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RESEARCH PAPER

Wire and arc additive manufacturing: a comparison between CMT and TopTIG processes applied to stainless steel

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Abstract

Wire and arc additive manufacturing (WAAM) enables the building of near net-shape components layer by layer by using arc welding technologies and wire filler metal as feedstock. The study aims at comparing the applicability of two innovative robotic arc welding technologies (cold metal transfer (CMT) and TopTIG) for additive manufacturing (AM) of stainless steel parts. Initially, a process development has been completed with the goal of optimizing material deposition rate during arc time. Both continuous and pulsed current programs were implemented. Then, different thick-walled samples composed of more than one overlapped weld bead per layer were manufactured in 316L stainless steel grade by CMT and TopTIG. Mechanical properties have been determined in as-build samples in different building orientations. WAAM applying CMT and TopTIG welding technologies is analyzed in terms of part quality (defined as the absence of defects such as pores, cracks, and/or lack of fusion defects); surface finishing; part accuracy; productivity; microstructural characteristics; and mechanical properties. Achieved mechanical properties and deposition rates are compared with the state of the art. Findings and conclusions of this work are applicable to the industrial manufacturing of stainless steel parts and requirements to apply these technologies to other expensive materials are finally discussed.

Keywords GMA welding · GTA welding · Deposition rate · Stainless steels

1 Introduction

Wire and arc additive manufacturing (WAAM) is gaining momentum since it is a promising alternative to traditional subtractive manufacturing for relatively large metal components (usually in the range from 0.4 m to several meters) with low to medium complex geometry and low buy-to-fly (BTF) ratios, i.e., the ratio of material weight procured to the weight of the finished product. A case study reported by Cranfield [1] indicates a BTF ratio of 45 for the manufacturing of a wing rib from a billet, however, with WAAM, this ratio is around 12.3, which implies a cost reduction of 58%.

WAAM combines arc welding and wire feedstock material for additive manufacturing (AM) purposes. The original idea of using arc welding technologies to generate 3D objects by depositing molten metal in superimposed layers is almost centenarian, but in the last years, several research groups have thoroughly investigated it using gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW). A comprehensive summary of previous research works and results can be found in [2]. These works have been mainly focused on titanium [3–7], aluminum [8, 9],

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nickel [10, 11], and steel alloys [12, 13]. Many of them include examples of developed WAAM demo parts for aeronautical applications.

WAAM has the following remarkable advantages: minimum human intervention and setup times, is based on readily available welding equipment, manipulators and filler metals, low capital cost, low material and deployment costs, unlimited build envelope, and high deposition rates [2, 14]. Reported deposition rates usually range from 1 to 4 kg/h for aluminum and steel, respectively. For Ti64 alloy, deposition rates up to 1.8 kg/h have been achieved [15] with commercial arc welding machines.

On the contrary, current limitations of WAAM are related to the process induced residual stresses and distortion, relatively poor part accuracy, and poor surface condition due to "stair stepping" and "surface waviness" [2]. For this reason, WAAM parts must be finished, usually by milling. Current WAAM surface waviness is around 0.5 mm [3], but depends on the arc welding process, parameters, and wall thickness.

Both the increment of deposition rate and the reduction of surface waviness or macro roughness can contribute to reduce manufacturing costs of WAAM parts. However, an increment of deposition rate usually entails higher residual stresses, distortions (due to the higher heat input), and a loss of fidelity in parts with higher buy-to-fly ratios which requires more machining time and raw material. This is basically why recently, it was concluded that increasing the deposition rate above 1 kg/h for Ti64 has no significant economic benefits in robot-based WAAM cells [16].

Today, it is considered that if WAAM deposition rates are kept at medium levels (around 1 kg/h for titanium and aluminum alloys and 3 kg/h for steels), this will result in buy-to-fly ratio of less than 1.5 and maximum cost savings [14].

However, if the deposition rate could be increased keeping the same buy-to-fly ratio and surface waviness, this would entail a significant reduction of WAAM manufacturing costs. This would bring along with a reduction of manufacturing time and an increase of system capacity utilization and productivity.

Figure 1 compares conventional build rates and process resolutions which are currently achieved by powder bed fusion additive manufacturing, blown powder-directed energy deposition, WAAM and high building rate wire-based AM processes like EBAM™ [17], and Rapid Plasma Deposition™ [18]. According to this reference, build rate depends on the square of the layer height, whereas both resolution and surface waviness show a linear dependence with layer height [18].

It is worth noting that many of the previous works have been completed in single-bead multilayer configuration with or without torch waving or lateral oscillation. Single bead layers can produce wall thickness from 2.5 [14] to around 10 mm [5]. Manufacturing of parts with thicker wall thickness will require the overlapping of multiple adjoining weld beads. In this case, the overlapping distance or center distance between adjacent beads (*d*) greatly affects to the surface quality and layer flatness.

Previous investigations on multi-bead overlapping models have concluded that it is impossible to achieve an ideal flat overlapped surface [20]. Ding et al. [20] has recently developed a highly accurate multi-bead overlapping model for the determination of optimal center distance to ensure a stable overlapping process in GMAW-based WAAM of mild steels [21]. In WAAM applications, uneven deposition surfaces can lead quickly to cumulative errors along vertical direction which can result in unstable process. Despite this issue, it can be corrected by implementing real-time monitoring to adjust and control arc length in real time; it impairs surface finishing and part accuracy leading to higher buy-to-fly ratios.

Up to now, GTAW- and PAW-based arc welding technologies have demonstrated to be more reliable processes for WAAM with fewer problems of sputtering, excessive heating, distortion, or porosity in comparison with GMAW. However, in these two technologies, the wire is not fed coaxially and this leads to process variations when changing the welding direction and extreme sensibility to arc length. In fact, many robotic welding systems require a rotary axis to orient the wire feeding nozzle and keep it matched with welding direction which limits applicability.

In this work, two innovative arc welding technologies (cold metal transfer (CMT) from Fronius Company [22] and TopTIG from Air Liquide company [23]) have been selected to be applied for AM of thick-walled stainless steel parts.

Nowadays, both technologies are considered as remarkable innovations in arc welding technologies. CMT technology is an improvement of short-circuit GMAW process which is

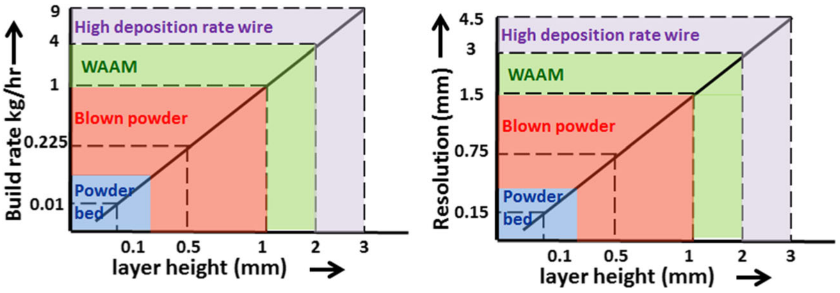

Fig. 1 Build rate and horizontal resolution vs layer height for different AM technologies [19]

based on controlled dip transference. CMT is characterized by alternating wire forward and retraction movement at high frequency. Advanced dynamic current waveform generates small molten droplets at the tip of the wire which are detached at low current with the help of mechanical retraction of the wire. This results in very low heat input, spatter-free metal transference, extremely stable electric arc, and sound welds [22]. During CMT welding, the arc length is detected and adjusted mechanically on its own. These characteristics make it especially well-suited for WAAM applications as it has been previously demonstrated [14, 24].

