Effect of the CMT advanced process combined with an active cooling technique on macro and microstructural aspects of aluminum WAAM

Felipe Ribeiro Teixeira, Fernando Matos Scotti and Ruham Pablo Reis
Federal University of Uberlândia (UFU), Center for Research and Development of Welding Processes (LAPROSOLDA), Uberlândia, MG, Brazil, and Américo Scotti
Federal University of Uberlândia (UFU), Center for Research and Development of Welding Processes (LAPROSOLDA), Uberlândia, MG, Brazil; Department of Engineering Science, University West Department of Engineering Science, Trollhattan, Sweden and Federal University of Parana (UFPR), Graduate Program in Materials Science and Engineering, Curitiba, PR, Brazil

Abstract

Purpose – This paper aims to assess the combined effect of the Cold Metal Transfer (CMT) advanced process and of a thermal management technique (near immersion active cooling [NIAC]) on the macro and microstructure of Al wall-like preforms built by wire arc additive manufacturing (WAAM). As specific objective, it sought to provide information on the effects of the electrode-positive/electrode-negative (EP/EN) parameter in the CMT advanced process fundamental characteristics.

Design/methodology/approach – Initially, bead-on-plate deposits were produced with different EP/EN ratios, still keeping the same deposition rate, and the outcomes on the electrical signal traces and bead formation were analyzed. In a second stage, the EP/EN parameter and the layer edge to water distance (LEWD) parameter from the NIAC technique were systematically varied and the resultant macro and microstructures compared with those formed by applying natural cooling.

Findings – Constraints of EP/EN setting range were uncovered and discussed. The use of the NIAC technique favors the formation of finer grains. For a given EP/EN value, a variation in the NIAC intensity (LEWD value) showed marginal effect on grain size. When the EP/EN parameter effect is isolated, i.e. for a given LEWD setting, it was observed that an increase in the EP/EN level favors coarser grains.

Originality/value – Both the EP/EN parameter and the use of an active cooling technique (NIAC) might be used, even in combination, as effective tools for achieving proper macro and microstructure in WAAM of thin wall builds.

Keywords Aluminum, Microstructure, WAAM, CMT advanced, Active cooling, Variable polarity

Paper type Research paper

1. Introduction

Among the various additive manufacturing methods currently available, the wire arc additive manufacturing (WAAM) has gained impetus because of their usually high deposition rate capacity, which makes the construction of large components viable. However, a high deposition rate usually implies a high thermal energy input, which, combined with thin wall profiles, leads to heat accumulation. Heat accumulation, in turn, occurs in WAAM of thin walls because of the heat conduction mechanism, which is predominantly from the top layer toward the previous layers. In this scenario, as the main conduction heat extraction path occurs along the building direction, heat dissipation becomes difficult in thin walls in relation to the heat input to the whole system. According to Zhao et al. (2011) and Yang et al. (2017), the heat accumulation intensifies as the number of layers increases, i.e. when the preform becomes taller. Consequently, the resulting thermal behavior (through which the heat accumulation is noticed) during the deposition will depend not only on the heat input but also on the part geometry, thermal properties and surrounding conditions.

Denlinger et al. (2015) approached the effects of heat accumulation indirectly dealing with part distortion and residual stresses by using different dwell times between passes in the deposition of Inconel 625 walls. The results showed that the heat accumulation is increased by decreasing the dwell times, resulting to larger distortion and higher residual stresses in the preforms. Besides that, Zhang et al. (2019) showed that the heat...
Effect of the CMT advanced process
Felipe Ribeiro Texeira et al.

accumulation may also affect the grain size and hardness found in the preforms. By analyzing Ti6Al4V walls deposited using gas tungsten arc additive manufacturing, Wu et al. (2017) observed variations in the interlayer oxidation levels and in the wall geometry along the deposition direction because of the heat accumulation. Similarly, Martina et al. (2012) also found geometric variation in Ti6Al4V WAAM, specifically in regions held at high temperatures for long times.

Aiming at mitigating the heat accumulation and its undesirable consequences, processes capable of combining high deposition rates while minimizing the heat input as much as possible, such as the Cold Metal Transfer (CMT) advanced (a gas metal arc [GMA] process variation), have been investigated. The CMT advanced variation associates the controlled short-circuit mode, characteristic of the CMT process, with a variable polarity mode. The resulting cycle is formed by a semi-cycle of direct current electrode positive (DCEP) short-circuits and a semi-cycle of direct current electrode negative (DCEN) short-circuits. The balance between these semi-cycles is defined within the process via a setting parameter called electrode-positive/electrode-negative (EP/EN). Besides reducing the heat input due to the time spent in the DCEN polarity (Park et al., 2013; Kim and Chung, 2017; Li et al., 2018), this process can result in other desirable characteristics for aluminum components produced by WAAM. When studying the deposition of an Al-Cu alloy, Cong et al. (2015) showed that the CMT advanced process led to lower porosity levels if compared with the other CMT variants. Nie et al. (2018) found relatively good mechanical properties and no anisotropy between the vertical and horizontal deposition directions with an ER4043 wire (Al-Si). By using different CMT variants to deposit Al-6Mg walls, Zhang et al. (2018) found a finer microstructure and a more random grain distribution with the CMT advanced process. In this case, an ultimate tensile stress level of 333 MPa was achieved, which is higher than the strength typically found for the wrought version of the same alloy.

