ANALYSIS OF COMPONENTS PRODUCED USING WIRE ARC ADDITIVE MANUFACTURING

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in fulfillment of the requirement for the degree of
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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 :

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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.

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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.

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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).

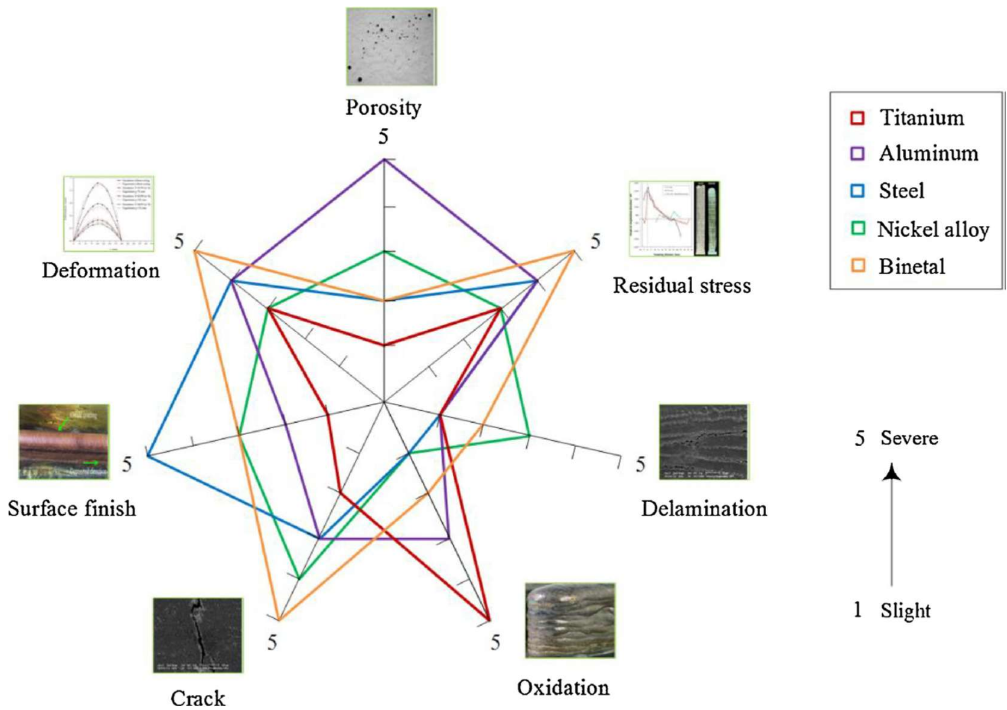

Figure 2.1 Correlation between materials and common defects in WAAM processes.

(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)

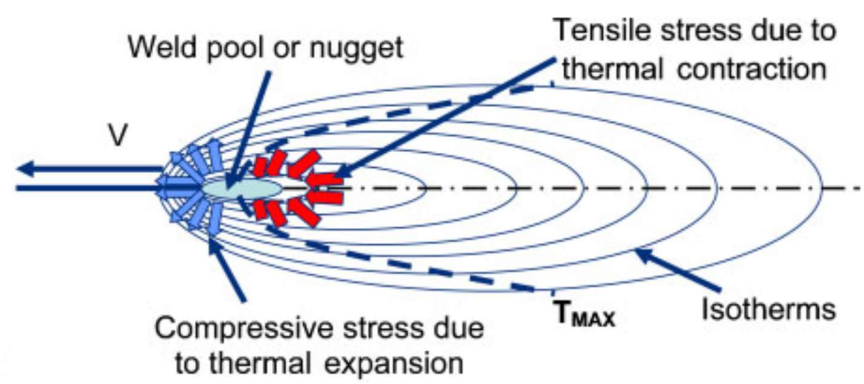

Figure 2.2 Stresses that occur on fabricated part during WAAM process.

(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).

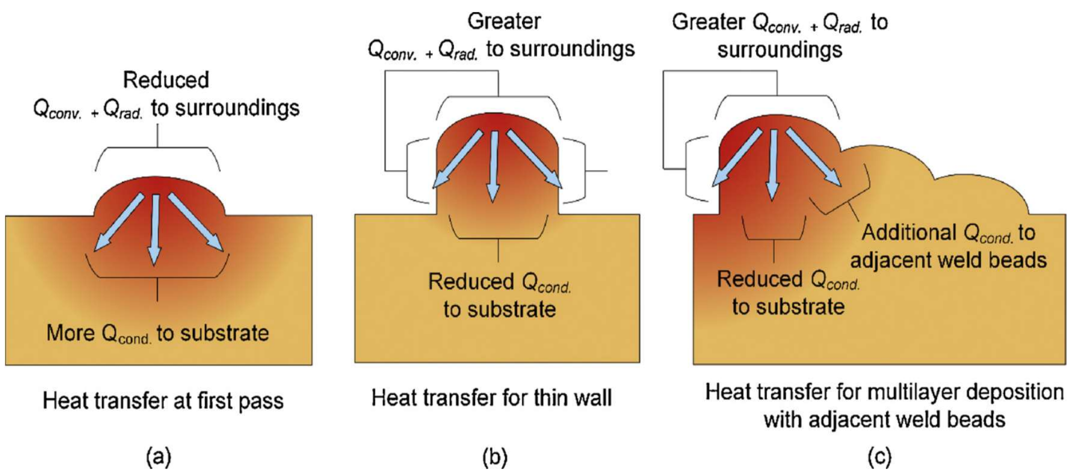

Figure 2.3 Schematic diagram of the heat dissipation process, conduction convection and radiation. (Cunningham et al., 2018)

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