

Effect of deposition current on bead geometry characteristics of low carbon steel single wall structure fabricated by wire arc additive manufacturing

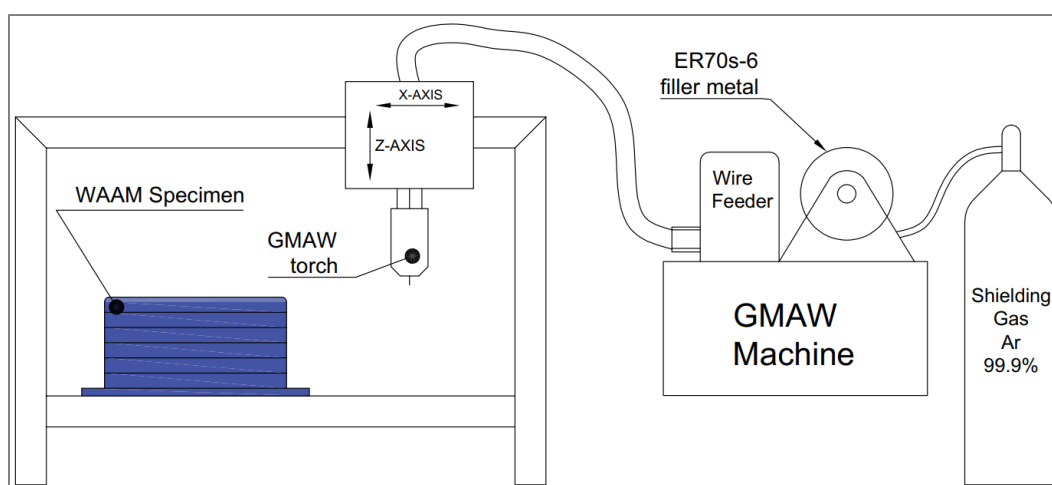
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Highlights:

- GMAW-based WAAM of low carbon steel ER70S-6 induced porosity with high deposition current
- Increased in deposition current will increasing the overall dimension of deposited layers
- The best area utilization in this study is specimen C with percentage area of 81.43%

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Abstract

Wire arc additive manufacturing (WAAM) is gaining popularity due to its ability to produce large metal parts quickly and efficiently. It produces less waste and has a more efficient production time than subtractive manufacturing. However, those capabilities come with unavoidable disadvantages, post-processing by machining becomes necessary to achieve the desired product dimension. Therefore, this research aimed to evaluate the bead geometry and utilization area of the WAAM-fabricated structure by varying the deposition current. The wall-structured specimens were fabricated using gas metal arc welding (GMAW) with motorized drivers for x, y, and z coordinates. The material used in this research was low carbon steel ER70S-6 filler metal with ASTM A36 low carbon steel substrate. The Varying parameter was deposition current with other related process parameters remaining constant. Material testing and characterization techniques included geometric measurement by profile projector plotted into a scattered diagram, and the cross section of the specimens were observed using a digital microscope. The experiment resulted in increased bead dimension in width and height along with increased deposition current. The largest bead dimension was achieved in 180A deposition current with average bead width and height was 6.84 mm and 1.6 mm respectively. The best deposition current was 160A, with highest area utilization of 81.43% and width uniformity.

Keywords: GMAW; Area utilization; Geometric measurement; Heat input; Layer dimension

1. Introduction

Wire arc additive manufacturing (WAAM) has attracted many researchers around the globe due to its capabilities to produce significant components more efficiently compared to other subtractive processes [1], [2]. It can also produce complex geometry parts with fewer post-processing steps needed [3], [4]. WAAM has been broadly applied to different classes of metals, and hence, WAAM can also make dissimilar metal structures [5], [6], [7], in-situ alloying [8], [9], [10], and cladding [11]. Due to those advantages, WAAM revolutionized the fabricating method of significant metal components, and it began to be applied in various industries [12], [13].

Despite excellent capabilities, WAAM requires several post-processes, such as machining. The machining must be carried out to obtain the desired dimension due to the low accuracy and poor surface finish [7], [14]. Because of those drawbacks, WAAM is not suitable for making finished product, instead it is excellent for rough work [15]. WAAM parameters also have a significant effect on the ease of machining and any further process [16]. There has been various work conducted to increase the accuracy of WAAM by varying its heat input on steel alloy [2], [7], [17], [18], [19], [20], [21], [22], aluminum alloy [15], [23], [24], and nickel alloy [1], [17], [25].

Gupta *et al.* have reported the effect of travel speed on the bead geometry of weld bead by varying only the travel speed parameter while another parameter remains constant [19]. The study showed that increased travel speed by 100 mm/min causes the bead width to decreased by 16.87%. Increased travel speed also impacts bead height, the study showed increasing travel speed by 100 mm/min will increase bead height by 16.57%. The increase in crown height is caused by increasing travel speed, caused by lower heat input to the base metal, which results in lower penetration, and the portion of bead penetration diverted into crown height [25].