The methodology implemented to reach the declared objectives was based on two different stages; the first one to examine the CMT advanced process working features (specific objective) and the second one to assess its effects and of the NIAC technique on microstructural aspects of the preforms produced (global objective). For both methodology stages, the feedstock used was an ER5356 Al wire. However, to achieve the full potential of such a combination, it turns necessary to further understand how the CMT advanced process (concerning EP/EN settings) influences the heat input, if material deposition rate is kept the same (condition not always observed in related publications). Consequently, a specific objective of this work was to provide information regarding the effects of the EP/EN parameter in the fundamental process characteristics, such as electric signals, feeding rates and bead formation.

2. Methodology and experimental procedures
The methodology implemented to reach the declared objectives was based on two different stages; the first one to examine the CMT advanced process working features (specific objective) and the second one to assess its effects and of the NIAC technique on microstructural aspects of the preforms produced (global objective). For both methodology stages, the feedstock used was an ER5356 Al wire with a diameter of 1.2 mm. Pure argon with a flow rate of 14 L/min was used as shielding gas. The wire feed speed (WFS) and travel speed (TS) were set at 6.1 m/min and 0.5 m/min, respectively, and the contact tube to work distance (CTWD) fixed at 14 mm. The WFS level was monitored by an optical encoder (resolution of 0.1 μm/min) positioned inside the wire feeder, between the wire spool and the drive roller assembly. The electrical signals (arc voltage and current) and WFS levels of each layer per wall were acquired by an A/D board at a rate of 5 kHz and 14 bits for 8 s. Calculated arc voltage and current (expressed in RMS), average instantaneous electric power and actual WFS values of the feedstock of each wall were used to support the analyses.

2.1 Experimental procedure for Cold Metal Transfer advanced process working features
To pursue the specific objective of examining the CMT advanced process working features, 11 bead-on-plate deposits
were carried out on 5,052 aluminum alloy plates (150 × 38.1 × 6.4 mm). The EP/EN parameter varied from −5.0 to +5.0, with 1.0 increments in the CMT advanced process (synergic line AlMg 5, φ = 1.2 mm, 100% Ar). The electrical signals (arc voltage and current) and WFS levels, along with the resulting visual aspect of the beads, were used to better understand how this process works and therefore affects material deposition.

2.2 Experimental procedure for assessment of wall-like preforms

After selecting feasible process parameters from the information gathered in the first stage, in this second stage (focusing on the global objective), an experimental design was followed based on the deposition of single-pass multi-layer linear preforms (single walls) to assess the combined effects of different EP/EN values (with the same synergic line of the first stage) and thermal management approaches (NIAC and NC) in terms of macro and microstructures produced. As briefly described in the introduction section and detailed by Da Silva et al. (2020), the NIAC technique is a thermal management approach to cool down the perform as it is built (minimizing heat accumulation). Figure 1 illustrates the NIAC experimental rig used, being the distance maintained between the top surface of the preform and the water liquid lamina its main parameter. Such distance is referred as LEWD, and it is used to indirectly set the cooling intensity promoted by the NIAC technique. A pneumatic/hydraulic system was used to fill the tank with water to keep the LEWD parameter, i.e. the cooling intensity, constant throughout the deposition time.

Three different EP/EN values (−2.0, 0.0 and +3.0) were selected as conditions for the CMT advanced process. Table 1 indicates the experimental design (one step at a time) used in this work stage. To singly evaluate the effect of the cooling conditions over the macro and microstructure, an intermediate level was fixed for the EP/EN parameter (0.0) for four different cooling conditions (runs 3 to 6), comprising the NIAC technique with three different LEWD values (10, 20 and 30 mm) and the NC approach (empty tank). When the interest was to investigate the influence of the CMT advanced process using an active cooling technique, an intermediate cooling condition (NIAC with LEWD set at 20 mm) was considered for EP/EN values set at −2.0, 0.0 and +3.0 (runs 1, 4 and 7).

As a way of comparing the effect of different EP/EN values without using an active cooling technique, walls were built using the NC approach with the EP/EN parameter set at −2.0, 0.0 and +3.0 (runs 2, 6 and 8). All walls (targeting 150-mm-long thin preforms) were made in alternating deposition directions with a dwell time of 10 s in between the layers. The fixed dwell time allowed the interpass temperature and cooling rates to change according to the cooling condition.

As the layer height varies depending on the parameters used (the deposition rate per unit of length, represented by the WFS considering a same TS), the number of layers for each wall was set in such a way they could achieve a minimum height of 40 mm. However, as previously mentioned, as the actual WFS does not correspond to the value set in the CMT Advanced equipment, and this difference depends on the EP/EN setting chosen to equalize the deposition rate per unit of length (WFS/TS constant, being the TS level always kept in 0.5 m/min) for all the walls, a special procedure was used to find the set WFS for each EP/EN of Table 1. To do so, first three different EP/EN settings were selected (−2.0, 0.0 and +3.0) for producing sound beads and testing (bead-on-plate approach) by successively adjusting the WFS selected in the equipment until 6.1 m/min (measured by the encoder) was actually achieved for each case. Therefore, the final and actual WFS levels are indicated in Table 2.

