dimension of 120 mm x 40 mm was prepared using the 3D CAD as shown in Figure 3.6. The dimensions of the fabricated part were taken and compared with the actual CAD model.

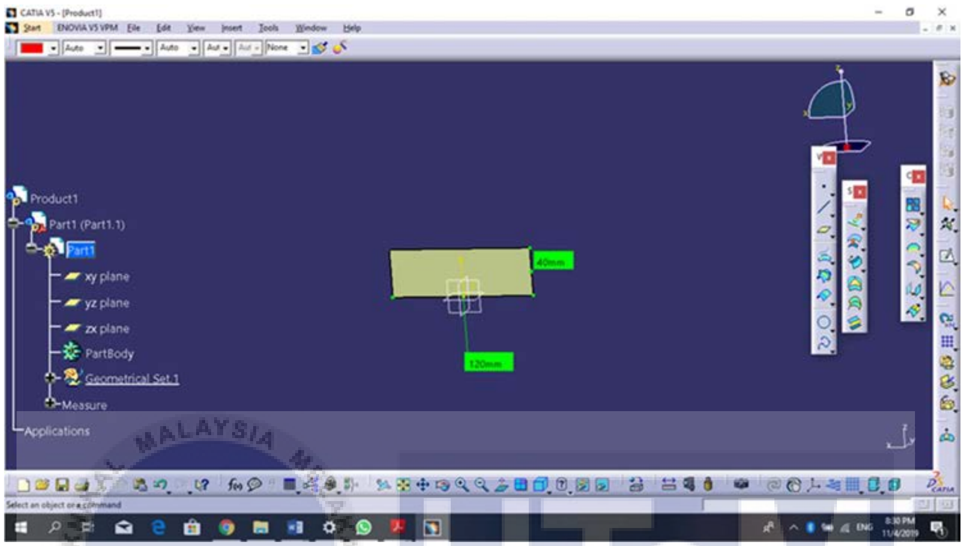


Figure 3.6 Three – dimensional modelling of a multi - layer (120 mm x 40 mm) using Catia software

The mechanical properties and microstructural of the fabricated metal part with and without thermoelectric cooling will be observed and examined. These analysis should be able to validate the effectiveness of thermoelectric cooling on WAAM process. This process should improve tensile strength, surface roughness, hardness and refined macrostructure of the WAAM fabricated metal part. The parameters that remains constant throughout this experiment are stated in Table 3.1.

Table 3.1 Constant parameter in the experiment

Parameter	**Value for each parameter**
Layer height, mm	2
Wire feed speed, mm	88
Voltage, V	17.24
Current, A	90

3.5 Fabrication of Samples by WAAM

In order to study the effect of deposited metal using WAAM with and without thermoelectric cooling, the two samples from the experiment were utilized for three different testing requirement to analyse the mechanical properties on the parts produced using WAAM. For tensile test and hardness test, the specimens were extracted parallel and perpendicular to the build direction respectively as shown in Figure 3.7.

American society for testing and material (ASTM) is a test standard where it provided procedures and definition for the mechanical testing. Hence, the dimensions for tensile specimens was based on ASTM A370 standard shown in Figure 3.8 and were cut by using computer numerical control (CNC) laser cutting machine as shown in Figure 3.9. ASTM A370 is one of many test standard that covers the mechanical testing of steel products such as stainless steel, cast steels and related alloy. For hardness test, the specimens were cut using hand grinder and for surface roughness, the specimens are observed based on the top layer of deposited metal of the fabricated part.

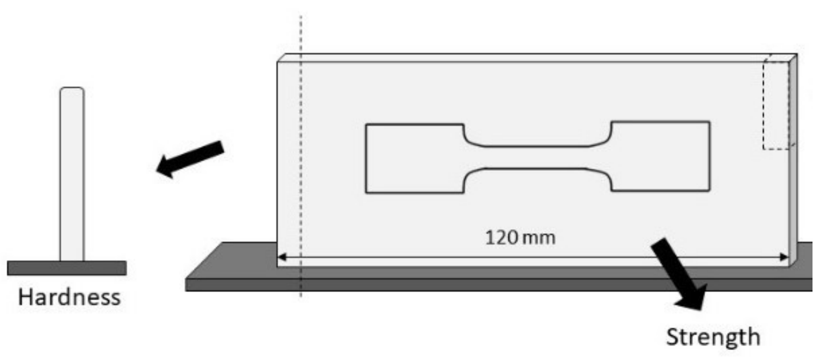


Figure 3.7 Schematic diagram of the sampling position

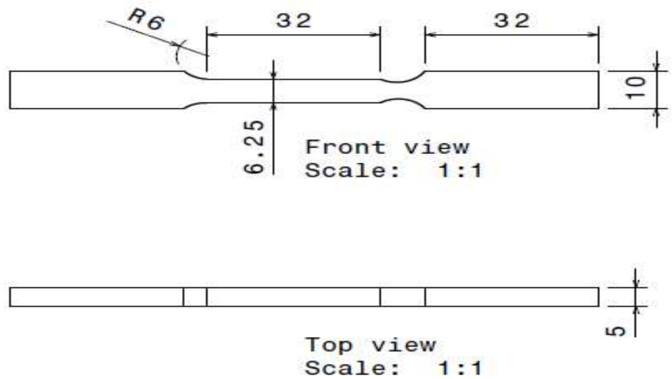


Figure 3.8 Dimensions of tensile sample

Figure 3.9 CNC laser cutting machine

3.6 Mechanical Tests

3.6.1 Surface roughness test

Surface roughness is a component surface texture that determine the quality of a product. It is quantified by the deviations in the direction of the build directions. Surface roughness can be expressed as Ra which is the mean deviation of the roughness profile and can be measured as a surface profile with a profilometer. Therefore, a 3D – non contact profilometer is used for this test as shown in Figure 3.10. The objective lens of the 3D – non contact profilometer was fixed and utilized to scan the surface profile of thin – walled part. The measurement of this method mainly depending on the image processing of objective lens that is less than 30 mm.