TopTIG is a patented robotic GTAW welding technology with integrated wire feeder [23]. The innovation of TopTIG technology relies on the design of the welding torch (Fig. 2). In conventional hot- or cold-wire GTAW systems, the wire is fed at an angle of approx. 90° with respect to the electrode and usually parallel to the welding direction. In the TopTIG process, the filler metal wire passes through the nozzle keeping a fixed angle with the electrode. In this way, the wire is constantly fed to the hottest zone of the arc independently of the welding direction and leading to higher deposition rates. This has a hot wire-like effect and welding speeds and deposition rates comparable to GMAW can be attained, i.e., 1.5 m/min and 3 kg/h, respectively, for stainless steel welding applications [23]. With this torch, the process is almost coaxial (it does not require adjustment of wire feeding direction), totally spatter-free, robust, and stable. Process stability is improved because the distance of the electrode to the workpiece become less important since the wire is always forced to enter the melt pool. Regarding WAAM processes, to the best of the authors' knowledge, there are no previous public scientific references regarding the implementation of TopTIG technology for additive manufacturing applications.

The main purpose of this work is to study the feasibility of CMT and TopTIG technologies for WAAM of stainless steel parts. The relation between welding process parameters, quality aspects of weld bead (including geometrical appearance and welding defects), and deposition rate was analyzed as part of the initial process optimization for both technologies. Mechanical properties in terms of tensile test have also been measured in two different directions (*X*, horizontal and *Z*, vertical). A comparison between CMT and TopTIG-based WAAM is presented in terms of productivity assessed by maximum deposition rate and part accuracy.

2 Experimental procedure

WAAM trials of stainless steels parts were performed in arc welding robotics cell. In the case of CMT, Fronius transplus synergic 4000 CMT R power source and Robacta drive CMT W/F++ 6.25-mm torch from Fronius International were used. Alternatively, TopTIG 220DC and patented torch from Air Liquide were employed for GTAW-based process.

Both CMT and TopTIG torches were attached to a 6-axis Kuka robot KR 16 KS model with a KRC2 controller (Fig. 3). Ar − 2% CO_2 was used as shielding gas for CMT application, whereas TopTIG was carried out with inert gas (Ar, 99.999% purity). In both cases, the gas flow was set at 16 L/min. Both continuous and pulsed current programs were tested as explained in Section 3.

In both technologies, 1-mm-diameter wire of 316L stainless steel grade from Praxair was employed as filler metal. Chemical composition given by the provider of the wire is shown in Table 1. Process development and thick-walled sample buildup were completed by depositing weld beads onto 10-mm-thickness plates of 316L alloy.

For the microstructural characterization, cross sections of single-weld beads and WAAM samples were cut, mounted, and polished. In order to reveal microstructure, samples were

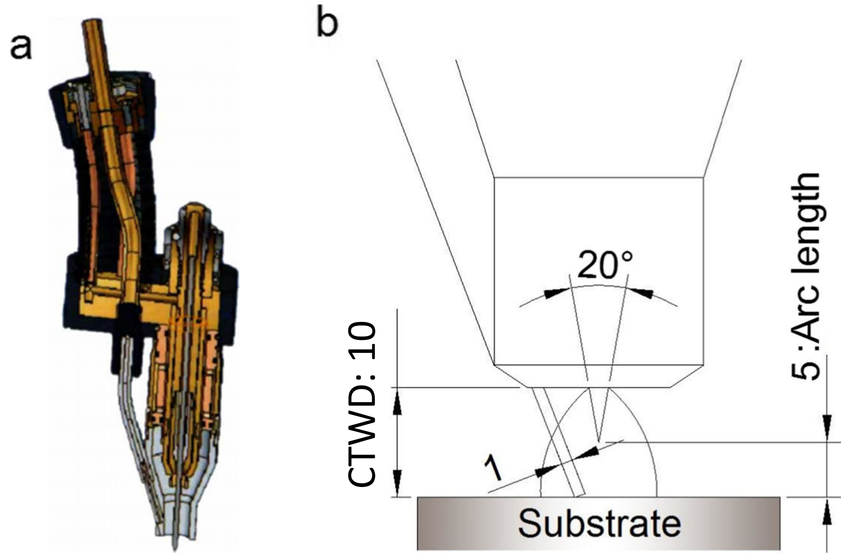

Fig. 2 TopTIG welding torch. **a** Cross-section view [23]. **b** Sketch of setup showing arc length and CTWD

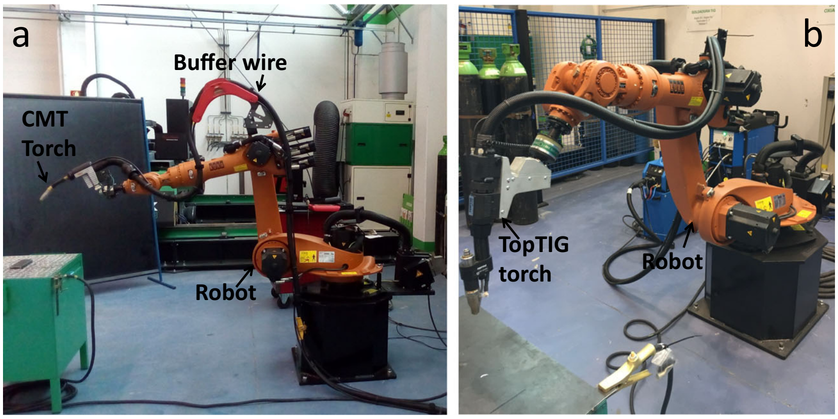

Fig. 3 WAAM robotic setup with **a** CMT and **b** TopTIG torches

etched with Marble solution (10 g $CuSO_4 + 50$ mL $H_2O +$ 50 mL HCl) during 10 s. After that, they were electrochemically etched in 80% NaOH solution. Light microscopy images were taken with an Olympus GX51 microscope.

Mechanical properties were evaluated in *X* (horizontal) and *Z* (vertical) directions in order to investigate the influence of the orientation and location. Flat dog bone tensile test specimens were extracted by electron discharge machining from thick-walled WAAM samples according to Fig. 4, i.e., 32-mm gauge length and 6 × 4 mm^2 cross-section within this length. Three samples were tested by each set of welding parameters in as-build state. Tensile tests were performed in a model Z100 ZWICK/Roell testing machine with a maximum load capacity of 100 kN. Specimens were tested at room temperature with a displacement rate of 1.6 mm/min and using an extensometer with a gauge length of 25 mm.

3 Results

This section includes experimental results that were obtained during CMT and TopTIG-based WAAM process development. After initial process optimization with single deposited weld beads, thick-walled WAAM parts composed by three overlapped weld beads per layer were manufactured with selected parameters in order to investigate process stability in large parts and resulting mechanical properties.

Results are divided by WAAM technology (CMT versus TopTIG) and a distinction is made between initial process optimization and microstructural and mechanical characterization of thick-walled parts.

Table 1 Chemical composition given by the provider of 316-L stainless steel wire (wt%)

Filler wire	Main alloying additions in filler wire (wt%)						
	C	Mn	Si	Cr	Ni	Mo	Fe
316L	0.025	1.8	0.4	19.0	12.0	2.5	Bal.