Cross-sections were taken from each wall, sandpaper ground, polished and etched (20% HF + 80% H2O). The macro and microstructural analysis was conducted by optical microscopy with polarizing filters. The planimetric procedure established in the ASTM E112-12 standard was used to measure the average grain area in each case as a representation of grain size. Additionally, microhardness testing (with 50 g of loading for 10 s) was carried out in three different regions (at

<table>
<thead>
<tr>
<th>Run</th>
<th>EP/EN</th>
<th>LEWD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−2.0</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>−2.0</td>
<td>NC</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
<td>NC</td>
</tr>
<tr>
<td>7</td>
<td>+3.0</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>+3.0</td>
<td>NC</td>
</tr>
</tbody>
</table>

Note: Where EP/EN stands for the polarity ratio of the CMT advanced process, LEWD for layer edge to water distance of the NIAC technique and NC for natural cooling.

<table>
<thead>
<tr>
<th>EP/EN</th>
<th>WFS_{set} (m/min)</th>
<th>WFS_{actual} (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−2.0</td>
<td>7.5</td>
<td>6.1</td>
</tr>
<tr>
<td>0.0</td>
<td>6.8</td>
<td>6.1</td>
</tr>
<tr>
<td>+3.0</td>
<td>6.3</td>
<td>6.1</td>
</tr>
</tbody>
</table>
the top, middle and bottom) of the samples, always from the center of a given layer to the center of the previous one, in such a way that the interface in between the selected layers was covered with indentations separated by 350 μm.

3. Results and discussion

3.1 Cold Metal Transfer advanced process working features

The EP/EN parameter regulates the proportion between the number of short-circuits during the EP) and EN semi-cycles within each full cycle, which is governed by the time spent in each electrode polarity. Figure 2 exemplifies the arc voltage and current waveforms of the CMT advanced process with the EP/EN parameter set at –1.0 and also at +1.0. In the first case [Figure 2(a)], the process operates with seven short-circuits in the positive semi-cycle and 13 in the negative one, whereas the number of short-circuits in each semi-cycle is inverted in the second case [Figure 2(b)]. The short-circuit duration is the same regardless the semi-cycle. It is important to notice that a total of twenty short-circuits for the full cycle is kept. It is worth mentioning that another possible approach, not explored in the present work, would be the variation of the number of short-circuits in a full cycle while maintaining the same ratio between the EP and EN semi-cycles, as demonstrated by Klein and Schnall (2020) and Hwang et al. (2020).

To illustrate the CMT advanced process working principles, Figure 3 shows an excerpt of actual arc voltage and current signals observed experimentally coupled with a schematic representation of the wire tip speed direction accompanied by illustrations of the wire dynamics next to the molten pool. Two short-circuit semi-cycles are shown, one in DCEP and other in DCEN. It can be noticed that the same principles apply for both polarities, although the current levels, sign and times may change. By following Figure 3, during the short-circuit phase (1), the current is kept low. At the end of this phase, the secondary drive roller reverts the wire movement upwards.

**Figure 2** Arc voltage and current waveforms with the EP/EN parameter set at –1.0 (a) and at +1.0 (b)

**Notes:** The red braces indicate the number of short-circuits in the EP semi-cycle; the blue braces correspond to the EN semi-cycle and the green grasess correspond to the full cycle.
(negative values of wire tip speed in the schematic graph), aiding the droplet detachment from the molten pool. After that, the current is boosted (2) and the arc is reignited, at the same time as the wire movement direction is reversed back to positive and a new droplet grows at the wire tip. During the burn phase (3), the current is lowered and the wire approaches the molten pool again until a new short-circuit happens (4), restarting the cycle from point 1. With the application of the CMT principles (waveform control with additional mechanical action in the wire tip), the metal transfer in DCEN does not seem to face major problems with droplet repulsion, as usually described in the current literature (Scotti et al., 2012), making it possible to transfer multiple droplets without reversing the polarity back to DCEP.

Figure 4 presents the number of short-circuits in each semi-cycle (EP and EN) and the total number of short-circuits in a full cycle for the entire spectrum of the EP/EN parameter. It is worth mentioning that the following description is valid only for the synergic line used in this work. Between −2.0 and +2.0, the total number of short-circuits in a full cycle is kept constant and equal to 20, but the timeshare in the EP semi-cycle expands as the EP/EN value is increased. With this parameter set at 0.0, the number of short-circuits in each semi-cycle is the same and equal to ten. For settings below −2.0, there is only one short-circuit in the positive semi-cycle, whereas the number of short-circuits in the negative semi-cycle increases as the EP/EN value decreases. Thus, for values below −2.0, the total number of short-circuits is no longer constant and it raises. An opposite scenario occurs when the EP/EN parameter is set above +2.0, i.e. the negative semi-cycle is kept with one short-circuit, whereas the positive semi-cycle experiences an increase in the number of such events. To sum up, it can be seen that the regulation of the EP/EN parameter does not present the same logic throughout its operational range in terms of the number of short circuits produced.

