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Robot-Assisted Double-Pulse Gas Metal Arc Welding for Wire and Arc Additive Manufacturing

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Abstract. The study presents the process of double-pulse gas metal arc welding (DP-GMAW) for wire-and-arc additive manufacturing (WAAM). The robot-assisted DP-GMAW process built up an aluminum laminate wall using the filler wire ER5356 of diameter 1.2 mm with industrial argon gas shielding on aluminum 5083 substrate material. There are two stages in the study including the single-pass build-up and the multi-pass build-up. In first stage, the effect of DP-GMAW parameters on the build-up dimension was investigated, including current (ampere), voltage (volt), travel speed (centimeters per minute), frequency (Hz), duty cycle (percent) and delta current (ampere). The dimension of bead width and bead height were used to represent the effect of parameters as well as the processability of DP-GMAW. The results were sketched in a process window of current and travel speed for the DP-GMAW single-pass forming. In the second stage, the experiments focused on the effect of DP-GMAW conditions on a laminate wall dimension. The suitable DP-GMAW condition was determined for building-up the desired laminate wall.

Keywords: Double-pulse gas metal arc welding (DP-GMAW) · Aluminum build-up process · Additive manufacturing · Aluminum wire-and-arc additive manufacturing (WAAM)

1 Introduction

The additive manufacturing (AM) is used as the build-up process for creating or repairing the metal part of complicated geometry to reduce the cost of material and investment [1–3]. Especially to create part and prototypes. For reach the demands of the aerospace, automotive, and rapid tooling industry. The recent focus of AM research has been shifted to fabricate complex shaped metal components, including titanium and nickel alloys that cannot be economically produced using conventional methods. The competitive position of AM for metal components relative to alternative manufacturing processes is a function of the geometrical complexity and production volume [3–6].

AM is the official industry standard term (ASTM F2792) for all applications of the technology. It is defined as the process of joining materials to make objects from 3D

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model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. To build-up material layer, the thermal process such as welding and laser melting, especially the wire-and-arc additive manufacturing (WAAM), are suitable because they meld the material and continuously form the layer upon layer. In this study, we focus on the gas metal arc welding (GMAW) process which has high flexibility because it could select the many characteristics of the current signal to matching with a working material. By applying the GMAW process on an aluminum bead forming, a preliminary experiment was studied on the comparison of the direct current (DC) and double pulse current (DP). Both the DC and DP current waveforms are shown in Fig. 1. The more detail of the DP current is shown in Fig. 4. The result showed that the welding using DC has the difficulty for control a uniform of the bead. On the other hand, for the weld using DP current formed a bead uniformly than direct current, as shown in Fig. 1. It was concluded that the DP-GMAW process has more uniform bead than that by DC on low heat condition. Therefore, the DP-GMAW process was used in this study in forming the laminate wall, especially building-up aluminum alloy based WAAM.

The study investigated effect of DP-GMAW parameters on bead dimension for build-up aluminum alloy and determined the build-up process window for single-layer. For the multi-layer process, the study focused on the effect of heat condition on laminate wall dimension and determined a suitable process condition for the multilayer wall.

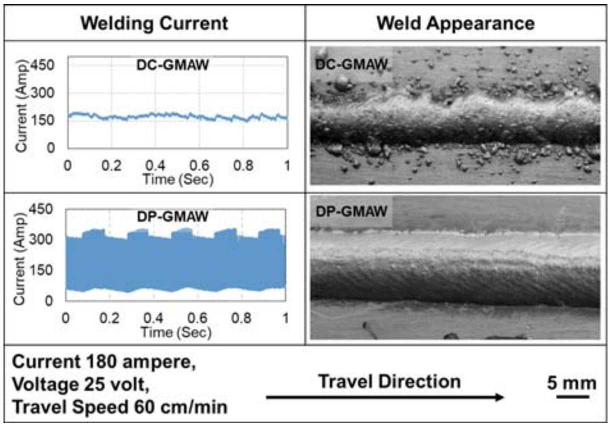


Fig. 1. The GMAW current comparison of weld bead appearance

2 Experimental Setup and Parameter

2.1 Experiment Material and Equipment

In this study, Aluminum alloy wire ER5356 with a diameter of 1.2 mm was used as the build-up material, the aluminum 5083 with a thickness of 15 mm used as substrate material, and industrial argon gas (99% purifier) used to shield during process build-up.