Keun Lee *et al.* investigated the bead geometry of aluminum produced by cold metal transfer (CMT) WAAM by varying heat input [15]. The geometry of the single bead changes depending on the welding conditions such as current, and voltage. The study showed that the deposition efficiency of the part will increase with increasing heat input. In addition, the current and voltage ratios have also been analyzed to investigate their effect on bead geometry. Increasing the current and voltage can increase the heat input and the bead dimension in width and height.

Dinovitzer researched the effect of welding parameters on bead geometry, and the microstructure of nickel alloy structure fabricated by WAAM [1]. Wire feed speed and travel speed are affecting the bead height and width. Bead width decreases with increased travel speed, and bead height increases linearly with wire feed speed. Gas shielding flow rate has no significant effect on the bead geometry of the specimens.

Zheng Dong studied the microstructure and corrosion behavior of ER70S-6 oval tube structure fabricated using WAAM [26]. The corrosion behavior between the WAAM-fabricated structure and rolled steel tube has been compared. The WAAM fabricated structure has higher porosity than the rolled steel structure due to the differences in the manufacturing process of the specimens, even though the porosity does not influence the corrosion performance of the specimens. The corrosion performance of WAAM structure is similar to that of the other materials, though it has slightly higher susceptibility to pitting corrosion.

Baskoro *et al.* [23] studied the effect of the intermittent wire feeding method in gas tungsten arc welding (GTAW) of 6063 aluminum alloy on bead geometry, mechanical properties, microstructure, and chemical composition. The wire feed speed impacts bead width more than any other dimensional bead features. The weld bead increases with increased wire feed speed, and vice versa. Although the amount of filler metal diluted in the weld joints varies, it does not cause any significant difference in mechanical properties due to the constant heat input.

Badoniya *et al.* studied the effect of cooling channel at the substrate and heat input on bead characteristics of low carbon steel fabricated by WAAM [2]. They reported that wire feed speed (WFS), travel speed (TS), and voltage (V) are highly affected the geometric characteristics of the layers. Increasing WFS increases the bead height, while increasing TS or V reduces bead height. The cooling strategy on the structure has high impact on the bead characteristic due to its ability to transfer heat and undergo solidification much faster. Penetration of the weld bead in the cooled substrate is shallow while the bead height and width expand.

Based on the literature review, much research been conducted to investigate the bead geometry of WAAM with various materials and process parameters. Although the data related to geometric analysis is highly accessible, few studies have been conducted to measure the useable cross-sectional area of WAAM structure of low carbon steel using conventional the GMAW method. Moreover, it is important to research the WAAM structure's geometry, its usable area

after machining, and its correlation with process parameters. Therefore, this study investigated the effect of deposition current on the bead geometry of the WAAM single-walled structure. The bead geometry includes layer height, bead height, and overall stacked layers height.

2. Materials and Methods

ASTM A36 steel plate with 250 mm x 60 mm x 5 mm dimension was used as a substrate, and ER70s-6 with 1.2 mm diameter filler metal used as an additive material. The chemical compositions of the selected materials are shown in Table 1. An OTC CPVE500 conventional GMAW machine with a motorized CNC driver was used for the experiment. A schematic illustration of the experimental setup can be seen in Figure 1. Argon welding grade shielding gas with a flow rate of 15 l/minute was used in this experiment. The selected welding parameters were adapted from various literature analyzes the bead gemoetry with different heat inputs [3], [21], [26], [27]. The varying parameter selected was deposition current due to its effect on bead geometry. Process parameters are shown in Table 2 with four different deposition currents of A, B, C and D.

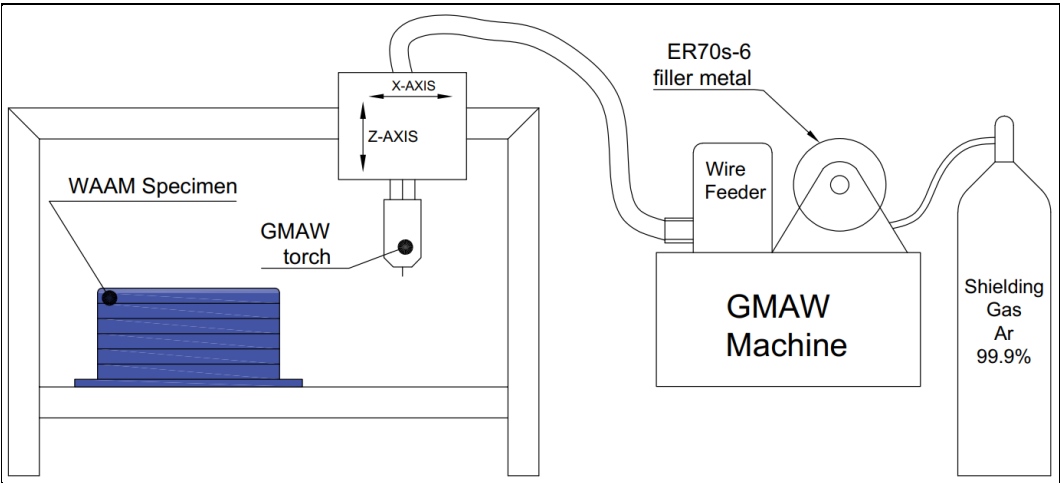
Table 1.
Chemical composition of ASTM A36 and ER70s-6 filler metal (wt%)