The specimen was placed on the levelling table at a suitable position and the table was adjusted manually to capture more focus measurement in the computer. Once the machine was set, the measurement was ready to be recorded. The roughness profile graph of the specimen was displayed and recorded. The test was repeated with other specimen.

Figure 3.10 3D - non contact profilometer

3.6.2 Hardness Test

AMH43 Automatic Microindentation Hardness Testing as shown in Figure 3.11 was used to investigate distribution characteristics of the microhardness in different points along the cross – section of specimens. A set of 5 points with an interval of 6 mm as shown in Figure 3.12 has been implemented along the cross – section of a multi – layer for the two specimens. During the experiment, the indenter of the instrument was pressed into the specimen from the bottom to the top layer by a force of 98.07 mN for 10 seconds. The readings of the hardness test was recorded. The test is then repeated with other specimen.

Figure 3.11 Vickers microhardness testing

Figure 3.12 Schematic diagram of 5 points implemented along the cross - section of WAAM sample with interval of 6 mm

3.6.3 Tensile Test

Tensile testing is one of the most crucial tests in order to provide valuable information about the strength of a material. Therefore, the specimens were tested for tensile test on a universal material testing machine as shown in Figure 3.13 at room temperature. A universal material testing AG – 10kNX machine is used to both test the tensile strength and compressive strength of materials.

Figure 3.13 Universal material testing AG – 10kNX machine

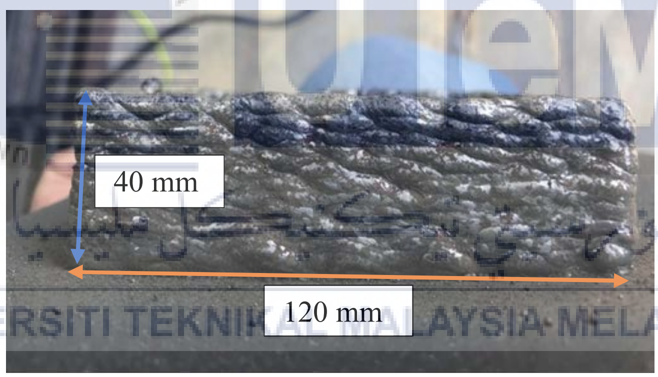
The machine was set to zero before inserting the specimen in the grips. Once the machine set, the specimen was placed in the machine load frame and were tested until it fracture which can be seen in Figure 3.14. The data obtained in the software were gathered and exported into an Excel spreadsheet.

Figure 3.14 One of tensile specimens after facture

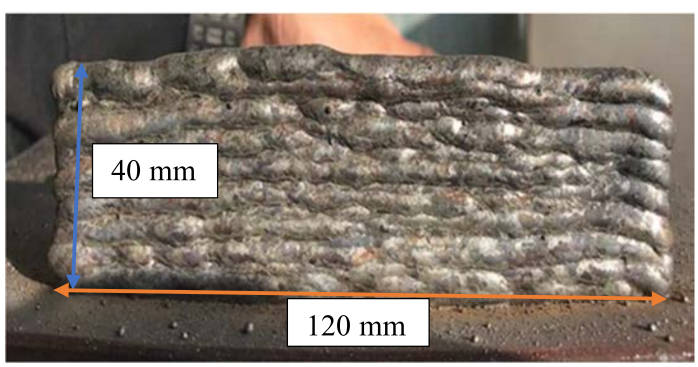
CHAPTER 4

RESULTS AND DISCUSSION

The accuracy of dimensional component part represents the ability of 3D printing to manufacture model that accurate to the 3D model. Two samples were printed for the experiment as shown in Figure 4.1 and the dimension for each samples are record. The wire feeding speed, layer height, current and voltage will be remains as constant in this experiment which are 88 mm/s, 2 mm, 90 A and 17.24 V respectively. The result shows that both of samples has the accurate dimensions to the 3D model which are 120 mm x 40 mm.



(a) Multi - layer product of WAAM with thermoelectric cooling



(b) Multi – layer product of WAAM without thermoelectric cooling

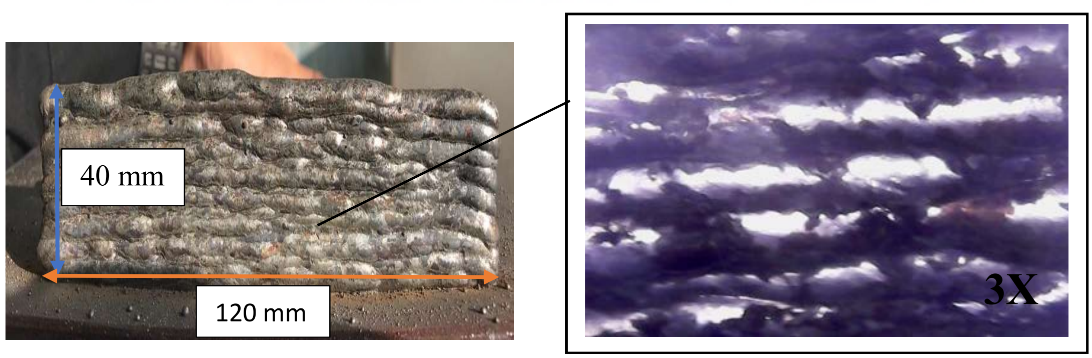
Figure 4.1 The 3D printed material using WAAM

4.1 Bead on Plate Deposition

4.1.1 Macroscopic Analysis

Visual examination of the weld indicated good weld bead with little spatter and less visible defects for both samples. The surface of the sample undergoes 3 times magnification under the microscope to investigate the macrostructure of the sample. The bead produced with thermoelectric cooling has thinner weld bead and more stable continuous deposition as shown in Figure 4.2(a). The bead produced without thermoelectric cooling exhibited a coarse columnar macrostructure with large grains as shown in Figure 4.2(b).