The laminate thin wall weld continually layer upon layer was chosen as the build-up geometry to perform the ability of the build-up process.

For the welding process, the experiment set-up shown in Fig. 2 consists of a DP-GMAW machine Astern 400 ADR made by Megmeet Electric Co. and weld power source WB-P500L made by OTC Daihen Co.. The DP-GMAW machine had a maximum current range at 400–720 A and voltage 50 V maximum adjusting. The power source WB-P500L had maximum current 400 A and voltage 34 V maximum adjusting. In this case of the machine parameters were compared by heat input concept to determine the same heat condition of welding parameters. Welding robotic OTC FD-V8 was employed to control a precision build-up path for the single-pass and multi-layer experiment. A process was planned to build from the base layer upon layer with increasing constant distance or constant layer height. The first starting layer used 15 mm as the contact tip to work distance (CTWD). Figure 3 represented the schematic of the process with process variables.

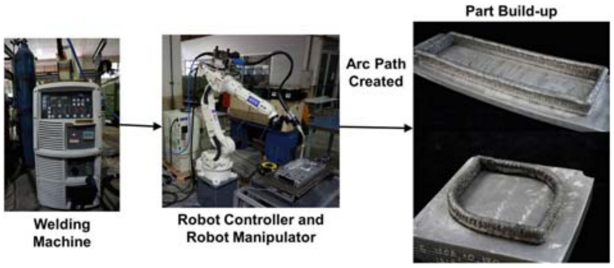


Fig. 2. Experimental setup.

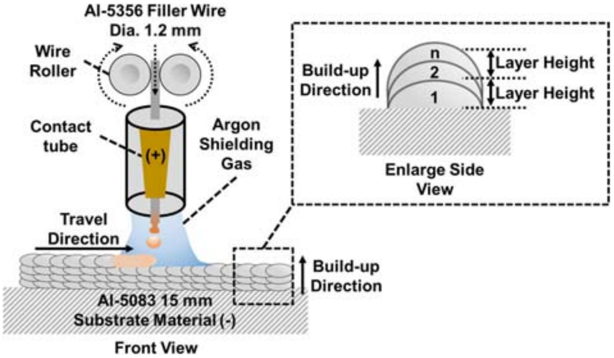
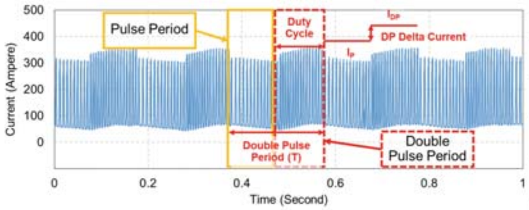


Fig. 3. Schematic of the WAAM process

2.2 Double-Pulse Parameters

In order to investigate the effect of DP parameters, the DP current signal during build-up was detected to get an actual level of a current pattern. Calibrated current sensing with a hall sensor (current transformer) was connected through the DAC device by the sampling rate of 5000 samples per second. The computer was used for converting and storing the weld signal data. The measured DP current signal collected from OTC WB-P500L welding machine, as shown in Fig. 4, is a suitable monitoring system this current pattern using the conditions of current 120 A, voltage 17.8 V, travel speed 100 cm per minute, frequency 5 Hz, duty cycle 50% and delta current 30 A. Moreover, from the measured current waveform shown in Fig. 4, the parameters including DP-frequency, DP-duty cycle and delta current were defined.



