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Influence of Process Parameters in Wire and Arc Additive Manufacturing (WAAM) Process

Nor Ana Rosli[1], *Mohd Rizal Alkahari*[2]*,
Faiz Redza Ramli[3], *Mohd Nizam Sudin*[4], *Shajahan Maidin*[5]

[1,2,3,4]*Faculty of Mechanical Engineering,*
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya Durian Tunggal, 76100, Melaka, Malaysia
**rizalalkahari@utem.edu.my*

[2]*Advanced Manufacturing Centre, Universiti Teknikal Malaysia Melaka,*
Hang Tuah Jaya Durian Tunggal, 76100, Melaka, Malaysia

[5]*Faculty of Manufacturing Engineering,*
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya Durian Tunggal, 76100, Melaka, Malaysia

[1,2,4,5]*Center of Advanced Research on Energy*
Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya Durian Tunggal, 76100, Melaka, Malaysia

ABSTRACT

Wire and arc additive manufacturing (WAAM) has developed a wide range of processes and applications. This technology is a new approach to modern manufacturing and is gaining interest from the research community due to its ability to create affordable, large-scale components. Nevertheless, WAAM may affected by porosity, humping and undercut. These issues need to be addressed in a specific way to achieve desired quality that is comparable to the traditional processing technique. This article examines various weld travel speeds, where defects start appearing. The effects of travel speed and wire feed speed (WFS) were also discussed. It was found that, travel speed and WFS had a major influence on deposition width and height and a stable deposited layer was produced between heat input values of 0.2620 kJ/mm and 0.32756 kJ/mm.

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Introduction

WAAM is one of the three-dimensional (3D) printing/additive manufacturing variants that involve the welding processes, such as inert gas and plasma welding [1]. Due to its potential and curiosity in understanding the process, many developments, mechanical properties and in process monitoring of the 3D metal printing have been reported [2, 3]. The potential of WAAM has gained much attention from the industrial manufacturing sector due to its capability to provide significant reductions in production cost and lead times [4]. WAAM uses a wire from a reel that feeds through a welding torch and passes a contact tip to supply the welding current. It also uses an electric arc as a heat source to deposit metal ornaments. The process can be divided into three distinctive methods depending on the wire being fed, which are gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and plasma arc welding (PAW) [5].

Besides the advantages offered by 3D printing in general, there is still a big gap between the knowledge and potential of 3D printing especially related to WAAM process that needs to be explored and optimized, such as process monitoring and control [6]. Some of the major challenges faced by all wire-feed AM processes, including WAAM, are the residual stresses and distortion generated during the process [7]. These problems may originate from the excessive energy input, high deposition rate or large temperature gradient due to the unfit input parameter at the beginning of the AM process. Therefore, optimum process parameters of WAAM are required to ensure the best possible final fabricated parts. WFS and travel speed are closely related to the quality of the formed part. A previous study showed that the travel speed significantly impacted the bead width, where it decreased as travel speed increased, whereas the bead height did not vary significantly. The relationship between the voltage and the theoretical wire speed was totally different from the one that was obtained experimentally, where in the theoretical case; the voltage increased as WFS was increased [8]. However, in practice the wire speed hardly reached the programmed value, therefore, the theoretically calculated voltages could not be reached. Dilthey claimed that there was a delay in droplet formation when the WFS was increased until enough energy from the arc was exposed to the wire [9]. As consequence, the distance between the wire and weld pool reduced and drastically changed the transfer modes.

In this study, the optimal process parameters of WAAM were studied in terms of WFS and travel speed of a 3D printer to enhance the quality of

WAAM process. The impacts of these two parameters were considered by analysing the defects formed on the multi-layer deposition.

Experimental Details

Experimental setup

The WAAM system consisted of a 3D printer machine, GMAW system and shielding gas system. The GMAW system is a heat source that was applied to melt the metal wire. The 3D printing machine with the GMAW system was developed in Universiti Teknikal Malaysia Melaka (UTeM) was used for this study. This is shown in Figure 1 [10].