(a) Deposited layer of WAAM with thermoelectric cooling system



(b) Deposited layer of WAAM without thermoelectric cooling system

Figure 4.2 The appearances comparison between (a) deposited layer produced with thermoelectric cooling and (b) deposited layer produced without thermoelectric cooling respectively

Based on the result, heat dissipation in the weld pool is main factor for this experiment. The weld metal cooling rate increases when the cold side of the thermoelectric cooling was attached directly to the surface of the wall in order to accelerate the heat dissipation at the surface of the weld pool. With the aid of thermoelectric cooling, it is helps to accelerate the heat dissipation without reducing or adjusting other parameters such as heat input, wire feed speed and more. By increasing the cooling rate, the solidification of weld bed is increased and finer weld metal macrostructure is produced. The result for the effect of cooling on weld pools is almost similar to Wells & Lukens (1986) where forced cooling gas was applied on GTA weld pools. Besides that, heat accumulation is slightly reduced since the heat dissipation becomes more effective. Therefore, the heat transfer becomes more variable in the build direction which provides more opportunity for development of steady state deposition as shown in Figure 4.2(a).

4.2 Mechanical Tests

4.2.1 Surface Roughness Analysis

The surface profile of each deposited metal specimens were scanned for four times with interval of approximately 0.05 mm to get more accurate value of surface roughness as shown in Figure 4.3 and 4.4. Table 4.1 and 4.2 present the values for surface roughness as observed by 3D – non contact profilometer.

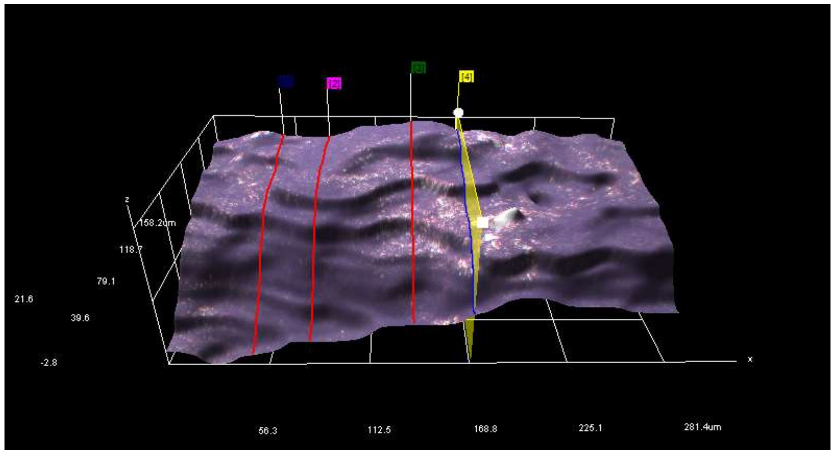


Figure 4.3 Surface profile of deposited metal without thermoelectric cooling

Table 4.1 The values for surface roughness parameter, *Ra* of deposited metal without thermoelectric cooling

Surface Profile	Surface Roughness, *Ra* (µm)
1	3.6
2	4.7
3	1.6
4	1.7
Average value of surface roughness, Ra	**1.7**

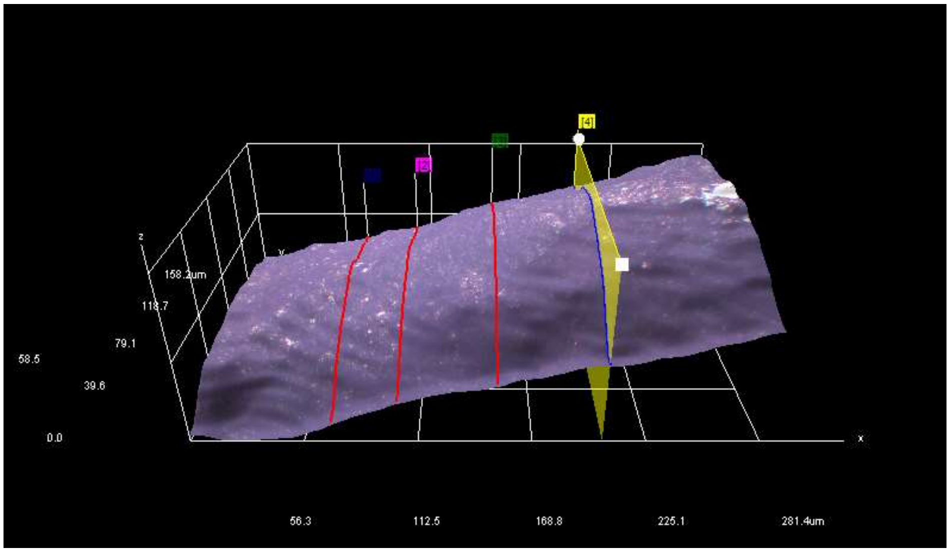


Figure 4.4 Surface profile of deposited metal with thermoelectric cooling

Table 4.2 The values for surface roughness parameter, *Ra* of deposited metal with thermoelectric cooling

Surface Profile	Surface Roughness, *Ra* (µm)
1	7.7
2	7.7
3	8.8
4	10.3
Average value of surface roughness, Ra	**10.3**

Theoretically, deposited metal with thermoelectric cooling system should have better surface roughness than deposited metal without thermoelectric cooling system. However, there are significant discrepancy between the average value of surface roughness, Ra of deposited metal without and with thermoelectric cooling system which are 1.7 µm and 10.3 µm respectively based on Table 4.1 and 4.2. These results indicated that deposited metal without thermoelectric cooling system has better surface roughness compared to deposited metal with thermoelectric cooling system.