I_{DP}	Double Pulse Peak Current (Ampere)
T_{DP}	Double Pulse Duration (ms)
I_P	Pulse Peak Current (Ampere)
T_P	Pulse Duration (ms)
T	Double Pulse Cycle Time (ms) ; $T = T_P + T_{DP}$;
I_{AVG}	Average Current (Ampere) ; $I_{AVG} = (I_{DP}T_{DP} + I_PT_P)/(T_{DP} + T_P)$
DP-Frequency	**Double Pulse Frequency (Hz) ; F = 1/T (1/Second)**
DP-Duty Cycle	**Double Pulse Current Duration In One Cycle/Period (%)**
DP-Delta Current	**Double Pulse Delta Current $I_{DP} - I_P$ (Ampere)**

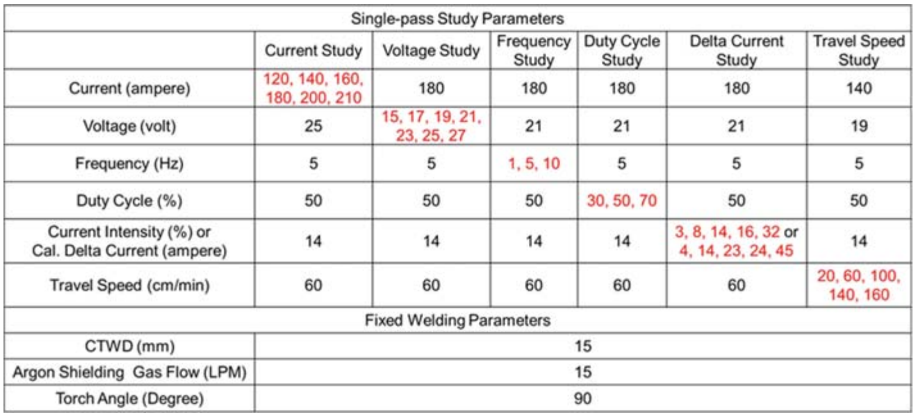
Fig. 4. Double pulse gas metal arc welding parameters

2.3 Experiment Parameters Study

In the experiment of the single-pass experiment, the effect of DP-GMAW variables consist of the current range 5 to 80 A, voltage 20 to 27 V, travel speed 20 to 160 cm per minute, frequency 0.5 to 10 Hz and duty cycle 30 to 70% and delta current 3 to 45 A. The Taguchi's method (Orthogonal Array Design) was chosen for the design of the experiment. Set of the first studied variables shown in Table 1.

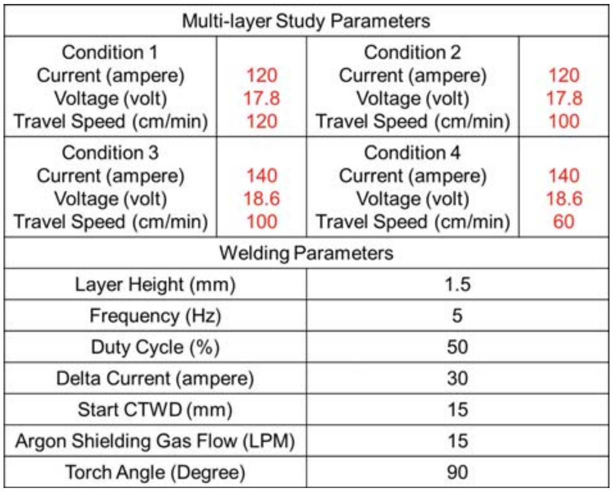
In the multi-layer build-up experiment, the effect of DP-GMAW variables consist of 4 conditions of DP parameters with constant DP parameters consist of frequency 5 Hz, duty cycle 50%, delta current 30 A and layer height 1.5 mm. The set of the multi-layer studied parameters are shown in Table 2.

