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# Influence of deposition angle in hybrid wire arc additive manufacturing

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**Abstract**
Additive manufacturing as a key enabling technology is increasingly being used in industry. So far, for metallic parts, the powder bed fusion based selective laser melting (SLM) or the directed energy deposition based laser metal deposition (LMD) process integrated in machine tools or linked to robot arm systems are the most widespread.
Wire based wire arc additive manufacturing (WAAM), as a technology with one of the highest build-up rates per unit of time will be of particular interest in the future and is being used more and more in hybrid machines. Materials and parameters for conventional arc welding with the welding torch in vertical (PA) position are well known and investigated. However, apart from the ideal PA-position, not much is known about deposition in so called 'forced' positions. This is becoming increasingly important in the case of particularly large components, as these can efficiently neither be clamped nor moved on a rotating and tilting table. More flexibility is achieved when the welding gun is moved as tool on curvilinear paths to build up complex parts without necessary part movement. This link to the component surface means to leave the ideal vertical position. To make this possible, optimal parameters must be found for each angular positions to enable high-quality and reliable build-up welding. Experimental investigations conducted within this study show that various dependencies exist and therefore angular positions can be interpolated. This enables a prediction of how various welding parameters must be set or have to be regulated at a given angle, based on which a control system can be programmed.

Wire Arc Additive Manufacturing, Inclined plane, CMT Welding

## 1. Introduction

Overlay welding has been known for years and extensively been used in industry. Much previous work has focused on parameter finding. Xiong et al. [1] and Ding et al. [2] investigated the best approximation of the cross-sectional representation as well as the ideal bead spacing for multi-lane welds. Adebayo et al. [3] examined the limit value of the wire feed speed $v_D$ as well as the changes in the individual widths $w$ and heights $h$ of multi-layer welds. All of these investigations have been carried out in the ideal, vertical, PA position. This paper examines the feasibility of welding outside the ideal PA position towards constrained positions for flexible WAAM with moving torch.

## 2. Methodology and investigation

CMT welding process from FRONIUS/GEFERTEC is used for the investigations. 1 mm diameter G3Si1 wire is welded on a 6 mm thick S235JR base plate. Further material combinations are feasible and will be examined if future studies. The welding torch was integrated into the tool spindle of a parallel kinematic multi-optional machine tool from METROM, allowing the torch to move and tilt freely. Three boundary considerations are of interest to deposit a weld bead on an inclined surface. The combination of inclined burner and inclined plane with:

1. Horizontal torch movement (PA, PB, PC)
2. Rising torch movement (vertical seam PF)
3. Falling torch movement (vertical-down seam PG).

In a series of a total of 83 tests with angle settings 0°, 15°, 30°, 45° and 60°, different machine ($v_f$) and wire feed speeds ($v_D$) were investigated. In principle, four layers were built on top of each other. The machine feed speeds examined are $v_f$ = 300, 450 and 600 mm/min, the wire feed speed ranges from $v_D$ = 2 to 9.4 m/min. The ratio of machine feed speed to wire feed speed corresponds to the value $\lambda$ ($\lambda = v_D / v_f$) and should be determined for ideal parameters and used for subsequent characterization of weld beads, Figure 1. Adebayo et al. [3] found that for PA position a humping effect (Fig. 1a) is very likely to occur above a limit for machine feed of 600 mm/min.

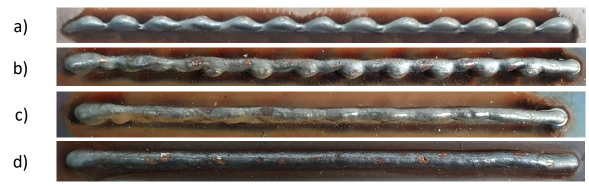


**Figure 1.**
a) Classic humping effect at 0°,
($v_D$ = 3 m/min, $v_f$ = 600 mm/min, $\lambda$ = **5**)
b) Humping effect and formation of pearls on the side at 60°,
($v_D$ = 6 m/min, $v_f$ = 600 mm/min, $\lambda$ = **10**)
c) Lateral pearl formation at 60°,
($v_D$ = 7 m/min, $v_f$ = 450 mm/min, $\lambda$ = **15**)
d) Very good weld with bead characteristics at 60°
($v_D$ = 6 m/min, $v_f$ = 300 mm/min, $\lambda$ = **20**)

Only those welding patterns are taken into account, which have typical bead characteristics without an excessive humping effect in the lower layers (Fig. 1d). It must be mentioned that a hump formation sometimes took place in the second layer but was corrected due to the good control of the CMT process in the layers above (Fig. 1c).

## 3. Results and Discussion

It is noticeable that the possible ratio of $\lambda$ becomes smaller with increasing angle (Table 1). In the case under consideration, the machine feed speed of 300 mm/min, possible wire feed speed decreases as the angle increases. Less mass and hence less energy can be absorbed by the wire feed per route section. If $v_f$ exceeds this value, weld pearls are created, which are formed according to the force of gravity.

When the machine feed rate is increased to 450 mm/min and towards the limit value of 600 mm/min, it becomes clear that the allowed ratio band is getting narrower and narrower - especially at higher angles. For $v_f > 400$ mm/min, hardly any usable results were achieved at 60° angle. For $v_f = 600$ mm/min, no usable results are possible at 60° angle. The maximum angle for the creation of a multi-layer weld for this machine feed rate is 45°.

The achievable values are shown in Table 1. It becomes clear that a ratio between 13 and 16 must be found for reworking free-form surfaces. Xiong et al. [1] noted that there is a limit $\lambda$ of 12.5 for the caterpillar geometry. Up to this value, the cross-section can be represented particularly well by a parabola [1, 2]. This ratio is close to the values found and offers integer values for $v_f$ and $v_D$ for further investigations.