3.1 CMT-based WAAM development

Single weld beads were deposited with both continuous and pulsed synergic CMT curves for stainless steels. Arc length was kept constant at 10- and 13-mm contact tip-workpiece distance (CTWD) was selected. This distance was considered optimum for ensuring good shielding during welding, stable arc ignition, and material transference. Table 2 shows sets of welding parameters which led to maximum material deposition rates and homogenous weld beads. Maximum wire feed speeds of 8 and 10 m/min were achieved for continuous and pulsed welding conditions. Material deposition rates calculated from these values are 3.0 and 3.7 kg/h, respectively. These deposition rates are estimated considering 100% arc time.

Figure 5 shows external appearance of single-weld beads and corresponding representative cross-sections. Despite the same arc ignition and extinction parameters being employed, more homogeneous weld beads with constant thickness and height along the entire weld seam were obtained for “pulsed 1” and “pulsed 3” welding conditions. This is considered a critical feature in order to avoid local accumulation of material in WAAM applications.

Table 3 includes height and width of single beads that were measured in cross sections. It is worth noting that single beads resulting from “continuous” and “pulsed 2” welding parameters are significantly narrower and shorter than the rest. Moreover, pulsed 3 weld bead shows excessive penetration and dilution in the center. Therefore, it was concluded that pulsed 1 welding conditions were the optimum ones for stainless steel CMT-based WAAM applications.

Pulsed 1 welding parameters were selected for the manufacturing of thick-walled WAAM demo parts. Three overlapped weld beads were applied per layer and five layers were deposited one of top another in demo parts

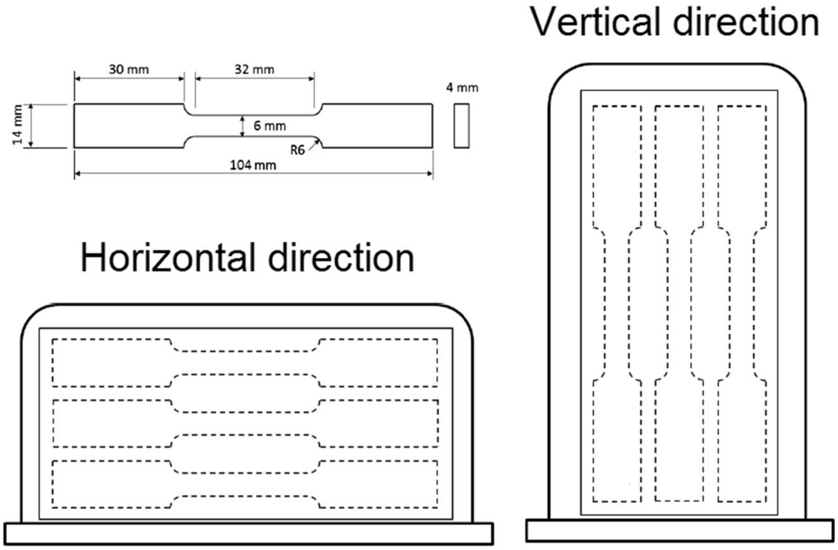

Fig. 4 Scheme of the tensile test specimens extracted from thick-walled WAAM samples

(3 × 5 samples). A dwell time between weld beads was introduced. Shorter dwell times led to wall collapse and material overhanging during welding due to high temperatures.

Deposition strategy is based on repeated sequence of a pair of layers (Fig. 6). Even and odd layers are both composed by three overlapped weld beads, but the welding direction is changed from layer to layer in each weld bead. That means that the starting point of one weld bead in layer *n* is coincident with finishing point of equivalent weld bead in layers $n-1$ and $n+1$. It was demonstrated that this deposition strategy yields the best performance in terms of homogeneous and even build-up. The direction of deposition of the weld beads in each layer and between layers is alternated, with the objective to minimize the effect of the different welding parameters at the ignition and the extinction of the arc. Being a layer by layer manufacturing process, it is essential to ensure an even and controlled growth in each layer.

In every layer, the first deposited weld bead was always the one in the center (bead 1) and afterwards, the two adjacent ones were deposited using 20° torch tilting angle from the vertical position (Fig. 6). Overlapping distance from two adjoining weld beads was fixed around 50% overlapping percentage according to the weld width measured in single weld beads (Table 3).

3.2 Characterization of CMT-based WAAM parts

Figure 7 displays cross section of 3 × 5 sample that was manufactured following the deposition strategy explained above. The welding robot was programmed to introduce a constant offset in *Z* direction from layer to layer of 2.1 mm. Manual or automated arc length corrections were not applied during the whole WAAM process.

The cross-section shows that the selected deposition strategy allows to build up straight thick-walled parts in a stable way, without internal defects and with high definition. Experimentally determined surface waviness or macroscopic roughness was 220 μm whereas wall thickness was close to 14 mm. Total height of 3 × 5 sample is close to 10.4 mm, i.e., 2.08 mm/layer which is very close to the selected Z offset. Finally, it must be noted the flatness of the weld deposit at the top layer showing only two shallow humps. It is evident that these humps result from the deposition of lateral weld beads and their edges are just connected but without overlapping.

From this characterization, it can be concluded that the developed multi-bead material deposition strategy enables to build sound straight walls with high accuracy, reduced roughness, and constant layer thickness. These features are critical in WAAM applications in order to maximize buy-to-fly ratios and approach as much as possible to the net shape of the final component [16].

Table 2 Single-bead CMT welding parameters leading to highest deposition rates

Reference	Current (A)	Wire feed speed (m/min)	Voltage (V)	Travel speed (m/min)	Arc length (mm)
Continuous	150	8	14.2	0.6	10
Pulsed 1	200	9.4	23.3	0.6	10
Pulsed 2	220	10	26.8	1.0	10
Pulsed 3	220	10	26.2	0.8	10

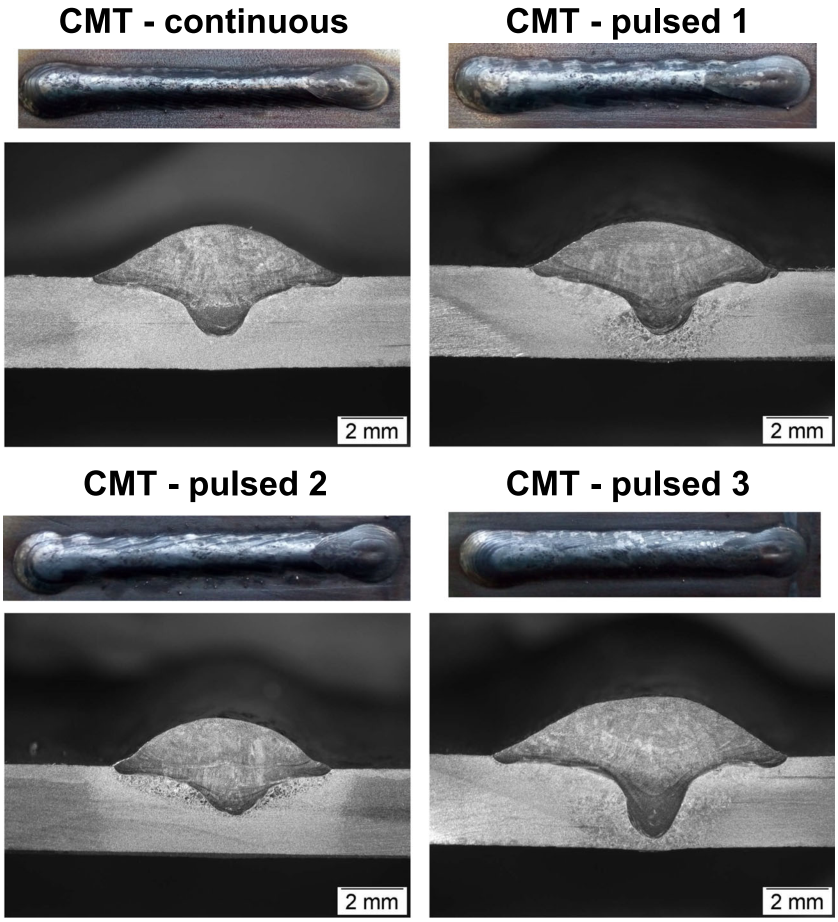

Fig. 5 External view and cross sections of CMT single beads deposited with welding parameters of Table 2