Table 1. Single-pass experiment parameters



Single-pass Study Parameters						
	Current Study	Voltage Study	Frequency Study	Duty Cycle Study	Delta Current Study	Travel Speed Study
Current (ampere)	120, 140, 160, 180, 200, 210	180	180	180	180	140
Voltage (volt)	25	15, 17, 19, 21, 23, 25, 27	21	21	21	19
Frequency (Hz)	5	5	1, 5, 10	5	5	5
Duty Cycle (%)	50	50	50	30, 50, 70	50	50
Current Intensity (%) or Cal. Delta Current (ampere)	14	14	14	14	3, 8, 14, 16, 32 or 4, 14, 23, 24, 45	14
Travel Speed (cm/min)	60	60	60	60	60	20, 60, 100, 140, 160
Fixed Welding Parameters						
CTWD (mm)	15					
Argon Shielding Gas Flow (LPM)	15					
Torch Angle (Degree)	90					

Table 2. Multi-layer experiment parameters



Multi-layer Study Parameters			
Condition 1 Current (ampere) Voltage (volt) Travel Speed (cm/min)	 120 17.8 120	Condition 2 Current (ampere) Voltage (volt) Travel Speed (cm/min)	 120 17.8 100
Condition 3 Current (ampere) Voltage (volt) Travel Speed (cm/min)	 140 18.6 100	Condition 4 Current (ampere) Voltage (volt) Travel Speed (cm/min)	 140 18.6 60
Welding Parameters			
Layer Height (mm)	1.5		
Frequency (Hz)	5		
Duty Cycle (%)	50		
Delta Current (ampere)	30		
Start CTWD (mm)	15		
Argon Shielding Gas Flow (LPM)	15		
Torch Angle (Degree)	90		

2.4 Build-Up Dimension

The dimension of the bead was used to represent the ability and effect of the process parameters. Figure 5 illustrates the measured dimension of the single-pass bead and multi-layer bead in the experiment. Moreover, bead width and height for multi-layer were measured in the minimum dimension defined as the effective dimension. In this study, the penetration depth was not measured due to the study focusing on bead effective formation and the penetration depth was not useful for AM process.

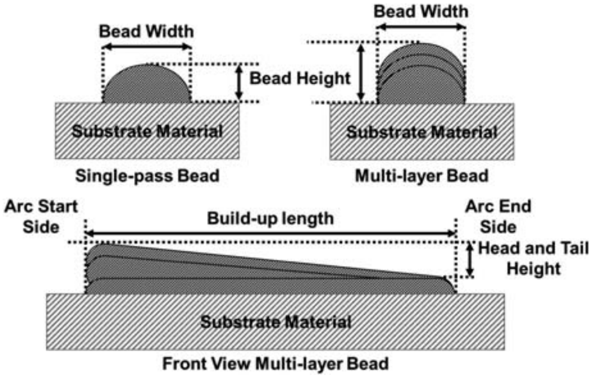


Fig. 5. Single-pass and multi-layer bead geometry

3 Experimented Results and Discussion

3.1 Single-Pass

In discussing the effect of current on the experiment, the welding current was set in the range of 120–210 A, with other parameters kept constant as shown in Table 1. The spatter occurred at the weld toe when too low current and improper voltage were applied. The increment of welding current resulted in a welding width and height increment. Figure 6 showed the weld appearance on current change. When the current was set in range of 120–210 A, excellent bead formation could be obtained. If lower current was applied, the lack of fusion might occurred even the travel speed was at low or high value. Similarly, if higher current was applied, two types of uncontrollable bead might occurred: overflow bead (high current with low travel speed) and the humping bead (high current with high travel speed).

In discussing the effect of voltage on the experiment, the arc voltage was set in the range of 15–27 V, with other parameters fixed as shown in Table 1. If the voltage was set at a low 15 V, the weld edge resulted in unevenness. If the voltage was set in the range of 25–27 V, the spatter of the weld toe occurred. The increment of the arc voltage resulted in an increment on the bead width but the bead height was decreased. Figure 6 showed the resultant weld appearance when voltage changed.

In discussing the effect of travel speed on the experiment, the travel speed was set in the range of 20–160 cm per minute with other parameters fixed, as shown in Table 1. The welding speed at 20 cm per minute resulted in uneven welding bead overflow because of too slow welding speed. If the welding speed of more than 160 cm per minute, bead humping (non-uniform bead) occurred due to too fast speed. The travel speed increment resulted in the decrement of bead width and bead height. Figure 6 showed the weld appearance depending on the travel speed. The travel speed is one of the main factors for the process because the speed could control the heat to form a bead and control the productivity rate.