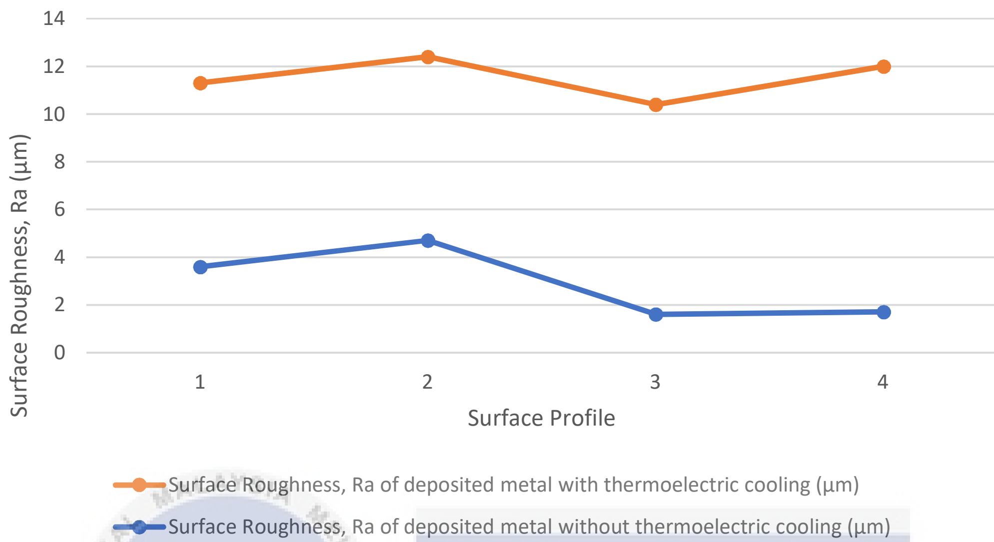


Figure 4.5 Graph of surface roughness of deposited metal with and without thermoelectric cooling

Based on the result presented in the Figure 4.5, there are no significant improvement on surface roughness of deposited metal with and without thermoelectric cooling. The use of an in – process active cooling system based on the thermoelectric cooling may have insignificant impact during the WAAM process due low heat dissipation and high heat accumulation within each layer of deposited metals. The result for this analysis is similar to Wu, Pan, Ding, Cuiuri, Li, & Fei (2018) experiment where forced cooling gas using compressed CO_2 was applied between deposited metal during WAAM process.

Therefore, there are a few factors that may influence the surface roughness of deposited metal produced during WAAM process such as unpredictable reheating effect induced from the layer stacking up, the distance from the thermoelectric cooling to the deposited metal that may be too far or misaligned and no improper shielding. It is possible to obtain different surface roughness along the height of the specimen due to the unpredictable reheating effect induced from the layer stacking up during WAAM process. The distance from the thermoelectric cooling to the deposited metal were may place too far and not aligned with the welding heat source resulting to an asymmetric heat dissipation, heat accumulation and residual stress distribution. According to *Local Cooling during Welding : Prediction and Control of Residual Stresses and Buckling Distortion* (n.d.), the distance from the cooling source to the weld pool is critical to WAAM process as the cooling source is the mechanism of stress reduction that influencing the weld pool shape and thermal field. Moreover, there is no improper shielding during WAAM process causes the welding process to become unstable and unpredictable.

Moreover, the 3D scanning process for surface roughness test may also contribute to inaccurate result. This is because the orientation of specimens for surface profile during 3D scanning were unbalanced hence, the number of points captured for surface profile were reduced which contributed to inaccurate result. This is because as the laser beam moves away from the surface, the number of points captured during scanning is reduced due to limit view angle. In order to obtain the highest number of points acquired, the orientation of the specimen must be balanced with the laser beam is perpendicular to the surface of the specimen. (Cuesta *et al.*, 2009)

4.2.2 Hardness Analysis

Hardness test were performed on the specimens to further investigate the mechanical properties of fabricated parts using WAAM. The average Vickers microhardness of the deposited metal were measured transversely and perpendicular to the direction of the build direction. Based on Table 4.3, the dispersion among measurement can be quantified by using the reproducibility limit, R, which can be calculated as shown in Equation (1) (Prado-Cerqueira *et al.*, 2018) and tabulated in Table 4.4:

$$R = \frac{d_{max} - d_{min}}{\langle \mathrm{d} \rangle}$$

Where d_{max} and d_{min} are the maximum and minimum diameters while $\langle \mathrm{d} \rangle$ is the mean of measure diameters.

Table 4.3 Vickers hardness test

Distance of points from substrate (mm)	**Vickers hardness of multi - layer specimen with thermoelectric cooling (HV)**	**Vickers hardness of multi - layer specimen without thermoelectric cooling (HV)**
6	0.304342	0.301125
12	0.441394	0.421339
18	0.433327	0.439164
24	0.476903	0.442431
30	0.543408	0.47921

Table 4.4 R values for hardness test

	Multi - layer specimen with thermoelectric cooling	**Multi - layer specimen without thermoelectric cooling**
d_{max}	0.543408	0.47921
d_{min}	0.304342	0.301125
$\langle \mathrm{d} \rangle$	0.4398748	0.4166538
R	0.5434864	0.42741712