The same welding deposition strategy was used to manufacture large parts for mechanical property characterization. Temperature was measured by four thermocouples attached to the substrate during the deposition of 31 superimposed single beads as can be observed in Fig. 8.

Figure 9 shows temperature evolution after each deposited layer. From the ninth layer on the interpass, temperature in the substrate is stabilized between 230 and 280 °C.

Table 4 includes mechanical properties that were determined in tensile test samples extracted from large walls (3 × 57 and 3 × 35 samples). Mechanical properties were determined both in vertical (*Z*) and horizontal (*X*) orientations in as-build state (Fig. 10). Results reveal a significant anisotropy in terms of yielding stresses for both continuous and pulsed welding parameters. Reduction of yield stress in vertical orientation is related to preferential orientation of austenite grains during solidification due to epitaxial grain growth.

There was no influence of the relative position on the testing samples in the wall and samples located in the first layers (close to the substrate) showed comparable results than those located at the top layers with minimum scattering between them, except for the CMT vertical pulsed samples. Parts manufactured with continuous and pulsed current curves had comparable elongations (*e*).

Table 3 Height, width, and deposition rates of CMT single beads

Reference	Bead geometry		Deposition rate (kg/h)
	Height (mm)	Width (mm)	
Continuous	1.4	6.5	3
Pulsed 1	1.5	7	3.4
Pulsed 2	1.4	6.5	3.7
Pulsed 3	1.7	9	3.7

3.3 TopTIG-based WAAM development

TopTIG process development was started by depositing single weld beads. Several trials were performed using non consumable electrode with 20° angle in the tip. A constant travel speed of 70 cm/min was selected for these trials, which is comparable to that defined for CMT.

Different welding trials with increased wire feed speeds were conducted for arc lengths from 3 to 5.5 mm at 220 A with continuous current program. Longer arc lengths were

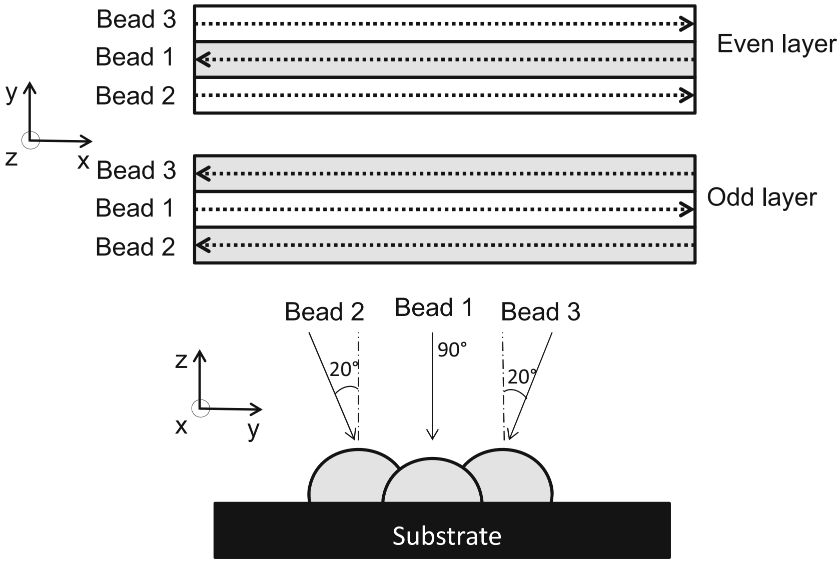

Fig. 6 Scheme of the CMT deposition strategy composed by a repeated sequence of a pair of layers and three weld beads per layer

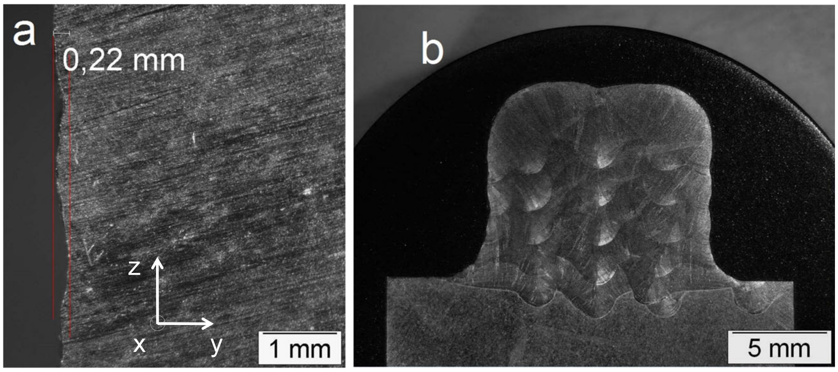

Fig. 7 Cross section of 3 × 5 samples manufactured by CMT WAAM process

not suitable because the arc ignition was not steady. Table 5 includes maximum wire feed speeds that were obtained for different arc lengths and resulting weld bead geometries. It is worth noting that higher wire feed speeds led to unstable transference, torch oscillation and incomplete melting of filler metal.

According to a previous work, there are two transference modes for TopTIG welding applications. Droplet transference is obtained at lowest wire feed speeds whereas a continuous liquid flow is observed at higher feed speeds [23]. The latest transference mode entails a continuous contact between filler metal and weld pool at the end of electric arc cone. This transfer mode is largely preferred since it provides highest deposition rates, minimum risk of tungsten electrode contamination, and continuous and regular welds. Moreover, it contributes to the total absence of porosity and sparks, enlarges electrode’s life and makes consecutive wire feeding start and stop events totally reliable.