Material	C	Cu	Mn	Si	P	S	Fe
ASTM A36	0.26	0.20	1.05	0.28	0.04	0.05	balance
ER 70s-6	0.10	0.50	1.65	1.05	0.02	0.03	balance

Table 2.
WAAM process parameters

Code	Deposition Current (A)	Voltage (V)	Gas Flow Rate (l/minute)	Travel speed (mm/minute)
A	120	20	15	480
B	140	20.5	15	480
C	160	21	15	480
D	180	21.5	15	480

Figure 1.
Schematic illustration for WAAM machine setup



Deposition strategies were adapted from these literatures [3], [7], [28] with bidirectional deposition. Bidirectional deposition was proven to be more effective building single-walled structure because of its capability to dissipate heat evenly on the edge of the wall and maintain the uniform dimension of the structure [7]. The specimens wall height and wall length were targeted at 60 mm and 230 mm, respectively. Toolpath strategy and targeted dimension are shown in Figure 2a. Interpass temperature between each layer was maintained at 100 °C to minimize the distortion and acts as a preheat to the next applied layer [29], [30]. All specimens must undergo X-ray radiography characterization to observe the defect that may be produced after welding.

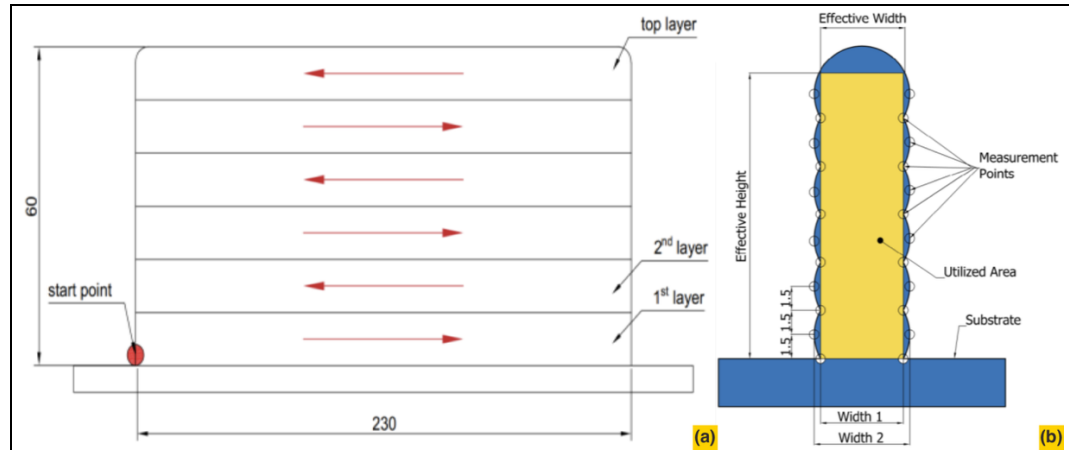
The bead height was measured using a digital caliper with 0.01 mm resolution. The measurement was conducted on the specimen at 100 °C interpass temperature. Since the linear regression method can summarize and analyze the relationship between two quantitative datasets [31], the method was applied to determine the effect of deposition current on the specimen's height by identifying the gradient value of the linear equation [2]. Pictographs for the height measurement method can be seen in Figure 4a.

All of the specimens were sectioned in the middle section by wire-EDM machine to avoid smeared metal on the edges and minimize microstructural changes of the specimens [32]. The profile projector was used to measure the width of the wall every 1.5 mm in the vertical axis, as

shown in Figure 2b. Cross-sectional area was observed using a Dino-Lite digital microscope to measure the area of the cross section and the utilized area will be determined using Eq. (1) [15]. The measured area of those specimens was polished and etched with 5% Nital to expose the macrostructure. In Figure 2b the yellow area shows the utilized area with effective length and practical width dimensions, while the red area is the machined or discarded area. Since the area of the Dinolite digital microscope was limited, the measurement of cross-sectional area was carried out in two different section, namely upper and bottom section. The first image was taken from the middle to the top of the cross-section, and the second from the middle to the bottom.

$$\text{Area utilization} = \frac{\text{Obtainable Area}}{\text{Cross Sectional Area}} \times 100\% \quad (1)$$

Figure 2.
(a) Illustration of
bidirectional
deposition strategy;
(b) Cross sectional
area and
measurement method



3. Results and Discussion

3.1. Specimen Results

Figure 3 shows the single-wall structure specimen. Three of the specimens have been built successfully with conditions A, B, and C. However, condition D has successfully been built into a single wall structure with major defects, i.e., porosity. The porosity was observed using X-ray radiography, and the result can be found in Figure 5. The length of all the specimens was approximately 230 mm, with different numbers of layers to reach 60 mm in height. The number of layers required to reach 60 mm in height can be seen in Table 3. Bowing was noticed in all specimen's substrate due to residual stress in welding, considering there was no preheat applied to the substrate. All the specimens were cut in the middle section using wire-EDM to observe the bead characteristics of the deposited part.