Aiming at assessing the influence of the WFS level in each semi-cycle of the CMT advanced process, an additional bead-on-plate deposition was carried out. In this case, the EP/EN parameter was set at 0.0 and the WFS value was increased from 6.1 to 7.1 m/min, whereas the other parameters remained unchanged. Figure 5 shows the arc voltage and current waveforms with such a change in the WFS level for the EP/EN parameter set at 0.0. As seen, when the WFS value is increased, the number of short-circuits does not change, but the peak current levels and, hence, the mean and RMS currents in each semi-cycle are slightly increased as a way of raising the melting rate to match the larger amount of material being fed through the electric arc. Besides that, Figure 5 shows the RMS current values calculated separately for the EP and EN semi-cycles with the EP/EN parameter set at 0.0 for both WFS values evaluated. As noticed, the current levels in the EP semi-cycle are always higher in amplitude than in the EN one, and this occurs regardless of the EP/EN parameter setting. The reason for such a difference is discussed further ahead together with the WFS data.

Figure 6 shows the tendency of the average absolute values and RMS currents according to the EP/EN value, being all the other parameters kept constant. As the current levels are higher in the positive semi-cycle when its repetition in time is increased (by increasing the EP/EN setting) the absolute average and RMS currents increase. Figure 7 presents the current and WFS signals for the EP/EN parameter set at 0.0. As seen, the WFS level measured appears constant regardless of the semi-cycle polarity, meaning that there is no major correction in terms of feeding rate throughout the process. The small variations seen in the WFS level (Figure 7) are attributed to intrinsic measurement errors. It should be noticed that because of the location where the WFS is measured (before the main drive roller assembly) the advance and retreat movements performed by the secondary drive roller (in the torch) are not perceived in the results, as such movements are accommodated in the buffer of the CMT process. As the fusion capacity in GMA processes is higher when in the negative polarity time, as in this case the arc climbs the electrode-wire in the search for oxides for
cathodic emission (Li et al., 2018; Assunção et al., 2019; Souza et al., 2010) and boosts its heating, the CMT advanced process compensates that by making the current contribution (directly proportional to its intensity) to the melting rate as being relatively smaller during the EN semi-cycles than it is in the EP semi-cycles, as seen in Figure 5. Therefore, it was found that, despite the current levels being lower during the EN semi-cycles, the melting rate of the wire remains the same all the way through and the WFS level can be kept constant.

Although the WFS level can be set by the user when using the CMT advanced process, the synergic control of the process makes adjustments in a way that the resultant feeding speed (measured) does not match the value that is selected (reminding that this finding is related to the present work conditions, not necessarily a general characteristic of the CMT advanced process). The actual average WFS measured via the encoder was lower than the set value for the entire spectrum of the EP/EN parameter. Besides that, for the same WFS setting, the lower the EP/EN parameter value, the lower the WFS measured, as depicted in Figure 8. It can be seen that such a variation is linear within the $-3$ to $+3$ range and reaches a
plateau for the extreme values. This behavior is in agreement with what is seen in Figure 4, as the number of short-circuits in the EP semi-cycle reaches the lower limit when EP/EN is lower than −3.0, as well as the number of short-circuits in the EN semi-cycle reaches the minimum limit when EP/EN is greater than +3.0. This is probably done to avoid changing the current levels too much between the EP and EN semi-cycles to account for the differences in the fusion capacities of the process in each polarity.

Figure 9 shows the typical aspect (top view) of the beads produced in the bead-on-plate depositions for the entire spectrum of the EP/EN parameter (plates digitally removed for better highlighting of the beads) for a TS set at 0.5 m/min. As seen, with the EP/EN parameter set at the negative end (−5.0, −4.0, −3.0) of its range, no continuous beads were formed. Instead, in this case, sequences of humps with weak adhesion to the substrate were deposited. To investigate whether the impaired bead formation would be related to the lower material deposition obtained for the conditions with the EP/EN set at the negative end (Figure 8), two additional bead-on-plate depositions were carried out for the EP/EN set at −4. At first, only the WFS level was increased from 6.1 m/min to 7.1 m/min. Subsequently, the WFS level was kept at 7.1 m/min and the TS was decreased from 0.5 m/min to 0.4 m/min. The increased deposition rate in both additional tests still did not achieve continuous beads; humps barely connected to each other were formed looking similar to what is shown in Figure 9 for the EP/EN at −3.0, −4.0 and −5.0.

Thus, this occurrence may be related to the higher electrode-wire melting occurrence and corresponded lower thermal energy input to the plate as the EN polarity is more present, which causes rapid cooling of the melt pool and hinders the wettability and continuity of the bead of material being deposited. Besides that, as mentioned by Fuerschbach (1998), Sarrafi and Kovacevic (2010) and Cho et al. (2015), the cathodic cleaning of the surface oxide in Al alloys substrates takes place when in the EP semi-cycle, which endures for very short times when the EP/EN parameter is in its negative end. The difficulty in removing the oxide layer from the plates in the EN semi-cycle, without the cathodic cleaning action, may have impaired a proper molten pool formation, as the energy required to fuse the oxide layer is higher than that to do so in the base material.