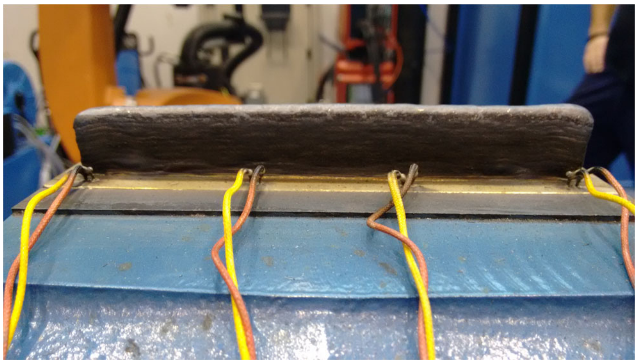

Fig. 8 Thermocouple localization close to the first bead deposited in the substrate

The increase of the maximum wire feed speed when using longer arc lengths can be explained by the fact that the wire comes into direct contact with the electric arc during a longer time. Note that the relative position of filler metal and electrode tip does not vary when changing arc length but the electric arc cone is taller. Therefore, the wire has more time to get melted before getting into contact with the substrate. If the wire feed speed is too high, the wire contacts the substrate when it is still in the solid state and exerts a mechanical force that tends to separate welding torch from the substrate. This effect gives rise to

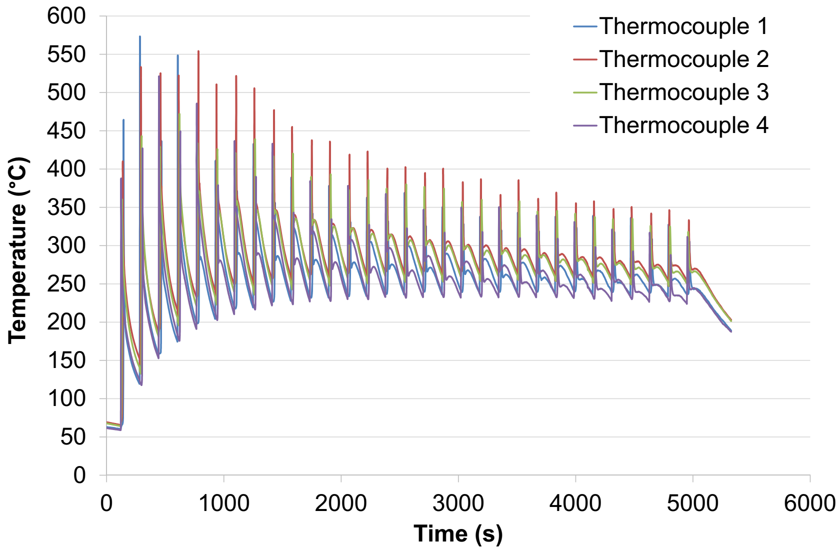

Fig. 9 Temperature record during the deposition of 31 single bead walls

Table 4 Mechanical properties achieved for both orientations with CMT technology in pulsed and continuous modes

Orientation	Mode	YS (MPa)	UTS (MPa)	*e* (%)
Vertical	Continuous	336.9 ± 1.7	574.1 ± 7.9	42.0 ± 3.7
	Pulsed	331.7 ± 5.4	536.0 ± 15.3	45.6 ± 16.7
Horizontal	Continuous	364.3 ± 13.9	577.3 ± 4.0	43.4 ± 4.7
	Pulsed	374.0 ± 11.2	588.0 ± 5.7	45.1 ± 3.5
Reference 316L [25]		346	651	47

torch oscillations and unstable transference with huge voltage variations and sparks.

Figure 11 represents the linear relationship between maximum wire feed speed which provides continuous transfer and arc length obtained from experimental results. This relationship is applicable to 1-mm diameter 316L filler metal and selected welding parameters, i.e., continuous current program, 220 A, and 70 cm/min travel speed.

From this study, it is concluded that maximum material deposition rates that can be obtained in TopTIG-based WAAM applications, are between 1.9 and 2.3 kg/h, corresponding to 5–6 m/min wire feed speeds.

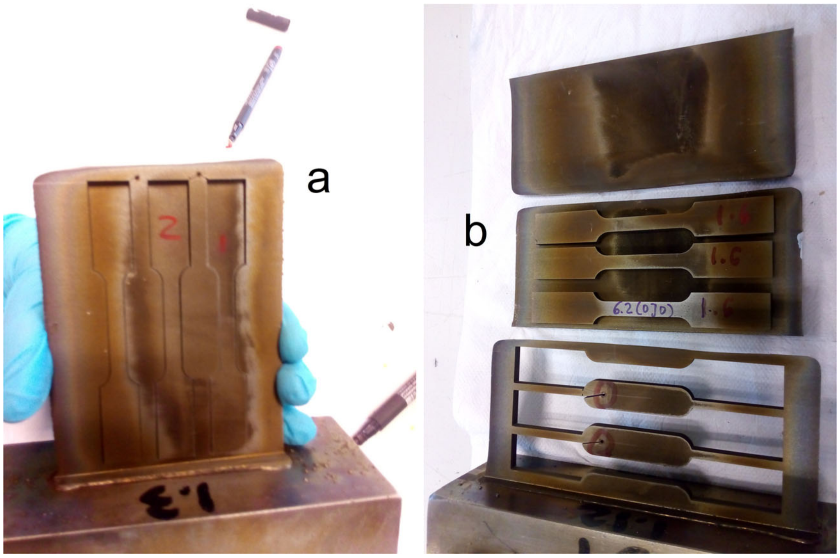

Fig. 10 Tensile test samples extracted from CMT WAAM walls in **a** vertical and **b** horizontal orientations

Table 5 Maximum wire feed speeds achieved at different arc length configuration in TopTIG single weld deposition trials

Reference	Wire feed speed (m/min)	Arc length (mm)	Bead geometry		Deposition rate (kg/h)
			Height (mm)	Thickness (mm)	
Continuous 1	2.9	3	1	4.9	1.1
Continuous 4	4	4	1.3	5.1	1.5
Continuous 3	5	5	1.5	5.1	1.9
Continuous 5	6	5.5	2.1	4.1	2.3

Figure 12 shows cross sections of single-weld beads deposited with welding parameters included in Table 5. Experimentally determined weld bead heights and widths are included in the same table. It is worth nothing the narrower thickness and higher aspect ratio (height/ width) of TopTIG weld beads in comparison with CMT samples. Moreover, TopTIG welds exhibit much lower dilution, especially at the longest arc lengths.

“Continuous 3” welding parameters included in Table 5 were considered as the optimum ones for current WAAM investigations since they provided stable transference and controlled dilution ensuring good connection between superposed layers.

The study was completed with the optimization of material deposition rate with pulsed current. As it is shown in Table 6, the maximum wire feed speed that was achieved with pulsed current was 4.2 m/min, that is, the average between 5.5 and 2.9 m/min. It is worth noting that TopTIG technology allows to use different wire feed speeds during current peaks and valleys. However, average value was significantly lower in comparison with continuous current program. The same can be said for material deposition rates (1.6 versus 1.9 kg/h) Fig 13.

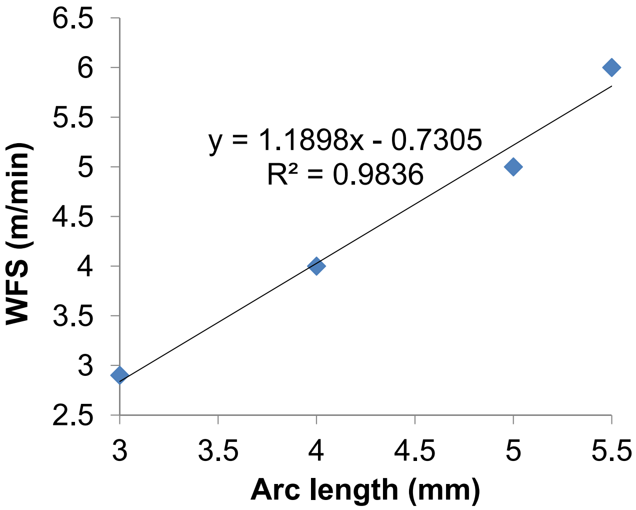

Fig. 11 Experimentally determined linear relationship between maximum wire feed speed for continuous liquid flow transfer and TopTIG arc length

Due to the higher deposition rates, continuous 3 welding parameters were implemented for the manufacturing of thick-walled WAAM demo parts. In a similar way to CMT samples, 3 × 5 samples were built leaving a dwell time between subsequent weld beads.