In discussing the effect of frequency from the experiment, the frequency was set in 1–10 Hz, with other parameters fixed, as shown in Table 1. The increment of frequency resulted in an increment in the number of double pulses cycle in one second with a shorter duration. If the frequency was as low as 1 Hz, the wavy weld edge occurred due to long difference deposition between pulse and double pulse (interval). The increment of frequency does not significantly increase the bead width and bead height. Figure 7 showed the weld appearance depending on the frequency change. The penetration depth would not be affected significantly by increasing the frequency if the input heat was no changed.

In discussing the effect of the duty cycle from the experiment, the duty cycle was set in the range of 30–70% with other parameters fixed, as shown in Table 1. If the duty cycle was increased, the double pulse duration was also increased. The increment of the duty cycle would not affect the bead width and the bead height significantly. Figure 7 showed the weld appearance depending on the duty cycle change. The circle mark indicated the pore (diameters less than 1 mm) occurred on weld toe as a lack of fusion. The increment of duty cycle would affect the penetration depth.

In discussing the effect of delta current from the experiment, the value of the delta current was set in the range of 4–45 A with other parameters fixed, as shown in Table 1. Note that the study did not focus on high delta current because too high delta current caused the uniform weld bead. For increasing the delta current, the difference of current between the pulses current and the double pulse current increased. The low delta current 4 A resulted in exceeding the curved welding toe because of no enough heat for forming. Moreover, high delta currents could make the bead pattern look like fish scales. However, the increment of the delta current would not affect the bead width and bead heights. Figure 7 showed the weld appearance depending on the delta current change. The circle mark indicated the pore (diameters less than 1 mm) on weld toe as a lack of fusion. We concluded that if the delta current was increased, the penetration depth would be increased.

It is observed from the single-pass build-up experiment, the DP-GMAW parameters significantly affected on the weld bead dimension. The variables include welding current, arc voltage, and travel speed. Alternatively, the variables that does not affect the bead geometry significantly consist of the frequency, duty cycle, and delta current. Figure 8 presents an overall effect of DP-GMAW parameters on the bead dimension. Therefore, a mapping for setting parameters was created in the study. The process window was constructed further with current in the range of 60–210 A and travel speeds in the range of 20–180 cm per minute.

For arc voltage recommend adjusting from the welding machine to maintain the stability of the arc perform. The results from the experiment can create a process window for aluminum single-pass build-up as shown in Fig. 9. The plot is divided into four main areas including lack of fusion area, adequate area, humping bead area, and overflow bead area. For the multi-layer experiment, the parameters in the adequate area were chosen as: current in the range of 120 to 140 A with travel speed in the range of 60 to 120 cm per minute.