In contrast, with the EP/EN parameter set from −2.0 to +5.0 sound beads were produced, being fish scale ripples observed with more intensity the longer the time spent in the EN semi-cycle (EP/EN set at −2), i.e. with lower heat input to the plates. Distinctively, smoother bead finishes were accomplished the more time was spent in the EP semi-cycle (EP/EN set toward +5), i.e. with higher heat input to the plates. To sum up, based on the results found and considering the setting of parameters, synergic line and consumables used, it can be said that the operational range of the EP/EN parameter in terms of the aspect of the beads ranges from −2 to +5.

Summarizing, the EP/EN parameter controls the ratio in the number of short circuits in each semi-cycle (EP and EN) of the CMT advanced process, whereas the number of short-circuits is kept constant in a full cycle (valid between −3.0 and +3 EP/EN values). The changes in EP/EN cause variation in the measured WFS, probably because of the control logics of the process, which adjusts the WFS level to sustain stability. The WFS level is not changed within the full cycle of the process, despite the changes between EP and EN. In fact, the effective current is lower in EN to compensate for the higher fusion rate associated. When the selected WFS is increased, for a same EP/EN value, the ratio between short circuits in EP and EN is maintained, as well as the total number of short circuits in a full cycle. However, the effective current in both semi-cycles is increased to accommodate the need for higher fusion rate. Finally, there is a correlation between EP/EN value and arc energy level, i.e. higher EP/EN values are associated with higher arc energies, which may lead to higher heat input. This indicates that the parameter may be used as a thermal management tool in WAAM. It is also expected that higher EP/EN values result in more cathodic cleaning in the base metal and molten pool, but less in the wire surface. Yet, the selection of the EP/EN parameter must consider the limitations in the lower end (−3.0, −4.0 and −5.0), as for the conditions tested in this work, it seemed incapable of producing sound beads (deposits).

3.2 Effects of the Cold Metal Transfer advanced process and of the near immersion active cooling technique over wall-like preforms

3.2.1 Arc energy

Figure 10 presents the resultant average instantaneous energy per unit of layer length for each of the walls. This approach is based on the integral of power as a function of time and can be applied to the analysis of any current (DC or AC) or welding/deposition conditions (steady or unsteady current behavior), as pointed by Jorge et al. (2017). As noticed, the arc energy raises as the EP/EN value is increased, as, as presented in Figure 6,
the correspondent current also increases, still the TS was the same. In addition, one can expect higher heat input when the arc energy is higher, keeping other conditions the same. As it could have been anticipated, the electrical signals were not significantly modified by the different cooling conditions. This result demonstrates consistency and proper selection of the height increment adopted after each layer, guaranteeing the same CTWD throughout the deposition time.

This scenario can be explained according to the electrical signal results presented so far. That is, the increase in the EP/EN level from its equilibrium setting, in this case from 0.0 to +3.0, leads the process to remain for a longer time in its EP semi-cycle, when the current range levels are higher than when in the EN semi-cycle, hence increasing the average instantaneous electric power. In contrast, if the EP/EN level is reduced from its equilibrium setting, in this case from 0.0 to −2.0, the logic goes the other way around. Thus, the arc energy available, which may affect the heat input to the preform under deposition and could have been also estimated by the ratio between the mean electrical power and the TS, is directly proportional to the EP/EN parameter levels.

3.2.2 Macro and microstructural characterization

The final microstructure in WAAM preforms strongly depends on the solidification conditions and further solid-state transformations because of the repetitive heating caused by the deposition of the successive layers (intrinsic heat treatment). In other words, the heat input, that comes hand in hand with the deposition of each new layer, increases the temperature of the previous layer, and also of the adjacent ones, to a degree normally sufficient to promote changes in the as-solidified microstructure, therefore forming a complex heat-affected zone (HAZ), as different layers experiences different thermal histories. Regarding the solidification process, it must be highlighted that the correlation with heat input is not straightforward. An increase in heat input may lead to a larger weld pool but not necessarily intensify the molten metal temperatures (although it may in fact happen). This phenomenon will be related to how the heat transfers from the weld pool to the unmolten material. To illustrate the microstructural changes that take place along and across a single layer, the HAZ may be related to the phase diagram of the alloy of interest, neglecting the kinetic effect of the rapid heating and cooling over phase transformation. A similar approach was suggested by Kou (2003) when analyzing the HAZ transformations in carbon steels. Therefore, the AWS ER5356 wire can be approximated to a binary Al-5% Mg alloy and analyzed through the phase diagram shown in Figure 11(a). For this specific alloy, the HAZ can be comprehended as the region subjected to re-heating at temperatures ranging approximately from 250°C to 575°C. Thus, from the phase diagram, three different regions based on the resultant microstructures might be distinguished within each layer formed during WAAM with the ER5356 wire:

- Region A, where the highest temperatures are achieved within the monophasic field \( \alpha \). Depending on the time within this region, the dissolution of \( \text{Al}_3\text{Mg}_2 \) and grain growth will happen. For instance, during a

Figure 11 (a) Al-Mg phase diagram (adapted from ASM (1990)); (b) typical HAZ macrostructure, identified based on the left side phase diagram, along the building (vertical) direction in walls made by WAAM with the Al-5%Mg alloy; (c) amplification (microstructure) of the transition between the regions with and without grain-coarsening shown in (b)