The selected deposition strategy was comparable to CMT in terms of repetitive even and odd layer sequence and alternating starting and ending points between adjacent and superposed weld beads, but there was an important difference in the weld bead sequence in each layer. In this case, the first deposited bead was the one at the edge, then the central one, and finally, the last at the other edge (Fig. 14). It is worth noting that TopTIG wire feed system is completely integrated in the torch and consequently, the position of the wire with respect to the welding direction lacks of importance. Nevertheless, in these 3 × 5 demo parts, the pipe of the filler metal feed system was fixed perpendicular to the welding direction and in-layer weld beads were always overlapped leaving this side free. Horizontal overlapping percentage around 60% was used, whereas 1.7 mm *Z*-offset distance was selected for these TopTIG demo parts. In this case, welding torch was always kept perpendicular to the substrate and tilting angles were not introduced.

3.4 Characterization of TopTIG-based WAAM parts

Figure 15 shows cross section of 3 × 5 sample that was manufactured by TopTIG following the deposition strategy described in Fig. 14. Again, the developed deposition strategy enables the building of defect-free thick and straight walls with very good definition. Surface waviness or macroscopic roughness was around 120 μm and total wall thickness was 11 mm which is significantly lower than for CMT (14 mm). Moreover, a hump is observed at the top in the region where first and second weld beads are overlapped.

Finally, large parts were manufactured for characterization of mechanical properties using the same welding parameters as for 3 × 5 samples (Fig. 16). As it was previously done for CMT samples, tensile test samples were machined from both vertical (*Z*) and horizontal (*X*) orientations after building and without applying any thermal treatment. Table 7 includes average mechanical properties determined in those samples.

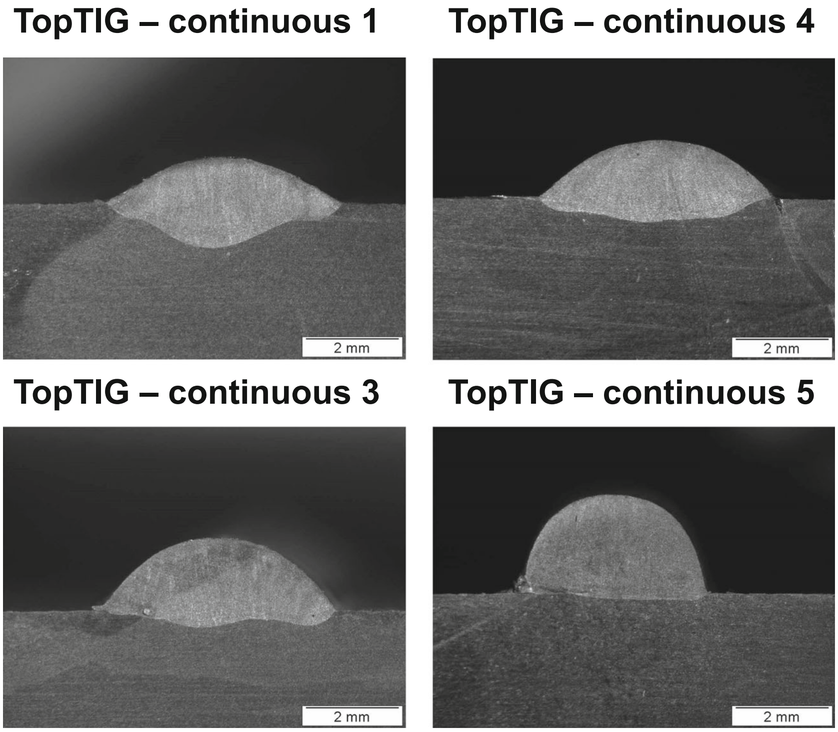

Fig. 12 Cross sections of single-weld beads deposited by TopTIG at different arc lengths and corresponding maximum wire feed rate

In this case, samples tested in vertical orientation showed lower yielding stress (YS) and tensile strength (UTS) values in comparison with horizontal ones (Table 7). The differences are around 40 and 50 MPa, respectively, and they mean a relevant material property anisotropy.

4 Discussion

Characterization of CMT- and TopTIG-based WAAM parts has demonstrated that it is feasible to build up thick-walled large components bead by bead in stable, reliable, and fully automated way. Metallographic characterization and x-ray inspection of manufactured parts showed a total absence of internal pores, cracks, or lack of fusion defects between adjoining beads or superposed layers.

The process development that has been performed addressed two main goals with the aim of making WAAM more cost-effective and economically competitive in comparison with conventional manufacturing technologies and alternative but expensive high build rate wire processes like EBAM™ [17] or Rapid Plasma Deposition™ [18] included in "high deposition rate wire" AM technologies in Fig. 1.

The first goal has been related to increase material deposition rate during arc time. CMT technology has demonstrated to provide almost double deposition rate in comparison with TopTIG (9.4–10 m/min versus 5–6 m/min wire feed rates) leading to deposition rates above 3.7 kg/h, which are similar to the highest values reported up to date for steels [14]. Despite this, the increase of arc length had a clear impact on the maximum wire feed speed and material deposition rate in TopTIG, the process does not allow to reach deposition rates above 2 kg/h.

It must be noted that reported material deposition rates are theoretical and they do not take into account dwell time between subsequent beads. This is the standard way of reporting material deposition rates, since both arc-on time and throughput greatly depend on the selected geometry [14]. Nevertheless, current study concludes that large economic benefit could be made if the arc time is maximized. Different alternatives to increase this arc-on time could be to work in different parts in parallel in the same robotics cell or to introduce forced cooling systems to reduce dwell time [24].

Table 6 Comparison between pulsed and continuous optimum single bead deposition TopTIG welding parameters

Reference	Current (A)	Wire feed speed (m/min)	Voltage (V)	Travel speed (m/min)	Arc length (mm)	Deposition rate (kg/h)
Pulsed	350/187	5.5/2.9	15.5	0.8	5	1.6
Continuous 3	220	5	15.5	0.7	5	1.9

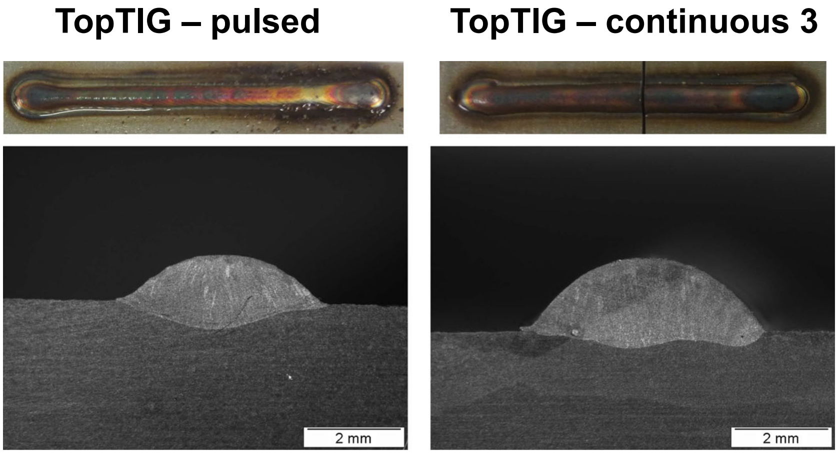

Fig. 13 Cross-sections of pulsed and continuous optimum single beads deposited by TopTIG

Dwell times have been applied to CMT and TopTIG based multilayer samples in current study.