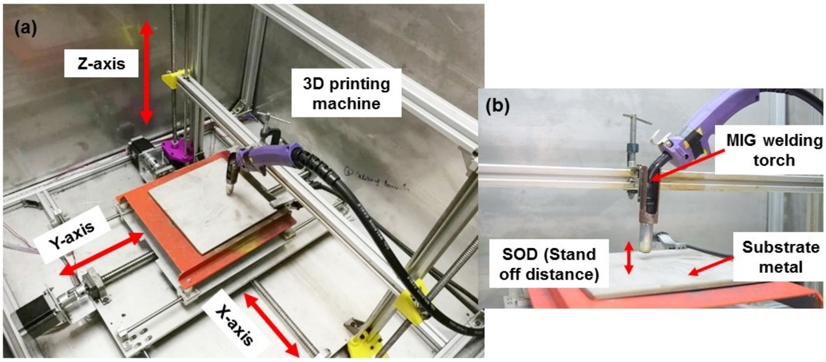


Figure 1: Experimental setup of WAAM system

A shielding gas that contained argon was utilised to avoid oxidation during the build-up process. The spool of the ER70S-6 with wire diameter of 1.2 mm was loaded on the wire-feeding system. It was also coaxial with the welding torch, which resulted in an easier tool path. The element content of the deposition wire (ER70S-6) is shown in Table 1. During the experiments, a 6 mm mild steel plate was employed as the base metal or substrate with dimensions of 300 mm × 300 mm × 300 mm. The stand-off distance (SOD) between the welding torch and substrate was constant at 5 mm. This was crucial to ensure uninterrupted deposition material and smooth wire-feeding supply to the melt pool. Low values of SOD were unable to supply smooth wire-feeding due to the small space, whereas high values of SOD resulted in wastage of wire deposition. The welding torch was mounted on the vertical plane of the z-axis direction and the substrate was placed on the horizontal plane of the x-axis and y-axis. The movement of each axis was driven by four stepper motors and controlled automatically through Repetier-Host. After performing deposition on each layer, the z-axis was increased by a predefined layer height, while the substrate remained stationary. The deposition direction between the adjacent layers was zig-zag pattern as shown in Figure 2. This was done to provide a uniform layer height across the wall and consequently prevent the production of hump that could produce a depression at the end, which accumulates with each deposited layer.

Table 1: Chemical composition of metal wire ER 70S-6

Element	C	Mn	S	Ni	V	Cr	Cu	Si	P	Mo
wt%	0.06-0.15	1.40-1.85	0.035 max	0.15 max	0.03 max	0.15	0.50	0.80-1.15	0.025	0.15 max

Detail of Experimentation

The experiments were conducted to identify the effects of travel speed and WFS on deposition characteristics. The process overview as illustrated by the overall flow in Figure 2.

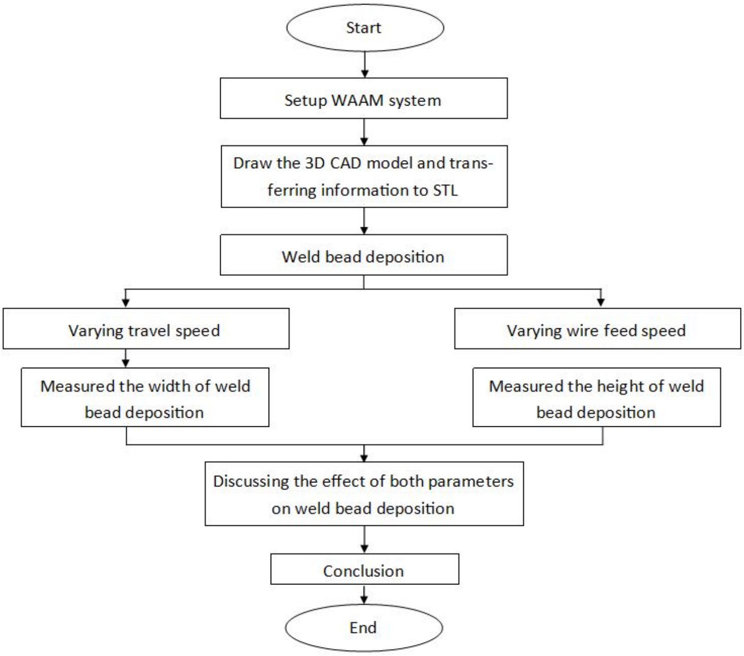


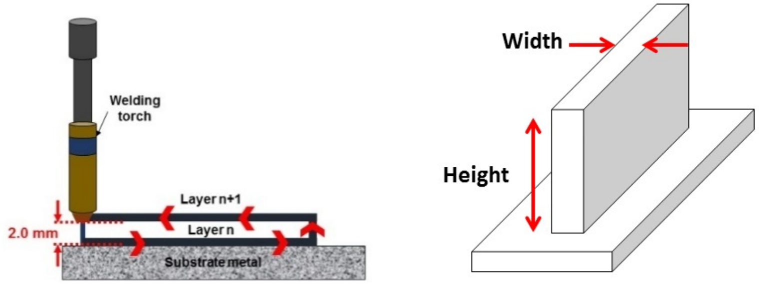
Figure 2: Flow chart for the study conducted