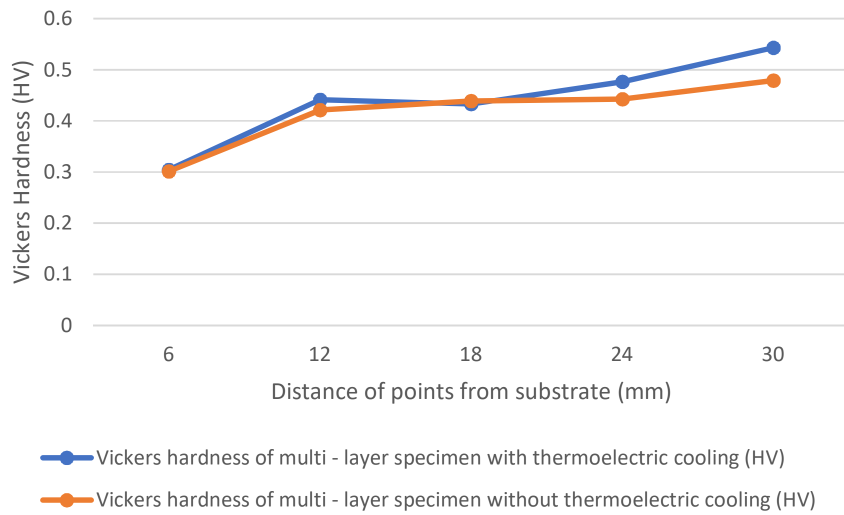


Figure 4.6 Graph of Vickers hardness tests

Based on Table 4.3 and 4.4, the Vickers hardness of multi – layer specimen with thermoelectric cooling has bigger hardness value which range from 0.304342 HV to 0.543408 with R values of 0.5434864. Meanwhile, the Vickers hardness of multi – layer specimen without thermoelectric cooling provides an adequate hardness value which range from 0.301125 HV to 0.47921 with R values of 0.42741712. According to the graph in Figure 4.6, the Vickers hardness of multi – layer specimen with thermoelectric cooling exhibits a slightly higher hardness value compared to multi – layer specimen without thermoelectric cooling. Although the thermoelectric cooling applied may has no effect on microstructures, the multi – layer specimen with thermoelectric cooling obtained using the WAAM process has exhibits more grain refinement which contribute to better performance in hardness.

The specimens for this hardness test can be divided into three different part which are the bottom part, the middle part and the top part. During the first layer of deposition, the bottom part has no thermal shock as it is in contact with the cold substrate. The middle part has lower thermal shock as it is in contact with the bottom part which is a warm weld bead deposited. Last but not least, the upper part has the highest thermal shock as it is in contact with thermoelectric cooling technology and room temperature.

Therefore, the result show an increasing trend of hardness profile as the upper part was close to the free surface which resulting to thermal chilling due to the contact with thermoelectric cooling and air at room temperature. Henckell et al. (2017) also has shown similar result which indicated that the position of deposited metal that is closest to weld torch and cooling source was the most effective in improving the layer geometry and mechanical properties through grain refinement and hardness.

4.2.3 Tensile Analysis

The tensile test can be related to plastic deformation which the deformation can be classified into two type of materials, ductile material and brittle material. Ductile materials are materials that have the ability to withstand tensile force with no crack. They able to hold the deformation when tensile force is applied and undergoes plastic deformation. Brittle materials are materials that have the ability to break when tensile force is applied without any elongation or plastic deformation.

Therefore, The dog – bone without thermoelectric cooling is brittle material because it broke when tensile force is applied as shown in Figure 4.7. This is because the surface of each deposited metal is oxidised due to slow heat dissipation during WAAM process. As more layers were deposited, these oxides were trapped between the layers and causes the material to become brittle.

The dog – bone sample with thermoelectric cooling is ductile material because it have the ability to withstand tensile force as shown in Figure 4.8. The tensile strength is very sensitive with the grains size because larger grains provide poor tensile strength to the decreased number of grain boundaries (Xiong, Mao and Zhao, 2019). As mentioned in section 'Hardness analysis', grain refinement can be improved by position the deposited metal closest to weld torch and cooling source which is also beneficial to improve the tensile strength.

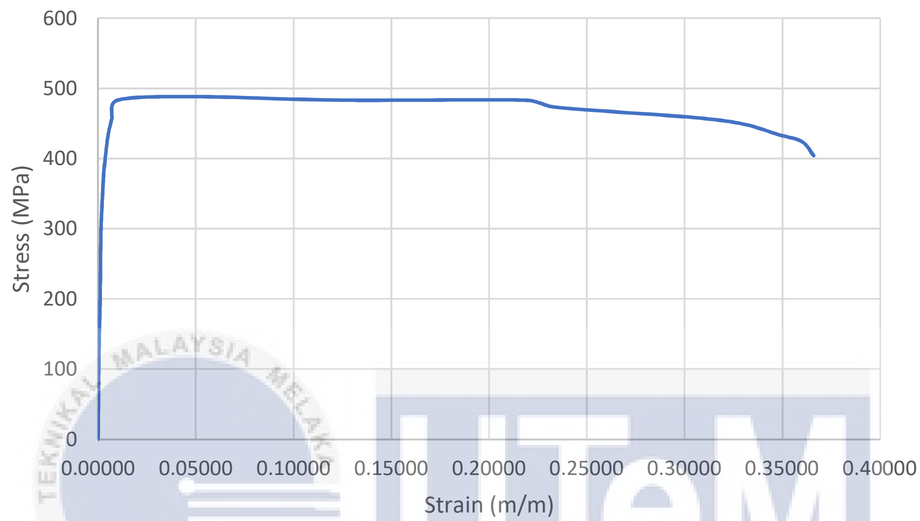


Figure 4.7 Graph of stress versus strain for dog - bone sample without thermoelectric cooling