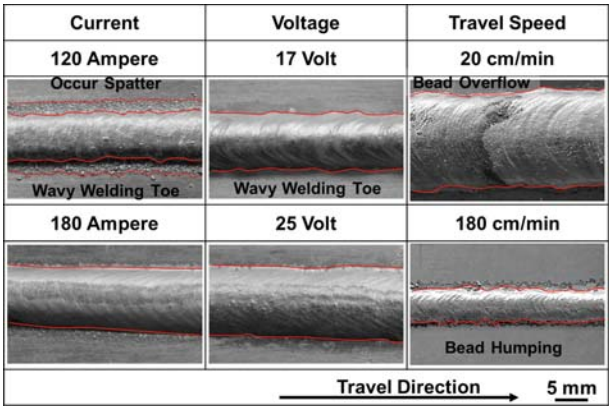


Fig. 6. Bead appearance on current, voltage, and travel speed change

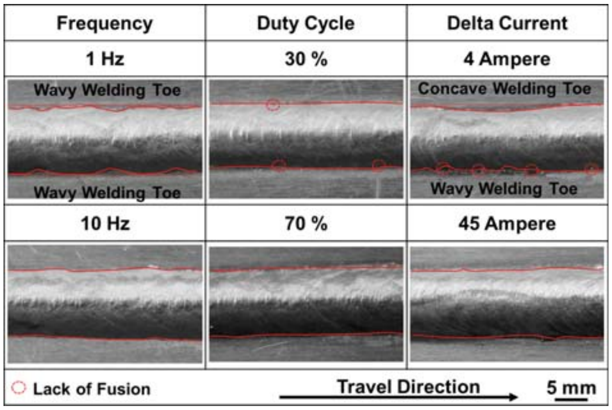


Fig. 7. Bead appearance on frequency, duty cycle, and delta current change

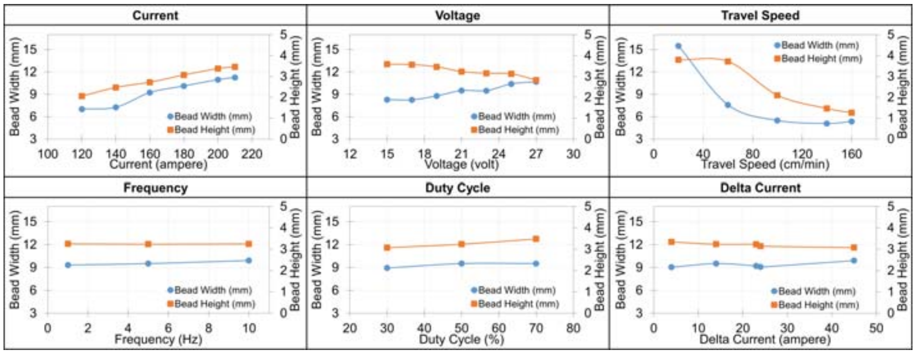


Fig. 8. Effect of DP-GMAW parameters on bead dimension

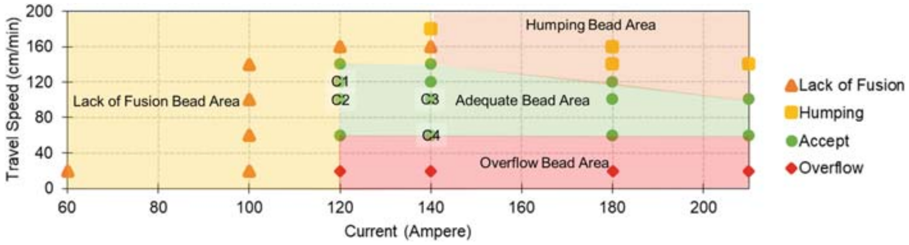


Fig. 9. DP-GMAW process parameters area for aluminum single-pass bead forming

3.2 Multi-layer Build-Up

The parameters condition consist of current at 140, 120 A and travel speed at 60, 100, 120 cm per minute with constant parameters as frequency 5 Hz, duty cycle 50%, the delta current of 140 A and layer height 1.5 mm. In the high heat condition 4 (0.2604 kJ/mm), the bead flow occurred and the laminate wall slope caused cumulative heat on the laminate appearance as shown in the bottom right side of Fig. 10. To avoid the bead flow, the heat could be reduced by increasing travel speed as condition 3 (0.1562 kJ/mm) or by decreasing current as condition 2 (0.1281 kJ/mm) or applying both conditions like condition 1 (0.1068 kJ/mm).

The effect of heat condition on laminate dimension are caused by the heat input. The increment of heat condition would decrease the effective laminate height. Besides, the height difference between the head and the tail have increased. The high heat condition had more cumulative temperature effect on the bead formation pattern or penetration change occurred laminate slope. The relation of heat condition and laminate dimension is represented in Fig. 11.

The recommendation for the layer height on laminate dimension should follow the laminate height properly. If the layer height was too low, the contact tip stuck occurred. If the layer height was too high, the lack of gas shielding might happen and cause the problem of bead oxidation and uncontrollable of bead formation.