In this work, five layers were deposited under different values of travel speed and WFS. The deposition was performed with a dimension of 70 mm in length. The parameters used for each sample are presented in Table 2. There were seven process parameters listed, namely WFS, wire material, wire diameter, welding current, welding voltage, travel speed, and layer height. Some of the process parameters remained constant while varying travel speed and WFS.

Table 2. Process condition for deposit layers

Condition	Unit	
Wire feed speed (WFS)	mm/s	72, 80, 88,120
Wire material	-	ER70S-6
Wire diameter (mm)	mm	1.2
Current, I	A	95
Voltage, V	V	17.24
Travel speed	mm/s	2,4,5,8,10,15
Layer height	mm	2.0

The main experiments were designed and conducted by setting the values of the travel speed and WFS to obtain different values of heat input. The test samples were made by superimposing five layers and applying the build orientation technique as shown in Figure 3. At the beginning, a SOD of 5 mm between the welding torch and substrate was measured. After the first layer, the increment of each layer was constant at 2.0 mm.



(a) (b)

Figure 3: (a) Deposition direction of multi-layer weld bead, (b) Nomenclature of deposited layer output parameters

Results and Discussion

In order to obtain deposition of the intended shape without any defects, the most important key is to understand the effect of the process parameters involved. This section analyses the effects of heat input, printing speed and WFS on the deposited layer. During the measuring process, the deposited layer was captured to obtain the width and height along the deposition.

Effect of travel speed

The results presented six samples that were fabricated with varied printing speeds between 2 mm/s and 15 mm/s, while the WFS was kept constant at 120 mm/s. During the experiments, the properly formed deposited layer was measured in terms of width and relations to the variables. Figure 4 shows that as printing speed increases, the heat input decreases due to their inversely proportional relationship. On the other hand, the increase of the printing speed leads to the decrease of width of the deposited layer. This is because faster travel speeds enhance the cooling rate but reduce the ratio of the temperature gradient to solidification growth [11]. The evolution of the geometric characteristics shows that the width of the deposits decreases because heat accumulation reduces with increasing speed. An irregular bead deposit also takes places when the heat input reduces, thus forming a defect known as "humping" between the layers. Humping is one of the common defects that occurs in welding, which prevents further deposition operation [11]. This occurrence is related to low energy input from the heat source and high travel speeds [12]. After an irregular layer was formed at the beginning, it continued to the end of the deposit layers. It was observed that printing speeds between 4 mm/s and 5 mm/s produced a steady deposition width with an appropriate heat input to melt the metal wire and form successful weld beads.

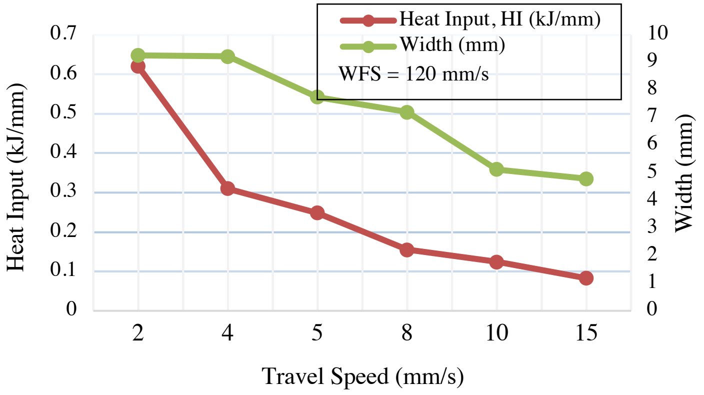
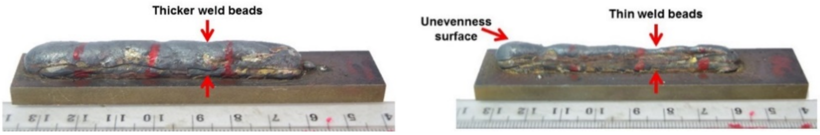


Figure 4: Effect of travel speed on deposit layers

As shown in Figure 5, two out of the six samples produced layer deposition with different travel speeds. At travel speed of 4 mm/s, a deposited layer with a thick width was formed without humping and regarded as a stable deposition. However, at travel speed of 8 mm/s, an unstable deposition was identified due to humping that occurred on the weld bead deposition. After five layers of deposition, the surface was uneven due to irregular deposition at the beginning. The formation of humping can also be described as periodic undulation that consists of hump and valley of the weld bead, which occur due to the backflow of molten metal [12]. Nonetheless, theoretically, higher travel speeds can be obtained by optimising various process parameters while maintaining the same heat input per distance [13].