The second goal was to achieve great definition on straight wall parts with minimum roughness or surface waviness. Definition or part accuracy is critical in order to improve buy-to-fly ratio and reduce material waste and machining times in final finishing operations. These two factors have an impact on the overall process cost, especially with expensive and difficult to machine alloys [16]. Developed material deposition strategies for CMT and TopTIG allow to reduce surface waviness and wall thickness oversize in comparison with previous works [2, 3].

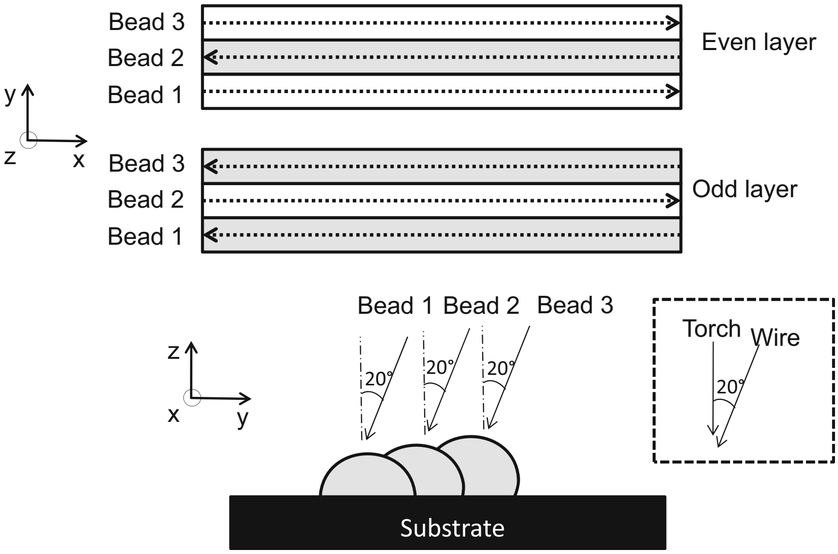

Fig. 14 Scheme of the TopTIG deposition strategy composed by a repeated sequence of a pair of layers and three weld beads per layer

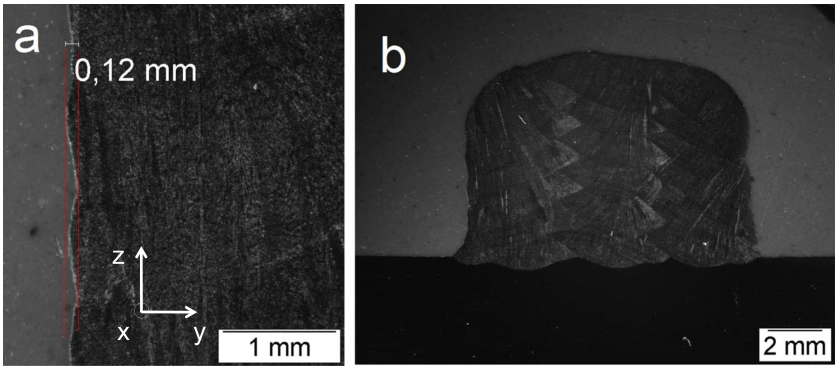

Fig. 15 Cross section of 3 × 5 samples manufactured by TopTIG WAAM process

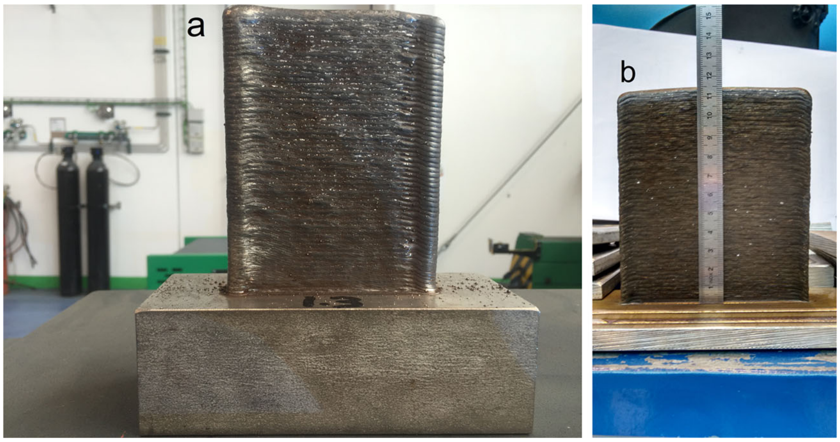

Fig. 16 Large parts manufactured by **a** CMT and **b** TopTIG for mechanical characterization

This reduction is especially important in thick-walled components were torch waving strategy was employed to make walls thicker [3, 14]. Currently, developed material deposition strategies for CMT and TopTIG are able to create 14- and 11-mm-thick walls which are thicker than maximum values reported for straight weld beads (without torch lateral waving) at slow traveling speeds, i.e., well below 10 mm [5]. Moreover, current material deposition strategies can be extended to a higher number of overlapped weld beads by layer, increasing the wall thickness, but keeping the same surface roughness and part accuracy. For CMT technology, the overlapping requirements between internal adjoining weld beads should be further investigated, since current optimization required the introduction of a tilting angle in the two-edge weld beads.

Another important discussion that can be made from the results is related to the repetitive and reliable nature of developed WAAM processes. Both characterization of 3 × 5 samples and manufacturing of large parts up to 115-mm height with almost 60 layers, have demonstrated that layers are created in an even way keeping a good flatness in horizontal and transverse directions. This is essential in order to ensure stable additive manufacturing process in a fully automated way.

It was shown that CMT is an especially stable process since local variations in part height and CTWD are compensated due to the advanced material transference mode of this technology. Therefore, it can be said that this process is constantly self-adjusted contributing to highly stable and reliable process. TopTIG technology is more sensitive to local CTWD variations and it requires a fine tuning of the *Z*-offset. This tuning must be very accurate in tall parts, since for high wire feed rates, the process window is quite narrow. Positive *Z*-offset deviations will lead to arc ignition instabilities when the CTWD goes above 5.5 mm and on the contrary, negative *Z*-offset deviations will result in torch oscillations due to the reduction of the wire and electric arc interaction time (unstable transference mode). At wire feed rates of 5 m/min, notable torch oscillations started when CTWD was lower than 4.6 mm.

Table 7 Mechanical properties achieved for both orientations with TopTIG technology in continuous mode

Orientation	YS (MPa)	UTS (MPa)	*e* (%)
Vertical	322.2 ± 2.7	539.9 ± 14.7	43.1 ± 6.9
Horizontal	365.5 ± 8.7	590.3 ± 3.6	42.3 ± 2.7
Reference 316 L [25]	346	651	47

The achievement of flat layers does not only contribute to process stability, but it also has an important economic impact. Current WAAM systems usually require advanced monitoring systems that read in real time the topography of last layer or the temperature of the weld pool. Advanced process control algorithm have been developed with the aim of making a close-loop WAAM process control based on this real time monitoring [13]. However, these systems increase the technical and cost requirements of WAAM robotic cells. This work has demonstrated that stable and reliable WAAM process can be performed in conventional robotic cells without any external monitoring system. Note that even TopTIG trials were performed without readily available active voltage control (AVC) option.