In Fig. 11, the heat condition 1 (0.10 kJ/mm/layer) has the lowest difference height (2.22 mm) with highest effective height (7.63 mm) was determined in term of the adequate condition to build-up aluminum alloy. However, this study focused on the process performance. The study of metallurgy cross-section evaluation and mechanical properties testing will be discussed on another paper. Moreover, the proposed process shows the advantage by comparing the cold metal transfer (CMT) on a single bead dimension [7] under the average heat input between 0.180–0.306 kJ/mm, the DP had 18% larger dimension in bead width and 20% higher dimension in bead height.

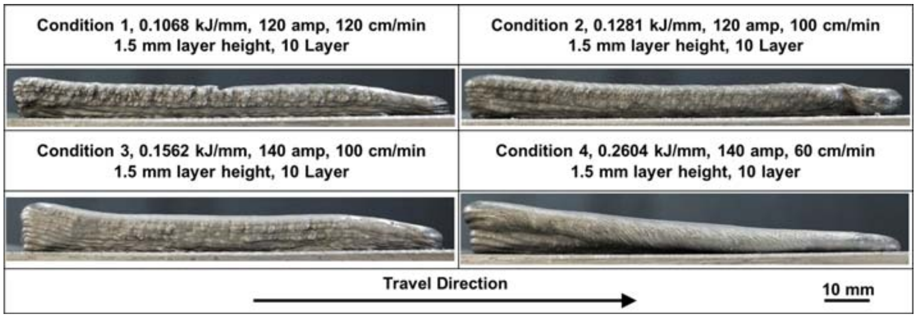


Fig. 10. Laminate wall appearance in each condition

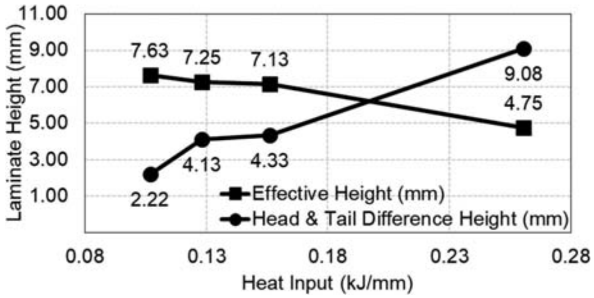


Fig. 11. Heat input condition effect on laminate head and tail difference height

4 Conclusion

The DP-GMAW parameters were investigated for the effect on build-up bead dimension for the single-pass build-up and the effect on multi-layer laminate dimension. It was concluded from the research that:

The main effect of process parameters on the bead dimension included current and travel speed. The main parameters should be adjusted in a range of 120–210 A and travel speed 60–140 cm per minute.

The double-pulse variables including frequency, duty cycle and delta current were not significant effects on bead dimension. However, the DP-variable should be adjusted on the adequate range to maintain the uniformly of bead dimension and appearance. The recommend range for frequency is 5–10 Hz, for duty cycle is 30–70%, and for delta current is 15–40 A.

The increment of heat condition resulted in the decrement of laminate height. The heat condition was the main effect on a laminate slope. To reduce the laminate slope, the lowest heat condition should be used for build-up. The adequate process condition determined in the study including the parameters: 120 A of current, voltage 17.8 V, travel speed 120 cm per minute, frequency at 5 Hz, duty cycle 50%, delta current 30 A and layer height 1.5 mm. Figure 12 is a resultant workpiece with uniform dimension which was built-up using the adequate process condition.

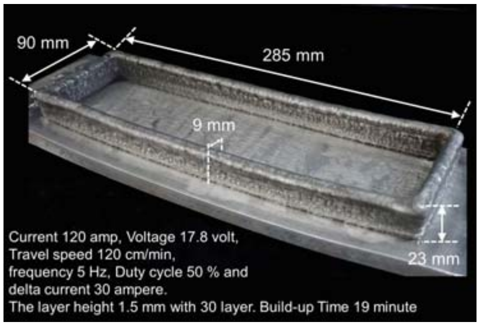


Fig. 12. Workpiece by the suitable DP-GMAW parameters

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