**Note:** Dispersed pores, typical of Al WAAM, can be also seen across the layers – details on the level of porosity found in this case were shown and discussed by Scotti et al. (2020)
microstructural evaluation in multi-pass welding with an Al-Mg wire, Jian et al. (2020) verified that the thermal cycle of the subsequent bead was capable of leading to a coarser grain at the interface with the previous bead. Likewise, the same phenomenon is possible in WAAM;

- Region B, where lower temperatures are reached within the monophasic field $\alpha$. In this case, as the temperatures are not high enough to promote rapid dissolution of precipitates and the time within the monophasic field is short, there might occur only partial dissolution of $\text{Al}_3\text{Mg}_2$. As commented by Reed-Hill (1973), the presence of second phase particles can inhibit grain growth. Thus, this region could remain with a grain size similar to the as-solidified state; and

- Region C, where the temperatures reached are below 250°C, which is insufficient to allow solid-state transformation, favoring the maintenance of the microstructure of the as-solidified state.

As respectively seen highlighted and amplified in Figure 11(b) and 11(c), during layer cooling [following the dashed red line in Figure 11(a) downwards], there is a precipitation of $\text{Al}_3\text{Mg}_2$ phase in regions of the types A and B, so that the region B becomes very similar to the region C and thus making it hard to differentiate them. In practice, it is only possible to distinguish two regions; one that undergoes grain growth (region A), which corresponds to the coarse grain HAZ, and another that does not (region B + C), which maintains a grain size compatible with the as-solidified state. Based on these facts, it can be said that the deposited walls are composed of multiple HAZs and fusion zones established intermittently along their building (vertical) direction. The sizes of these regions and the microstructures within will depend on the thermal history they experience as a consequence of the deposition parameters and cooling conditions applied.

To singly evaluate the effect of the different cooling conditions over the macrostructure that is formed for a given CMT advanced process scenario, Figure 12(a) presents the typical macrographic images sampled at different heights of the walls deposited with the EP/EN parameter set at 0.0 for different NIAC settings (LEWD set at 10, 20, and 30 mm) and for the NC approach. Figure 12(b) presents the average grain areas measured along the building direction of the same preforms and locations. As perceived, the average grain sizes were statistically the same for all the cases in which the NIAC technique was used, independently from the LEWD value used. Besides that, with such an active cooling technique, there was no significant variation in the macrostructure along the building direction, indicating that the water cooling provided thermal management consistency throughout all the layers. These results are a direct consequence of the capability of such a technique of mitigating heat accumulation even after only 10 s of dwell time in between layers, regardless the layer position in the building direction. When looking at the case with the NC approach, it can be observed that the average grain size increases along the building direction and the overall microstructure is coarser than those achieved with the NIAC technique. This result can be attributed to the increasing heat accumulation along the building direction, as the dwell time applied was not long enough to keep similar interpass temperatures.

In support to this finding, the concomitant deviation in the geometry of the layers (widening and flattening) also contributes to the NC effects. As demonstrated and discussed by Scotti et al. (2020), as the natural heat extraction is not efficient enough to cope with the heat input that goes along with each layer deposition, the interpass temperatures progressively increase layer by layer and, as a consequence, they become wider and flatter the higher they are in the preforms. Due to the higher temperatures and varying geometry previously verified with this NC condition, the lower a layer is located in the preforms, the more it gets affected by repetitive heating cycles (heat accumulation) and consequent grain growth (deeper HAZs). As seen in the far-right column of images in Figure 12(a), the fusion and re-fusion boundaries in between each layer cannot be easily identified because of the multiple heating cycles (as indicated by the red arrows in the other conditions).

In another perspective, to singly evaluate the effect of the CMT advanced process parameter on the macrostructure that is formed for a given cooling condition, Figure 13(a) shows the typical macrographic images sampled from different heights of the walls deposited with the NIAC technique with the LEWD
Figure 13 Typical macrographic images (a) and average grain areas (b) along the building direction of the walls deposited with the NIAC technique with the LEWD parameter set at 20 mm for different EP/EN values (−2.0, 0.0 and +3.0).

Note: The width along the building direction is almost the same within each wall.