3.2. Layer Measurement

Figure 6 shows the measurement result of the specimens with different deposition current. The number of layers required to obtain the desired height was different in each deposition current. A smaller value of deposition current needed more layers to achieve a 60 mm height compared to the specimen built with a higher current. This phenomenon is caused by the wire feed rate that increases along with increased deposition current, resulting larger value of bead width and height [2], [33], [34].

Figure 3.
The WAAM single-
wall structure
specimen



Figure 4.
Measurement
method for layer
geometric
characteristics:
(a) Measurement of
layer height and;
(b) Width
measurement by
profile projector

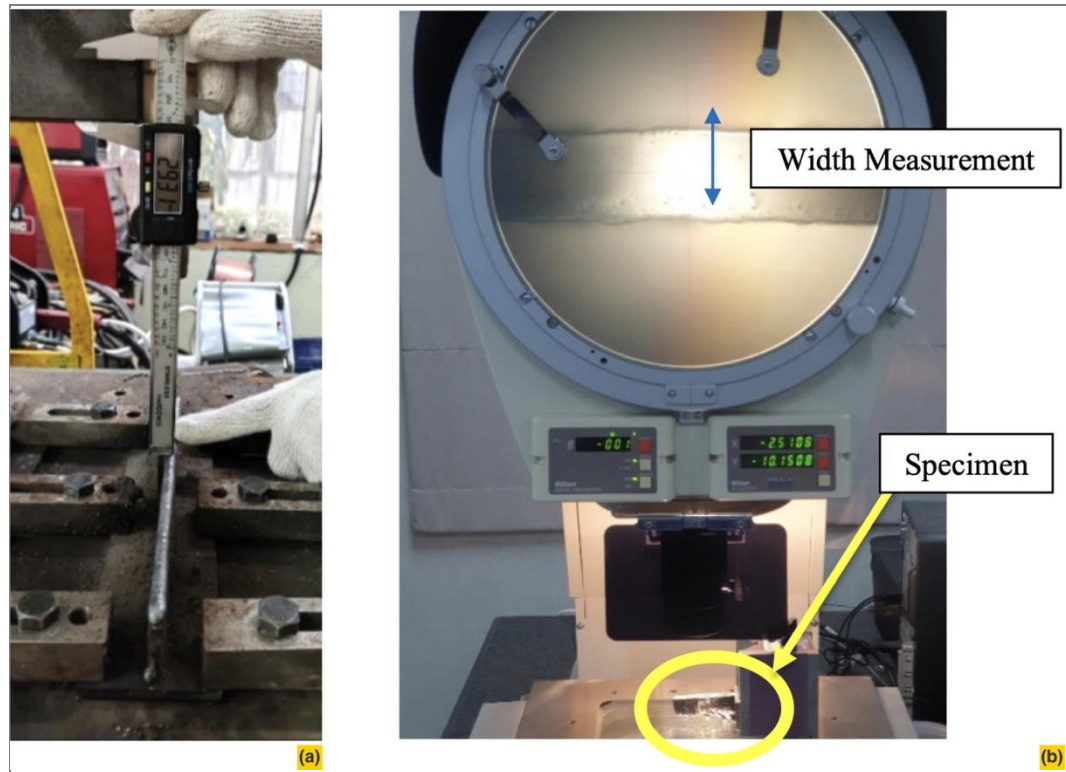


Figure 5.
X-Ray
characterization of
condition D
deposition current
resulted high
amount of porosity

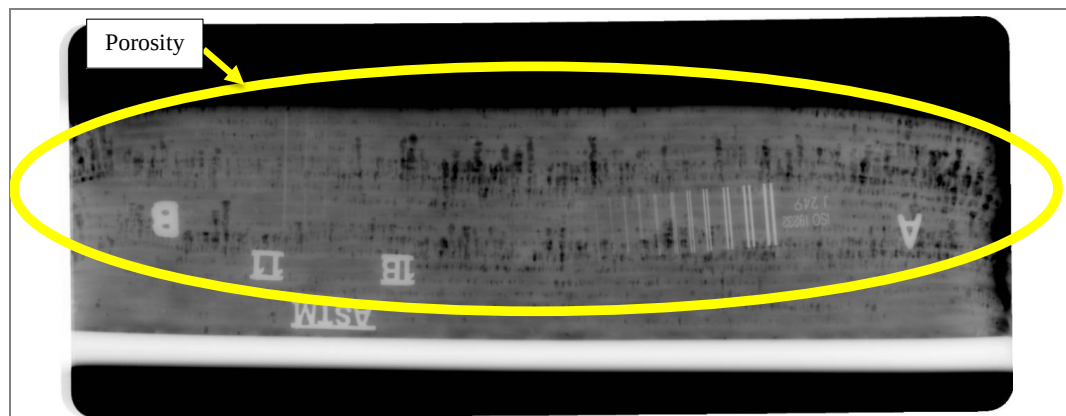
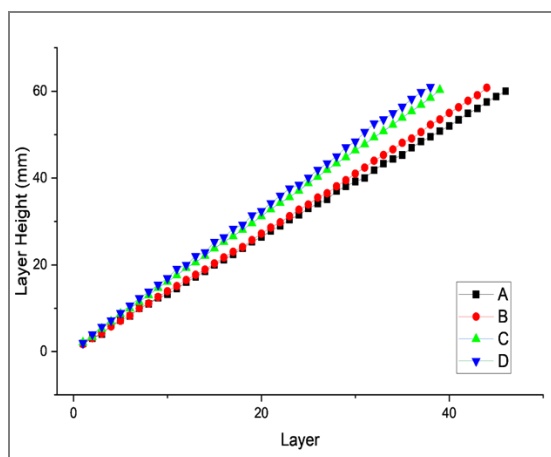