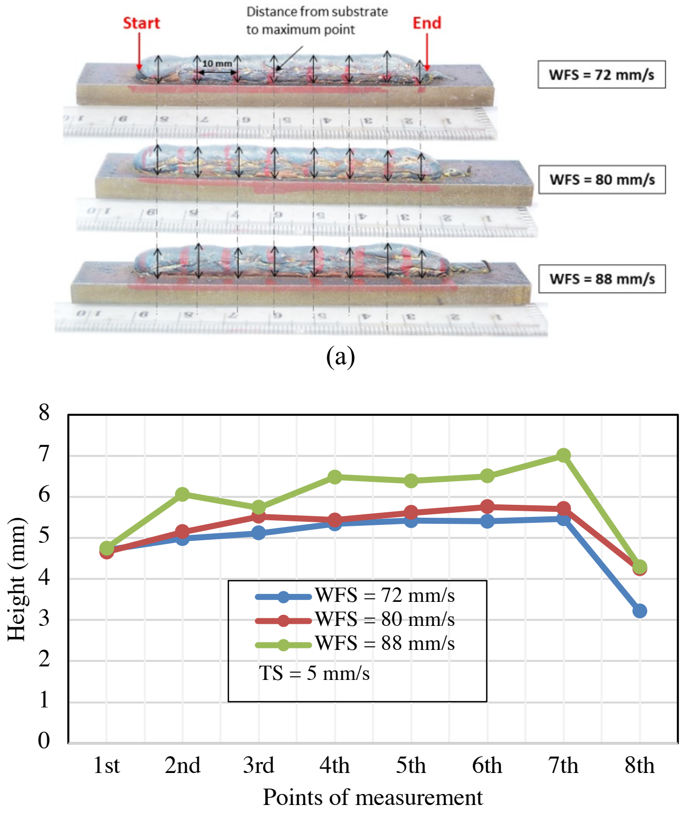


(a) (b)

Figure 5: Various speed of weld deposition; (a) Travel speed 4 mm/s, and (b) Travel speed 8 mm/s

Effect of wire feed speed

WFS is one of the process parameters verified as a factor that influences the quality of a deposit. In this study, the WFS was varied from 72 mm/s to 88 mm/s. The height of the multi-layer deposition was, measured at eight different points along the layer surface as shown in Figure 6(a) and Figure 6(b). The results showed that the increase of WFS increased the unevenness of the bead surface within the framework of a constant travel speed. The deposition height increased rapidly with the increase of WFS and there was also a slight increase in deposition width. This was related to the overlapping process of the molten weld bead. The increasing WFS with a constant travel speed caused the material being deposited per unit time to increase by a constant heat input from the arc to the weld pool. Therefore, the process became unstable, undercut and lack of fusion might occur.



(a)

(b)

Figure 6: (a) Height was measured at eight different points, (b) Influence of wire feed speed on the layer deposit surface

The layer appearance is a clear indication of whether the layer deposition is stable or not. As shown in Figure 6(a), the layer looks unstable when the WFS is increased. Continuous layer deposition can still be obtained but the increasing amount of wire that is added to melt the pool leads to irregular layer deposition and influences the weld profile. Therefore, more energy is needed to melt the metal wire at higher WFS.

Conclusion

The purpose of this paper was to investigate the effects of travel speed and WFS. Therefore, the following conclusions were made:

- Travel speed and WFS had a major influence on deposition width and height.
- Based on the effect of travel speed on the deposited layer, it was concluded that the width of the deposit decreased due to heat accumulation, which reduced with increasing travel speed. As WFS increased, the deposition height also increased rapidly.
- An unstable deposition was identified at travel speed of 8 mm/s due to humping. As travel speed increased, the deposited layer became worse and defect started to occur. It started at the initial deposition and the increment of each layer became unstable. However, higher travel speeds could still be obtained by optimising other process parameters while maintaining the heat input per distance.
- A stable deposition was produced between heat input values of 0.2620 kJ/mm and 0.32756 kJ/mm.

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