Parameter set at 20 mm for different EP/EN values (−2.0, 0.0 and +3.0). Figure 13(b) presents the average grain areas along the building direction of the same preforms and locations. As seen, for the same cooling condition, the increase in the EP/EN value enlarged the grain size. As also discussed by Zhang et al. (2018), the CMT advanced process tends to lead to a finer grain size than the DCEP mode, as there is a dendrite fragmentation process promoted by a stronger stirring effect in the molten pool in first case, which is related to its periodic polarity inversion. However, also for the CMT advanced process, Zhang et al. (2020) and Klein and Schnall (2020) observed that the grain size was coarser as the time in the positive semi-cycle was increased. In this circumstance, their studies suggest that this behavior results from the higher heat input attributed to the longer time spent in the positive polarity, i.e. it would be as if the temperature gradient at the solid–liquid interface had a greater effect on the formation of the solidification structure than the stirring effect which acts on the molten pool because of the variable polarity of the process. Thus, the increase in arc energy as the EP polarity time is extended in detriment of the EN polarity time, in turn, backs up the possibility of a higher heat input promoting grain growth, which may occur because of two reasons: first, due to the molten pool solidification condition and second, due to the solid-state transformation governed by the repetitive heating. Regarding the molten pool solidification, as evidenced by different authors (Kou and Le, 1982; Munitz, 1985; Paul and Debroy, 1988), the slower the cooling rate, the coarser the microstructure. Thus, the higher arc energy associated with the higher EP/EN values entails slower cooling rates and, consequently, larger grain sizes in the as-solidified state. For the same reason, the subsequent layer depositions, also with potentially high heat inputs, will provide more intense heating recurrences of the previous layers, resulting in the preform exposure to longer times and higher temperatures in the monophasic field of the Al-Mg phase diagram, which allows further grain growth and larger HAZs. Indeed, these thermal-related features are demonstrated in a recently conducted study by Scotti et al. (2020), with the same deposition conditions as that used in this work.

Figure 14(a) shows the typical macrographic images taken from different heights of the walls deposited with the NC approach for different EP/EN values (−2.0, 0.0 and +3.0). Figure 14(b) presents the average grain areas along the building direction of the same preforms and locations. The results are consistent with what was previously discussed in Figure 13, the increase in the EP/EN values results in larger grains due to the higher arc energy available. Moreover, it can be observed in Figure 14(a) that the macrostructure varies along the building direction, in such a way that the grains become coarser as more layers are deposited and the walls become taller. Such a behavior, similarly also observed by Wu et al. (2017) and Martina et al. (2012), is attributed to the occurrence of heat accumulation, which gets more prominent as new layers are deposited in the absence of an active cooling strategy. Even though lower EP/EN values provide lower heat inputs, the heat sinking provided by the NC approach is not sufficient, at least not with the short dwell time used in between the layers in the present work, to prevent the rise of heat accumulation and its effects, which become more evident as more layers are added to the walls. Thus, although the overall average grain area numbers have been shown to be smaller with lower EP/EN settings, a tendency to grain size increase is still verified along the building (vertical) direction. The faster cooling rates provided by the NIAC technique certainly also play an important role in the microstructure produced. As depicted by Scotti et al. (2020), the lower the LEWD value, i.e. the closer the cooling water lamina gets to the deposition level, the more intense the heat sinking becomes to cool down the preform. Therefore, the grains being nucleated have less thermal energy and time to grow. Also, as the layers, from a short distance below the level of deposition, are rapidly submerged into and kept in thermal equilibrium with the water, which is not allowed to heat up, the grains from that moment on do not grow anymore.
Besides the variation in grain size, the walls deposited under the NC condition also presented a considerable dissolution of $\text{Al}_3\text{Mg}_2$ when compared to those ones deposited with the NIAC technique. As aforementioned, the repetitive heating cycles in the NC condition are such that longer times within the $\alpha$-phase field develop, which allows the dissolution of $\text{Al}_3\text{Mg}_2$. The optical microscopy images in Figure 15 illustrate this behavior by comparing the resultant structures for two walls built with the EP/EN parameter set at 0.0 with different cooling conditions, one with NIAC and another with NC, in two different regions: top and middle of the wall. In the micrographic images shown in Figure 15, the $\text{Al}_3\text{Mg}_2$ phase appears as the darker tiny particles present both in the interior and along the boundaries of the grains. From the microstructures belonging to the top region of the walls [Figure 15(a) and 15(c)], it is noticeable that, as the last layer was not re-heated, the presence of dark areas indicates that the $\text{Al}_3\text{Mg}_2$ particles were not dissolved. The microstructure corresponding to the middle of the wall produced with NIAC technique [Figure 15(b)] exhibits a more intense presence of dark areas in the as-solidified region in comparison with the HAZ. This fact indicates that the $\text{Al}_3\text{Mg}_2$ phase in the HAZ is at least partially dissolved due to the re-heating in the temperature range of the $\alpha$-phase field. Last, the microstructure corresponding to the middle of the wall produced with the NC condition [Figure 15(d)] reveals very few $\text{Al}_3\text{Mg}_2$ particles within the layers. In this case, as the layers are repetitively heated and their temperature builds up to higher ranges, as shown by Scotti et al. (2020), the $\text{Al}_3\text{Mg}_2$ phase might be almost completely dissolved over the deposition time.

3.2.3 Microhardness characterization

Figure 16 presents the microhardness collection from three regions along the building direction of the walls deposited with the EP/EN parameter set at 0.0 for all the cooling conditions evaluated. As seen, there is no clear tendency of hardness variation along the height of the walls. In Figure 17, the average microhardness values and respective standard deviations were compiled for all the deposition and cooling conditions combined. Although the grain size was affected by both the EP/EN parameter and cooling condition, not only whether an active cooling strategy (NIAC) is used or not (NC), but including in terms of the intensity of the cooling imposed (LEWD parameter), the deposition process and thermal management applied had no significant statistical effect over the material hardness levels produced.