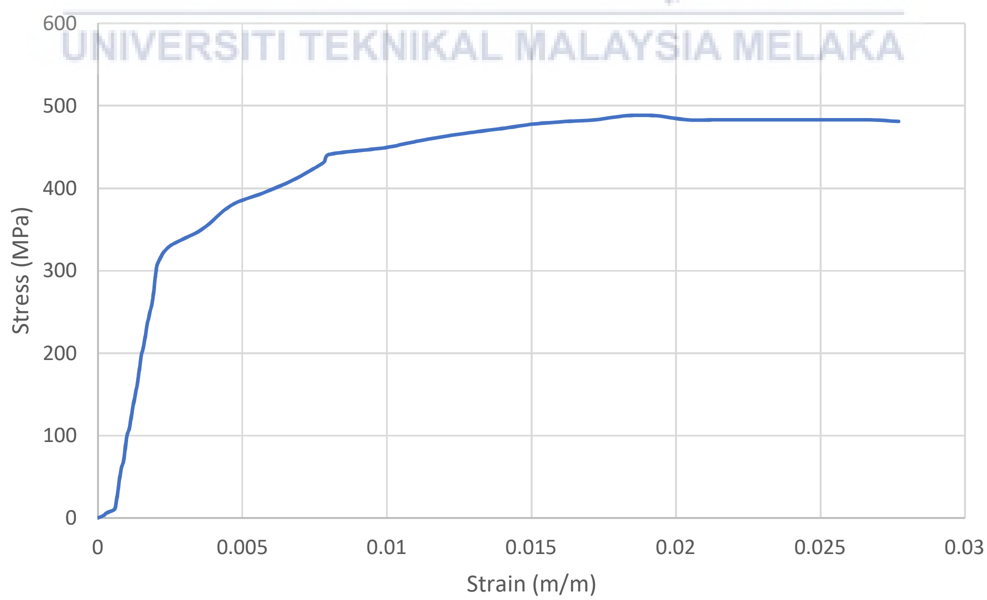


Figure 4.8 Graph of stress versus strain for dog - bone sample with thermoelectric cooling

According to Figure 4.9, there are huge significant differences between dog – bone sample with and without thermoelectric cooling system where both specimens showed variance amount of plastic deformation. The dog – bone sample with and without thermoelectric cooling have similar tensile strength where the highest tensile strength for both specimens are 488 MPa. However, dog – bone sample with thermoelectric cooling exhibits an extremely smaller elongation at failure compared to dog – bone sample without thermoelectric cooling. This is due to dog – bone sample with thermoelectric cooling has smaller range of strain where the highest strain value is 0.0361 m/m whereas the highest strain value for dog – bone sample without thermoelectric cooling is 0.366 m/m.

Besides that, since the dog – bone sample with thermoelectric cooling became a ductile material, the stress – strain curve of the sample deviates from the straight – line relationship as the strain increases faster than stress. The plastic deformation for the sample became permanent as it reacted plastically to any further increase in force or stress. For this reason, the specimen cannot return to its original condition when the force is removed. For the dog – bone sample without thermoelectric cooling that became a brittle material, there was little plastic deformation occur and the specimen fractured near the end of the linear – elastic portion of the curve.

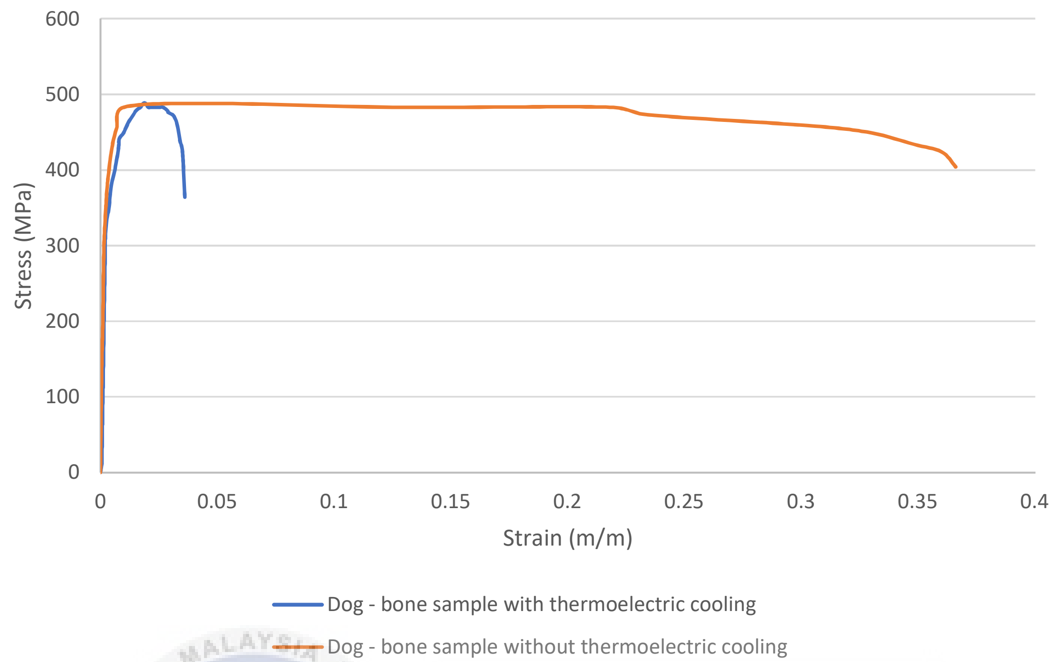


Figure 4.9 Graph of stress versus strain for dog - bone sample with and without thermoelectric cooling

Moreover, the ultimate tensile strength (UTS) is the maximum tensile strength that material can withstand when tensile force is applied. The ultimate tensile strength (UTS) can be calculated using the Equation (2) and tabulated in Table 4.5:

$$UTS = \frac{P_{max}}{A_o}$$

Where P_{max} is the maximum tensile force applied onto the sample and A_o is the cross – sectional area of sample.

Table 4.5 Ultimate tensile strength (UTS) for tensile test

	UTS (MPa)
Dog – bone sample without thermoelectric cooling	824
Dog – bone sample with thermoelectric cooling	315.5