**Table 1.** Ratio $\lambda$ as a function of angle and machine feed

| Angle | 0° | 15° | 30° | 45° | 60° |
|---|---|---|---|---|---|
| $v_f$ in mm/min | Ratio $\lambda$ | | | | |
| 300 | 10 to 31 | 13 to 31 | 13 to 27 | 13 to 31 | 7 to 20 |
| 450 | 7 to 21 | 9 to 21 | 9 to 20 | 11 to 21 | disregarded |
| 600 | 12 to 16 | 10to 16 | 13 to 16 | 13 to 16 | disregarded |

The introduced energy per unit length can be calculated using the following formula:

$$E_{Line} = \frac{I_W \cdot U_W \cdot \eta_{th} \cdot 60}{v_f}$$

Since the welding current $I_W$ correlates with the wire feed speed $v_D$ in the CMT process, it can also be said that the energy $E_{Line}$ is proportional to the speed ratio $\lambda$. However, the welding voltage $U_W$ also increases with the welding current $I_W$, so that there is no direct proportionality. Thus, with the same ratio $\lambda$, different energy per unit length can be introduced into the substrate. The CMT characteristic applied here enables the following line energies in the range of possible wire feeds, with the best option highlighted (Table 2):

**Table 2.** Characteristic values of the applied CMT-process

| $v_D$ | $v_f$ | $\lambda$ | $U_W$ | $I_W$ | $U_W I_W$ | $\eta$ | $E_{Line}$ |
|---|---|---|---|---|---|---|---|
| m/ min | mm/ min | | V | A | VA | | kJ/m |
| 2 | 160 | 12,5 | 8,9 | 68,0 | 605,2 | 0,8 | 181,560 |
| 3 | 240 | 12,5 | 9,8 | 83,0 | 813,4 | 0,8 | 162,680 |
| 4 | 320 | 12,5 | 10,4 | 97,0 | 1008,8 | 0,8 | 151,320 |
| **5** | **400** | **12,5** | **11,5** | **120,0** | **1380,0** | **0,8** | **165,600** |
| 6 | 480 | 12,5 | 11,9 | 152,0 | 1808,8 | 0,8 | 180,880 |
| 7 | 560 | 12,5 | 12,8 | 170,0 | 2176,0 | 0,8 | 186,514 |
| 8 | 640 | 12,5 | 14,4 | 185,0 | 2664,0 | 0,8 | 199,800 |
| 9 | 720 | 12,5 | 15,9 | 198,0 | 3148,2 | 0,8 | 209,880 |
| 9,4 | 752 | 12,5 | 16,4 | 204,0 | 3345,6 | 0,8 | 213,549 |

Additional investigations showed that the lowest possible energy input is advantageous. With the premise of achieving maximum welding speed with a sufficient weld bead shape, the best combination is found to be a feed speed of 400 mm/min with a wire feed speed of 5 m/min. With this combination, the welded metal does not form any lateral weld pearls even at an angle of 60°. The assumption that this effective combination, which works at a 60° angle, is also applicable in smaller angular positions has been confirmed.

## 4. Conclusions

A setting has now been found for the horizontal torch movement. The investigations have shown that the weld bead geometry is stable for different angles (Table 3). The achieved mean weld bead width *w* is 5.93 mm with a standard deviation of 0.11, the mean weld bead height *h* is 2.72 mm with a standard deviation of 0.13.

**Table 3.** determined values *w* and *h* in horizontal burner movement

| Angle | $v_D$ | $v_f$ | $\lambda$ | $U_W$ | $I_W$ | $E_{Line}$ | *w* | *h* | *w/h* |
|---|---|---|---|---|---|---|---|---|---|
| | m/min | mm/min | | V | A | kJ/m | mm | mm | |
| 0 | 5.6 | 450 | 12.44 | 11.8 | 139.0 | 174.95 | 5.955 | 2.675 | 2.23 |
| 0 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.923 | 2.616 | 2.26 |
| 0 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.924 | 2.563 | 2.31 |
| 0 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.893 | 2.652 | 2.22 |
| 15 | 5.6 | 450 | 12.44 | 11.8 | 139.0 | 174.95 | 6.143 | 2.670 | 2.30 |
| 15 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.820 | 2.688 | 2.17 |
| 30 | 5.6 | 450 | 12.44 | 11.8 | 139.0 | 174.95 | 6.093 | 2.825 | 2.16 |
| 30 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.873 | 2.670 | 2.20 |
| 45 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.856 | 2.966 | 1.97 |
| 60 | 5 | 400 | 12.50 | 11.5 | 120.0 | 165.60 | 5.831 | 2.865 | 2.04 |
| Standard deviation | 0.29 | 24.15 | 0.03 | 0.14 | 9.18 | 4.52 | 0.11 | 0.13 | 0.11 |
| Arithmetic average | 5.18 | 415.00 | 12.48 | 11.59 | 125.70 | 168.41 | 5.93 | 2.72 | 2.19 |

## 5. Summary and Outlook

For build-up welding according to a path contour in the 3D space, the path geometry must be split according to a horizontal (1), rising (2) or falling (3) torch movement. Initial investigations have been carried out accordingly for the horizontal movement and inclined torch.

In future investigations, the parameters for the falling and the rising torch movement must be researched. It can be assumed that the parameters for the horizontal movement are also valid for the downward weld, since this position is suggested as mitigation when the humping effect occurs [3]. The limits are even further set accordingly. A very narrow limit area is expected for the increasing movement, since this is the most technically demanding welding [4].

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