Table 3.
Layer height
measurement result

Code	Deposition Current (A)	Number of layers	Average layer height (mm)	Linear Regression Equation
A	120	46	1.30	$y = 1.2896x + 0.5803$
B	140	44	1.38	$y = 1.369x + 0.0083$
C	160	39	1.54	$y = 1.5312x + 0.4837$
D	180	38	1.60	$y = 1.6041x + 0.5228$

Figure 6.
Height of the specimen
with different
deposition currents



Welding conditions C and D have significant different in number of layers, which is possible due to difference in percentage of dilution between the interlayer joints. Figure 6 shows that an increased deposition current led to increased gradient of the linear regression of the data, which means the bead height was increasing along with increased deposition current. Welding condition D has the highest gradient of 1.604, while A has the lowest gradient of 1.289, as shown in Table 3. Linear equations of the scattered data in each welding condition can be seen in Table 3.

The width of the printed layer had great variation in each welding condition as shown in Figure 7. The first five layers had a smaller width compared to the following layers. This can happen due to lower heat input in the first layer because no preheating was applied to the surface [15]. After the first five layers, the width of the specimen becomes more consistent. The average result of the deposited layer in each condition is shown Table 3. Welding condition D had higher standard error of 0.0809, which means the bead variation of the specimen was high. Oh *et al.* presented this phenomenon as a flow down in their research [7]. The flow down will result in inconsistent layer width due to excessive heat input, which is influenced by deposition current, as shown in Figure 9. Increasing the deposition current also increased the bead width, as seen in Table 4. Condition D had the highest average width of 6.84 mm, while condition A had 4.75 mm.

Figure 7.
The width of the deposited layer with different deposition conditions

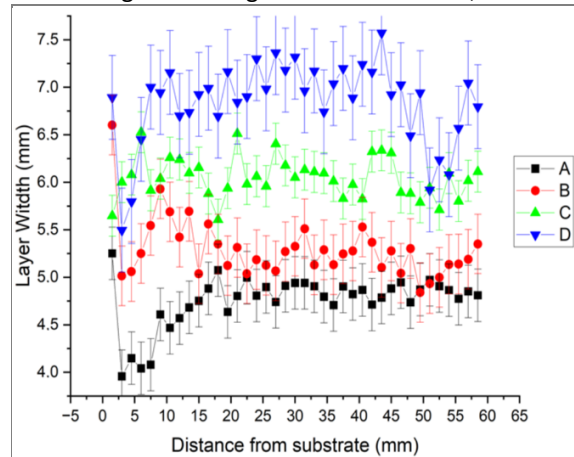


Figure 8.
Correlation between deposition current and to width and height of the deposited layer

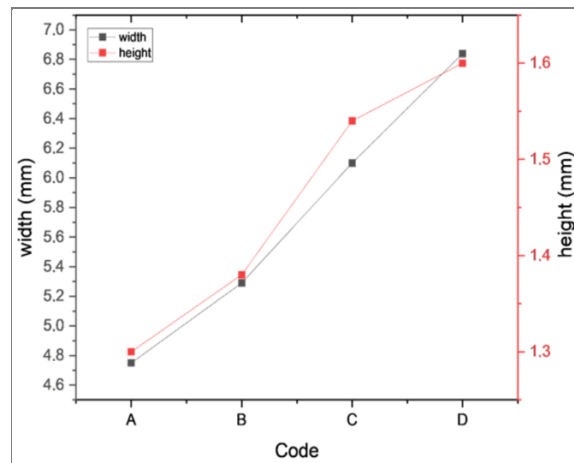


Figure 8 shows the relationship between the bead geometry characteristics and deposition current. Layer width and height would increase along with increased deposition current. The deposition current had greater effect on layer width compared to the height. It was verified by the increase in width when the deposition current was increased. The width increased by approximately 1 mm by increasing the deposition current every 20 A, which means the relation between deposition current and width is almost linear. Meanwhile the layer height and deposition current had no linear correlation due to height decline in 180 A. This phenomenon can cause the larger width of the bead with a shallow height. This phenomenon was called flow down, which was also verified by another research conducted by Oh *et al.* [7]. The flow down can occur owing to excessive heat input applied to the deposited layer, considering the lack of height development that occurred in the highest deposition current, i.e., 180 A. As shown in Figure 9b, the flow down caused the actual layer height to be lower than expected in Figure 9a.