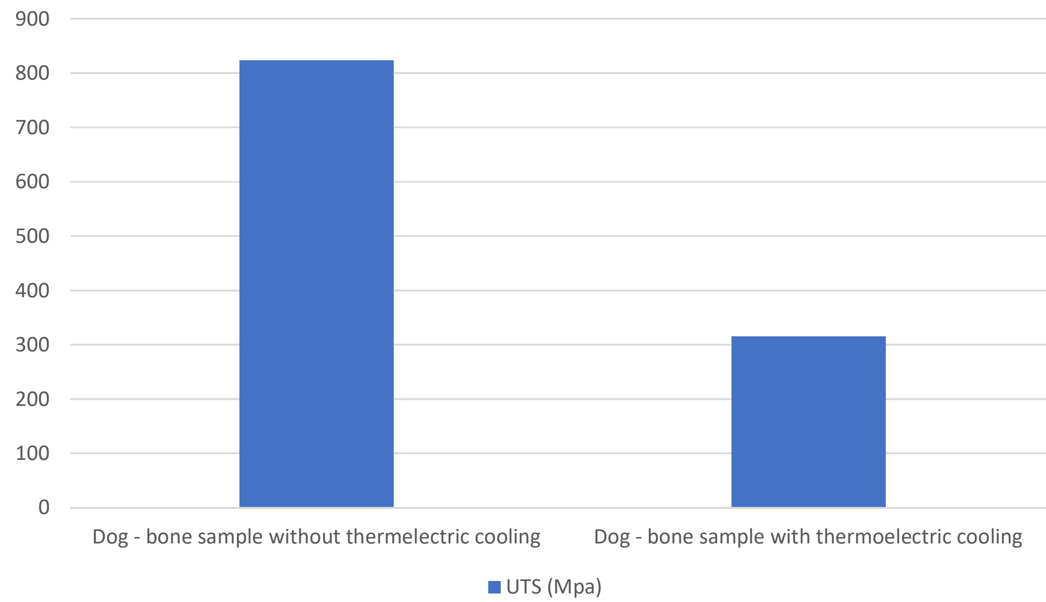


Figure 4.10 Graph of UTS for dog – bone sample with and without thermoelectric cooling

Based on Table 4.5 and Figure 4.10, the dog – bone sample without thermoelectric cooling exhibits higher UTS compared to the dog – bone sample with thermoelectric cooling. The dog – bone without thermoelectric cooling has higher UTS due to material hardening as there are small amount of plastic deformation occurred. However, the material of dog – bone sample with thermoelectric cooling was not harden very well causes the specimen to experience permanent plastic deformation and resulting in a lower ultimate tensile strength.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In this study, an in – process active cooling system based on the thermoelectric cooling is applied to WAAM process. Therefore, the effect of deposited metal using wire arc additive manufacturing with and without thermoelectric cooling were investigated. The macroscopic and mechanical properties of the deposited metal produced by wire arc additive manufacturing were analysed.

The main finding in macroscopic analysis was the visual examination of the weld that indicated good weld bead with little spatter and less visible defects for both samples. With the aid of thermoelectric cooling, the deposited layer form a refined weld metal macrostructure and more stable deposition. The weld metal cooling rate increases with thermoelectric cooling. By increasing the cooling rate, the solidification of weld bead is increased and a finer weld metal macrostructure is produced.

Besides that, there are no significant improvement on surface roughness of deposited metal with and without thermoelectric cooling. The use of an in – process active cooling system based on the thermoelectric cooling may have insignificant impact during the WAAM process. There are a few factors that influence on surface roughness of deposited metal during WAAM process and scanning process such as unpredictable reheating effect induced from the layer stacking up during WAAM process, the distance from the thermoelectric cooling to the deposited metal were placed too far and not aligned with the welding heat source, improper shielding during WAAM process and the orientation of specimens for surface profile during 3D scanning were unbalanced. These factors have contributed to unstable and unpredictable welding process that can lead to inaccurate results.

Therefore, there are a few measures that can be taken to improve the surface roughness of deposited metal. Firstly, make sure the thermoelectric cooling system has sufficient capacity to rapidly cool down the hot metal surface to prevent unpredictable reheating effect induced from the layer stacking up. Secondly, the distance from the thermoelectric cooling to the deposited metal need to be place as close as possible to the metal surface and aligned to the welding heat source to ensure high and symmetric heat dissipation. Next, set up a proper shielding chamber to ensure the welding process become stable. Furthermore, the surface of the specimen must be balanced and is place perpendicular to the laser beam in order to ensure better view for scanning.

The multi – layer specimen with thermoelectric cooling obtained using the WAAM process has exhibits more grain refinement which contribute to better performance in hardness. Although the thermoelectric cooling applied may has no effect on microstructures, the Vickers hardness of multi – layer specimen with thermoelectric cooling exhibits a slightly higher hardness value compared to multi – layer specimen without thermoelectric cooling. This is because the upper part was close to the free surface which resulting to thermal chilling due to the contact with thermoelectric cooling and air at room temperature hence, the deposited metal that is positioned closest to weld torch and cooling source is the most effective in improving the layer geometry and mechanical properties through grain refinement and hardness.

There are no significant improvement on tensile test between dog – bone sample with and without thermoelectric cooling. The dog – bone sample with thermoelectric cooling became ductile material because it able to withstand tensile force and undergoes plastic deformation. Meanwhile, the dog – bone sample without thermoelectric cooling became brittle material as it broke when tensile force were applied. Due to slow heat dissipation during WAAM process, the surface of each deposited metal is oxidised and causes the material to become brittle. Besides that, as ductile material, the stress – strain curve of the sample deviates from the straight – line relationship as the strain increases faster than stress. The plastic deformation for the sample became permanent as it reacted plastically to any further increase in force or stress. For brittle material, there was little plastic deformation occur and the specimen fractured near the end of the linear – elastic portion of the curve. Moreover, the dog – bone sample without thermoelectric cooling exhibits higher UTS compared to the dog – bone sample with thermoelectric cooling due to material hardening.

There are various engineering materials such as titanium and aluminium that can be used to conduct an experiment under the same conditions of this project to have better understanding on the effect of different types of wire feed on deposited metal produced. This is because titanium and aluminium are widely used in aircraft industry. Therefore, by conducting further studies on wire arc additive manufacturing process, it will help to improve wire arc additive manufacturing process in order to fulfil demands of bigger production. Moreover, further investigation should focus more on the effects of other active cooling system such forced interpass cooling gas, cold metal transfer welding and others on the deposited metal produced using wire arc additive manufacturing process in order to compare, analyse and improve the effectiveness of this process.