Klein and Schnall (2020) also observed different grain sizes and no major average microhardness variation in aluminum parts manufactured by WAAM. To assess whether the hardness could be related to the differences in grain size or not, they quantified the theoretical increase in yield strength (using...
the Hall–Petch law and in the hardness (using Tabor’s classic hardness-yield stress formula) as a function of grain size. By considering two regions with distinct grain sizes (34 and 63 μm), they were able to notice a low discrepancy in the properties, which was assigned to the low Hall–Petch coefficient for the aluminum. Thus, on the one hand, although there are differences in grain size, small variations in hardness are expected for this material. On the other hand, a higher hardness variation should be achieved for other materials as a result of changes in grain size. From a positive perspective, the nearly-unvaried hardness levels indicate that the parts produced in the present work were not embrittled, despite the faster cooling rates implied by the NIAC technique, notably with the LEWD parameter set at 10 mm as revealed by Scotti et al. (2020).

Ultimately, both the CMT advanced process, through its electrode polarity balance (EP/EN parameter), and the NIAC technique, by means of its cooling intensity (LEWD parameter), are tools capable of affecting the grain size in WAAM of Al, at least for the deposition conditions used. The capability of positively affecting not only the thermal cycles and geometries of the resultant preforms, as previously demonstrated by Scotti et al. (2020), as well as of modifying their grain size, as revealed in this present work, with two independent thermal management tools opens up the windows for finding optimal deposition parameters in WAAM. These optimal conditions, aiming at a comprehensive manufacturing solution, should embrace from production-related factors, such as the geometrical quality of the preforms and production time, to the mechanical performance features of the final parts as, for instance, affected by their grain size and consistency across their volume, which should be pursued not only via post heat treatments but rather preferably in-situ, i.e. during the deposition time. These capabilities of changing the preforms in different facets based on the deposition process and on an active cooling technique are also promising for the processing of alloys that are known for being more prone to metallurgical transformations, and hence to changes, for instance, in mechanical and corrosion properties, such as low-alloy and tool steels, stainless steels in their variety, Ti alloys, Ni alloys and even high-strength Al alloys. Besides that, the microhardness results found in the present work (generally between 65–80 HV) are in accordance with the range reported by Su et al. (2019) and Hwang et al. (2020), who also used Al-Mg wires to additively manufacture aluminum parts.

4. Conclusions

The current work globally aimed at providing a more comprehensive vision on the effect of both the CMT advanced process and of an active cooling technique NIAC on the resultant macro and microstructure and correlated microhardness of WAAM with an ER5356 Al wire. As complement, a specific objective was to provide information on
the effects of the EP/EN parameter in the fundamental process characteristics.

1 From the results to attend the specific objective, it was possible to conclude that:
   - The EP/EN parameter affects the balance in the number of short-circuits in each polarity. The higher its setting, the higher the number of short-circuits and the time spent in the positive semi-cycle.
   - The current levels in the positive (EP) semi-cycle are always higher in amplitude than in the negative (EN) one. This behavior is used to compensate the higher melting rate of the wire obtained as a consequence of the climbing effect promoted throughout the negative semi-cycle. Thus, as the absolute average and RMS currents increase as the EP/EN parameter is increased, it is possible to maintain the deposition rate with different arc energies.
   - In terms of visual aspects, unsound beads were formed when the EP/EN parameter was set at the negative end (−5.0, −4.0 and −3.0).

2 From the results to attend the global objective, it was possible to conclude that:
   - The use of the NIAC technique favors the formation of finer grains in the preforms when compared with the NC approach with a short dwell time in between layers. For a fixed EP/EN setting, a variation in the NIAC intensity (LEWD setting) had a mild effect on the average grain size.
   - When the effect of EP/EN parameter is isolated, i.e. for a fixed LEWD setting, it is observed that decreasing the EP/EN value also favors the formation of finer grains.
   - A greater dissolution of Al\textsubscript{3}Mg\textsubscript{2} was observed for the walls deposited with the NC approach than for those deposited with the NIAC technique.
   - Although a variation in grain size was verified in the preforms produced with the ER5356 Al wire, this alloy did not exhibit change in the resultant microhardness as the deposition conditions were changed.

To sum up, by affecting the heat input, through the EP/EN parameter in the CMT advanced process, and also the heat extraction capacity, through the LEWD setting in the NIAC technique, the approach of combining this process and active cooling technique stand as a tool that can be used to improve the quality of preforms, at least for the spectrum of conditions evaluated. The concepts on the dissolution of secondary phases because of the re-heating cycles may be rather relevant when dealing with precipitation-hardenable alloys, although it was not the case in this work. This result expands the possibilities in terms of deposition planning and complements the results found by Scotti et al. (2020). Proper deposition parameters selection and thermal management approach requires a holistic view and should aim at producing near net shape builds with optimal deposition time, consistent and smooth geometry and proper mechanical properties, preferably without the need for further heat treatment. Hence, it is important to have a comprehensive roll of tools.

It is important to mention that the above conclusions are concerned with the current work experimental conditions. Further research will be implemented by the authors to explore the trends when applied to large parts and faster travel and WFS (heat inputs), for instance.

References


Effect of the CMT advanced process

Felipe Ribeiro Teixeira et al.


Further reading


Corresponding author

Felipe Ribeiro Teixeira can be contacted at: teixeira.304@hotmail.com

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com