Figure 9.
X-Ray characterization of condition D deposition current resulted high amount of porosity

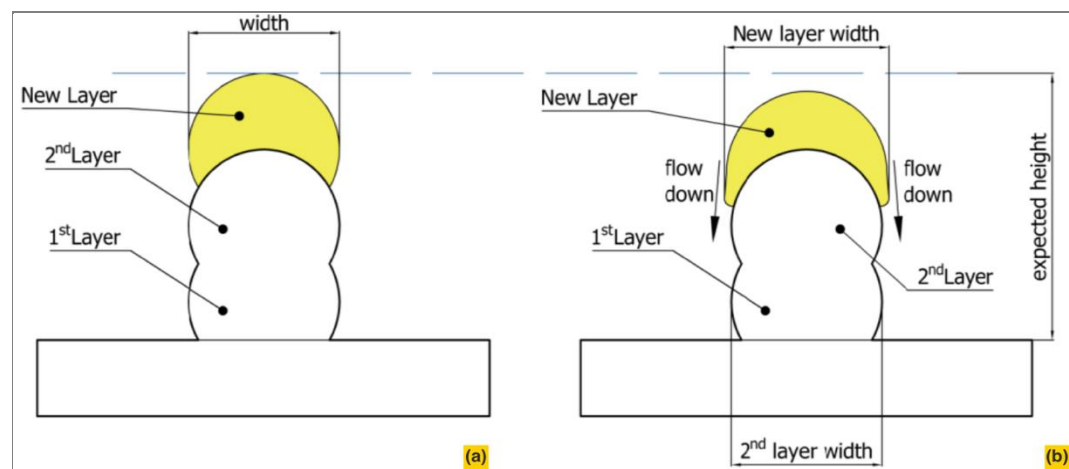


Table 4.
Layer width measurement result

Code	Deposition Current (A)	Number of layers	Average Width (mm)	Standard Error
A	120	46	4.75	0.0442
B	140	44	5.29	0.0501
C	160	39	6.10	0.0345
D	180	38	6.84	0.0707

3.3. Cross-section Measurement

As depicted in [Figure 8](#), the deposition current influenced the bead geometry of each layer. All the specimens resulted in a very rough surface with relatively large variation of width depending on the deposition current applied to fabricate the specimens. Those rough surface areas should be machined to obtain a good surface finish with uniform width. The machining time and the lifetime of the cutting tools will be affected by the volume of machined areas. Since WAAM can fabricate a near-net shape product, the total machined volume will be much lower compared to the traditional subtractive process [\[7\]](#). The total cross-sectional area was used to determine the utilization of the area. Calculation for area utilization was adapted from [\[15\]](#) and modified into Eq. (2).

$$\text{Area utilization} = \frac{\text{Effective Width} \times \text{Effective height}}{\text{Total Area}} \times 100\% \quad (2)$$

The result of effective height was a compilation from the upper and bottom sections of the cross section, while the effective width was taken from the smallest width of each specimen, whether it was at the bottom or upper sections.

Measurement of the cross-sectional area was shown in [Figure 10](#) of the upper section and [Figure 11](#) of the bottom section. DL1 and DL2 in the figures represent the effective width and effective height respectively. The effective height and width combined from the upper and bottom sections were substituted into Eq. (2) to achieve area utilization. The total area in Eq. (2) was also achieved from the summation of the upper and bottom areas of the cross section. Area utilization results are shown in [Table 5](#), with condition C deposition current having the highest area utilization namely 80.581%. Correlation between deposition current and area utilization is depicted in [Figure 12](#). A 120A deposition current had the lowest value of area utilization of 72.065% due to a low value of effective width. Low deposition current means lower heat input, weld bead with lower heat input tends to build the weld bead upwards, which causes the weld bead width to be smaller and minimum penetration [\[17\]](#). Increasing the current from 120A to 160A could cause an increase in the area utilization to maximum of 80.581%, then it went down along with increased deposition current to 180A with area utilization of 74.382%. Lower area utilization in high current areas was caused by inconsistency of the layer geometry, flow down, and severe porosity present in the specimen.

[Figure 12](#) shows that the area utilization increased along with the deposition current increase to 160A. Higher deposition currents than 160A will result in a decrease in the value of area utilization. The decreased value in 210A was caused by severe porosity inside the specimen as shown in [Figure 5](#), flow down, and inconsistent layer width. The highest area utilization was achieved using 160A deposition current with 80.581% total area of cross-section area. The lowest value was in 120A deposition current with 72.065% area of cross section.