REFERENCES

Busachi, A., Erkoyuncu, J., Colegrove, P., Martina, F. and Ding, J., 2015. Designing a WAAM based manufacturing system for defence applications, *Procedia CIRP*., 37(2013), pp. 48–53. doi: 10.1016/j.procir.2015.08.085.

Cheng, X., Fisher J, Prask J.W., Henry J., Gnäupel-Herold, Thomas Yen, Roy, B. T. and Sougata, 2003. Residual stress modification by post-weld treatment and its beneficial effect on fatigue strength of welded structures, *International Journal of Fatigue*, 25(9–11), pp. 1259–1269. doi: 10.1016/j.ijfatigue.2003.08.020.

Colegrove, P., Ikeagu, C., Thistlethwaite, A., Williams, S., Nagyl, T., Suder, W., Steuwer, A. and Pirling, T., 2009. Welding process impact on residual stress and distortion, *Science and Technology of Welding and Joining*, 14(8), pp. 717–725. doi: 10.1179/136217109X406938.

Cuesta, E., Carlos Rico, J., Fernández, P., Blanco, D. and Valiño, G., 2009. Influence of roughness on surface scanning by means of a laser stripe system, pp. 1157–1166. doi: 10.1007/s00170-008-1794-9.

Cunningham, C. R., Flynn, J. M., Shokrani, A., Dhokia, V. and Newman, S. T., 2018. Invited review article: Strategies and processes for high quality wire arc additive manufacturing, *Additive Manufacturing*, 22, pp. 672–686. doi: 10.1016/j.addma.2018.06.020.

Ding, D., Pan, Z..Cuiuri, D. and Li, H., 2015. Wire-feed additive manufacturing of metal components: technologies, developments and future interests, *International Journal of Advanced Manufacturing Technology*, 81(1–4), pp. 465–481. doi: 10.1007/s00170-015-7077-3.

Henckell, P., Günther, K., Ali, Y., Bergmann, J. P., Scholz, J. and Forêt, P., 2017. The Influence of Gas Cooling in Context of Wire Arc Additive Manufacturing — A Novel Strategy of Affecting Grain Structure and Size, in: *The Minerals Metals & Materials Series (Ed.), TMS 2017 146th Annual Meeting & Exhibition Supplemental Proceedings, Springer International Publishing, Cham*, pp. 147–156. doi: 10.1007/978-3-319-51493-2.

Knezović, N. and Topić, A. 2018. Wire and Arc Additive Manufacturing (WAAM)–A New Advance in Manufacturing, *In International Conference "New Technologies, Development and Applications"*, *Springer*, *Cham*, pp. 65-71.

Maria, V. D. A. E., 2006. Local Cooling during Welding : Prediction and Control of Residual Stresses and Buckling Distortion, PhD thesis, Delft University of Technology , Delft, The Netherlands.

Mercedes, P., Medina-s, G. and Carou, D., 2018. Surface Quality Enhancement of Fused Deposition Modeling (FDM) Printed Samples Based on the Selection of Critical Printing Parameters, *Materials 2018*, 11(8), p. 1382. doi: 10.3390/ma11081382.

Prado-Cerqueira, J. L., Camacho, A. M., Diéguez, J, L., Rodríguez-Prieto, Á., Aragón, A. M., Lorenzo-Martín, C., and Yanguas-Gil, Á., 2018. Analysis of favorable process conditions for the manufacturing of thin-wall pieces of mild steel obtained by wire and arc additive manufacturing (WAAM)', *Materials*, 11(8). doi: 10.3390/ma11081449.

Sachs, E., Cima, M., Cornie, J., Brancazio, D., Bredt, J., Curodeau, A., Esterman, M., Fan, T., Harris, C., Kremmin, K., Lee, S. J., Pruitt, B., Williams, P., (1990) 'Dimensional Printing : Rapid Tooling and Prototypes Directly from CAD Representation', *International Solid Freeform Fabrication Symposium*, pp. 289-296.

Shi, J., Li, F., Chen, S., Zhao, Y., and Tian, H., 2018. Effect of in-process active cooling on forming quality and efficiency of tandem GMAW–based additive manufacturing, *International Journal of Advanced Manufacturing Technology*. The International Journal of Advanced Manufacturing Technology, pp. 1-8 doi: 10.1007/s00170-018-2927-4.

Wang, Z., Palmer, T. A. and Beese, A. M., 2016. Acta Materialia Effect of processing parameters on microstructure and tensile properties of austenitic stainless steel 304L made by directed energy deposition additive manufacturing, *Acta Materialia*, 110, pp. 226–235. doi: 10.1016/j.actamat.2016.03.019.

Wells, M. and Lukens, W. , 1986. Effect of forced gas cooling on GTA weld pools, *Welding Journal*, pp. 314–320.

Wu, B., Ding, D., Pan, Z., Cuiuri, D., Li, H., Han, J., and Fei, Z., 2017. Effects of heat accumulation on the arc characteristics and metal transfer behavior in Wire Arc Additive Manufacturing of Ti6Al4V, *Journal of Materials Processing Technology*, 250, pp. 304–312. doi: 10.1016/j.jmatprotec.2017.07.037.

Wu, B., Pan, Z., Ding, D., Cuiuri, D., Li, H., Xu, J., and Norrish, J., 2018. A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement, *Journal of Manufacturing Processes*, 35, pp. 127–139. doi: 10.1016/j.jmapro.2018.08.001.

Wu, B., Pan, Z., Ding, D., Cuiuri, D., Li, H. and Fei, Z. (2018) 'The effects of forced interpass cooling on the material properties of wire arc additively manufactured Ti6Al4V alloy', *Journal of Materials Processing Technology*, 258, pp. 97–105. doi: 10.1016/j.jmatprotec.2018.03.024.

Xiong, J., Mao, Y. and Zhao, H., 2019. Additive manufacturing of high- strength weathering steel parts fabricated by gas tungsten arc : Microstructure and mechanical properties, *Proceddings of the Instituiton of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, pp. 1–11. doi: 10.1177/0954405419828590.