Figure 10.
Area utilization
measurement for
upper section of the
cross section:
(a) 120A;
(b) 140A;
(c) 160A;
(d) 180A

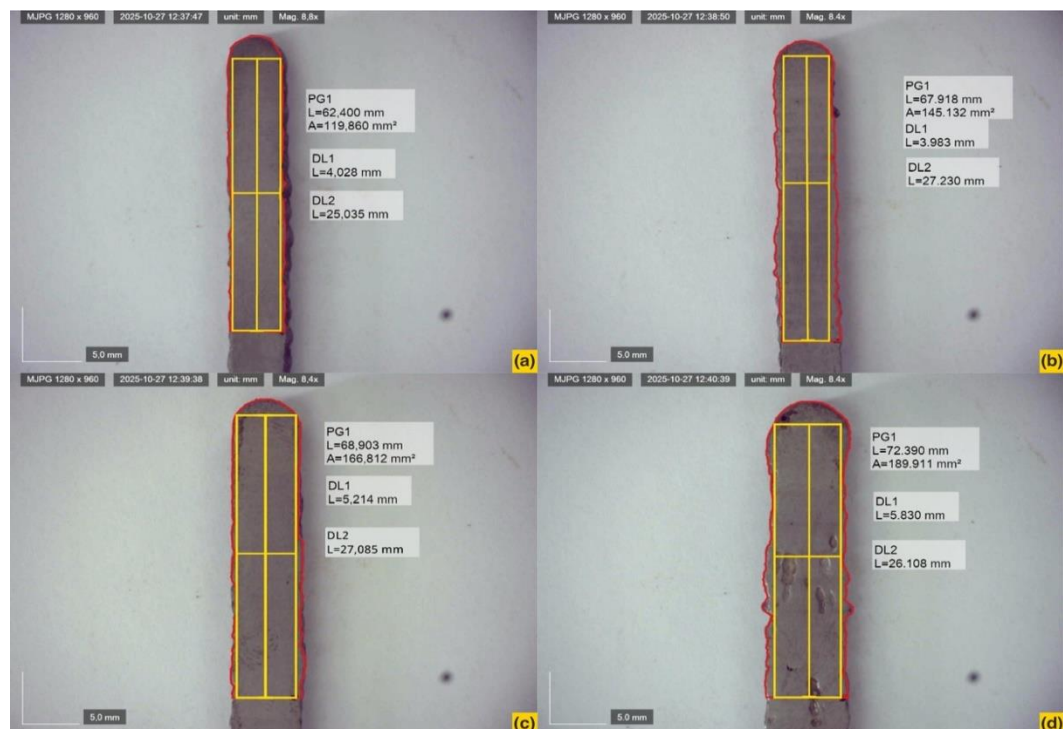


Figure 11.
Area utilization
measurement for
bottom section of
the cross section:
(a) 120A;
(b) 140A;
(c) 160A;
(d) 180A

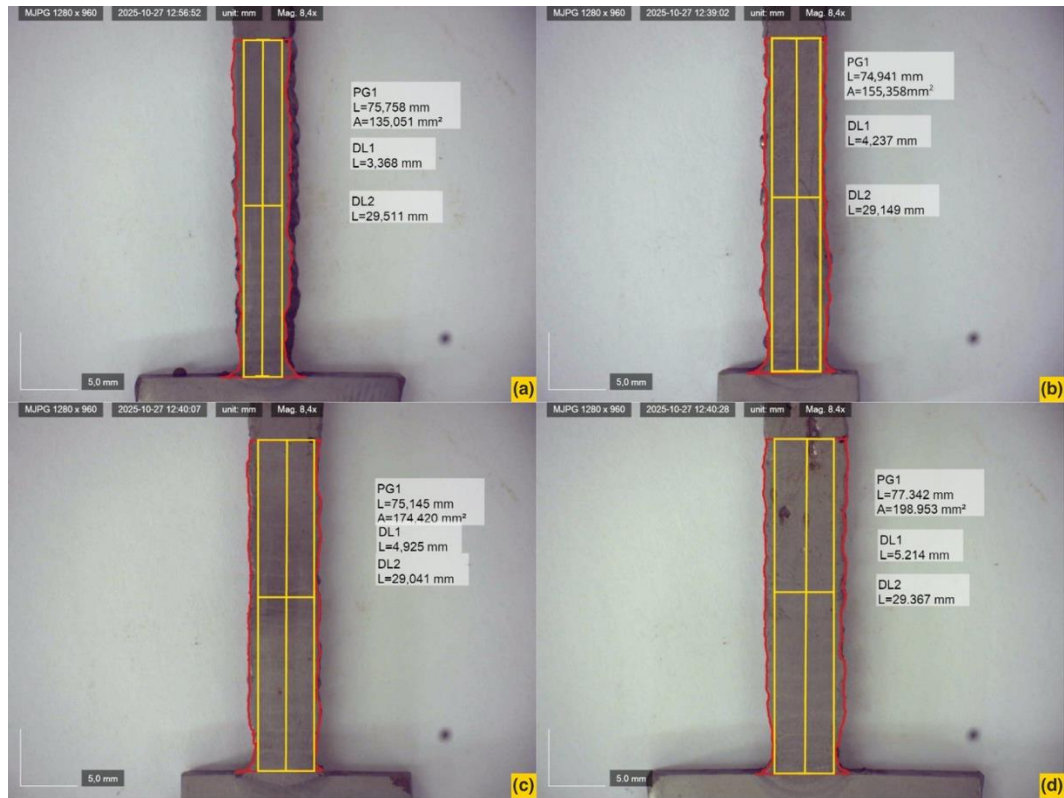
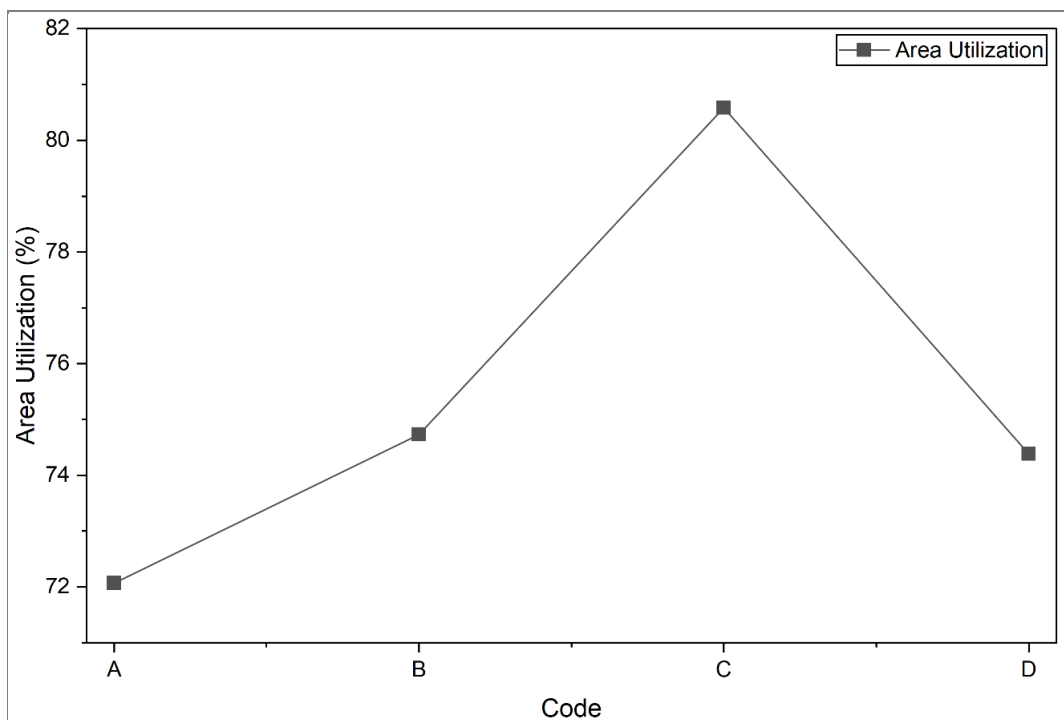


Table 5.
Layer geometric
characteristics and area
utilization

Code	Effective Height (mm)	Effective Width (mm)	Total Area (mm ²)	Utilization Area (%)
A	54.546	3.368	254.921	72.065
B	56.379	3.983	300.490	74.730
C	56.126	4.925	343.032	80.581
D	55.475	5.214	388.864	74.382

Figure 12.
Area utilization for
every deposition
condition



4. Conclusion

This paper investigated the effect of deposition current on the geometric characteristic of single-walled structure low-carbon steel specimens. The conventional GMAW process has proven

capable of building single-wall structure specimens with varying deposition current. Deposition current highly affected the bead geometric characteristics in various ways. Based on the testing and measurement results, it is possible to conclude the following:

- a. Using four different deposition currents, the height of each layer was analyzed quantitatively. The height of the layer was increased by increasing the deposition current. The maximum layer height was 1.6 mm with 180A deposition current.
- b. Deposition current affected the bead width of the specimens, increasing the deposition current led to an increase in the layer width almost linearly. Every 20A increase in deposition current caused the layer width to increase by approximately 12%. The highest layer width was achieved by the highest deposition current of 180A, with average layer width of 6.84 mm.
- c. The highest area utilization of 80.581% was obtained by applying 160A deposition current. Increasing the current from 120A to 160A caused an increase in the area utilization of 8.516%, while increasing the deposition current to 180A leads to lower area utilization from 80.581% to 74.382%. Lower area utilization in high current was caused by inconsistency of the layer geometry, flow down, and severe porosity present in the specimen.

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Authors' Declaration

Authors' contributions and responsibilities - Danny Wicaksono: Writing original draft, conceptualization, methodology, experimentation, testing and measurement, analysis. Ario Sunar Baskoro: conceptualization, supervision, funding acquisition, resources, writing-review & editing. Gandjar Kiswanto: conceptualization, supervision. Nicholas Ego Guarsa: experimentation, testing and measurement, analysis. Junaidi Syarif: Analysis, writing-review & editing.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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