A great benefit of CMT and TopTIG over existing GTAW- and PAW-based AM technologies relies on the coaxial nature of the process. In CMT, the filler metal itself is the electrode and it creates the electric arc. In TopTIG, the filler metal is fed through the torch directly to the electric arc cone and close to its tip. This confers coaxial properties to the welding and material deposition process. This coaxiality was further tested in square-shaped paths by superposing single-layer weld beads (Fig. 17). Coaxial nature of both CMT and TopTIG processes reduces also machine complexity (the requirement of extra axis for wire feed system or part orientation is missed) and CAM path

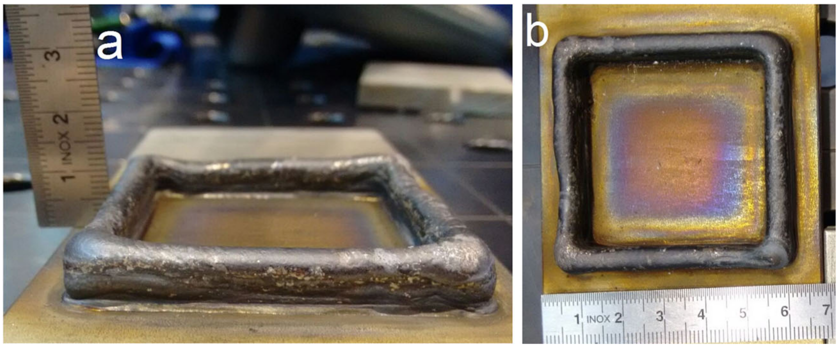

Fig. 17 Square shape built made by TopTIG

programming for complex parts. This also promotes cost reduction of WAAM.

Despite a non-consumable electrode is used in TopTIG technology, there were no electrode degradation problems even after long welding times. Extended electrode life was ensured by applying proper post welding gas flow times. This reduced the electrode sharpening requirements to several welding hours. Nevertheless, current TopTIG robotic cells usually integrate a fully automated electrode sharpening unit which restores electrode's tip in really short times.

Other advantages of CMT and TopTIG WAAM robotic cells over existing AM systems include lower capital cost, unlimited build envelope, and competitive production rates with minimum material waste. Furthermore, according to a recent paper [4] the ubiquitous nature of arc welding implies a strong supply chain capability and competitive cost environment for the future that can contribute to the early adoption of these technologies by the industry and especially by small and medium companies with limited investment possibilities.

In terms of mechanical properties, a clear anisotropy in as-build condition was observed. This anisotropy should be further investigated and taken into account for the design of real WAAM components. What is concluded from current results is that yield stress of vertically oriented samples is lower than horizontal samples in both technologies and irrespectively of the current program (continuous or pulsed). A reduction of tensile strength in vertically oriented parts is also observed in TopTIG and pulsed CMT samples. Elongation is quite similar in both orientations and comparable for CMT and TopTIG with different current programs. In general the scattering of the mechanical properties is remarkably low. Comparing with the reference of 316L given by the provider of the substrates, the achieved mechanical properties of walls manufactured by both technologies are quite similar to standards for this material.

Finally, despite this study being focused on stainless steel, it must be noted that CMT- and TopTIG-based WAAM processes can be even more interesting for expensive weldable alloys such as titanium, aluminum, or nickel superalloys. Current technical and scientific WAAM literature is mainly focused in Ti64 alloy as a good candidate for substituting wrought or cast parts by WAAM parts. Researchers from Cranfield University have already tested CMT for WAAM applications of Ti64 alloys [24] and well as Gefertec [26]. Therefore, current results with CMT and TopTIG could be easily transferable to other alloys of interest. Of course, this transference would require initial process development including optimization of single weld beads and material deposition strategy.

5 Conclusions

Main conclusions that were obtained from this work are summarized herein:

- Both CMT and TopTIG innovative arc welding technologies are feasible to manufacture bead by bead stainless steel parts, including thick-walled components, with high accuracy and reduced surface waviness (below 220 μm).
- A process optimization in terms of material deposition rate has been completed leading to material deposition rates during arc time of up to 3.7 kg/h and above 2 kg/h for CMT and TopTIG, respectively.
- An advanced material deposition strategy has been developed for both CMT and TopTIG which allows to build up straight walls with optimum flatness and high accuracy. This ensures high process stability and reliability and avoids the requirement of using complex real time monitoring systems.
- Coaxial nature of both processes provides high flexibility and reduces machine complexity and CAM time.
- Stainless steel samples manufactured by CMT and TopTIG-based WAAM exhibited anisotropy in terms of mechanical properties in the as-build state with lower strength values in the vertical (*Z*) orientation, but there was a narrow scattering of data in samples extracted from different heights (layers at the bottom or at the top of the walls).
- Current results can be transferable to other expensive alloys, following the same process and material deposition optimization procedure.

References

1. Cranfield University, “WAAM Technology,” 2015
2. Ding D, Pan Z, Cuiuri D, Li H (2015) Wire-feed additive manufacturing of metal components: technologies, developments and future interests. Int J Adv Manuf Technol 81(1–4):465–481
3. A. Addison, J. Ding, F. Martina, H. Lockett, S. Williams, and X. Zhang, “Manufacture of complex titanium parts using wire + arc additive manufacture,” in Titanium Europe 2015 Conference, 2015, p. 14
4. I. D. Harris, “New developments in welding and metal additive manufacturing using directed energy deposition (DED),” in Titanium Europe 2015 Conference, 2015, p. 27
5. Baufeld B, Van der Biest O, Gault R (2010) Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: microstructure and mechanical properties. Mater Des 31:106–111
6. Colegrove P (2013) High deposition rate high quality metal additive manufacture using wire + arc. Technology
7. N. P. Hoye, E. C. Appel, D. Cuiuri, and H. Li, “Characterisation of metal deposition during additive manufacturing of Ti-6Al-4V BY arc-wire methods,” in 24th annual international solid freeform fabrication symposium, 2013, pp. 1015–1023
8. J. Gu, B. Cong, J. Ding, S. W. Williams, and Y. Zhai, “Wire + arc additive manufacturing of aluminium,” in SFF Symposium, 2014, pp. 451–458
9. Cong B, Ding J, Williams S (2015) Effect of arc mode in cold metal transfer process on porosity of additively manufactured Al-6.3%Cu alloy. Int J Adv Manuf Technol 76(9–12):1593–1606
10. D. E. Cooper, “The high deposition rate additive manufacture of nickel superalloys and metal matrix composites,” University of Warwick, 2016
11. Xu F, Lv Y, Liu Y, Shu F, He P, Xu B (2013) Microstructural evolution and mechanical properties of Inconel 625 alloy during pulsed plasma arc deposition process. J Mater Sci Technol 29(5): 480–488
12. Youheng F, Guilan W, Haiou Z, Liye L (2017) Optimization of surface appearance for wire and arc additive manufacturing of Bainite steel. Int J Adv Manuf Technol 91(1–4):301–3013
13. Kapil S, Legesse F, Kulkarni P, Joshi P, Desai A, Karunakaran KP (2016) Hybrid-layered manufacturing using tungsten inert gas cladding. Prog Addit Manuf 1:79–91
14. Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P (2016) Wire + arc additive manufacturing. Mater Sci Technol 32(7):641–647
15. Martina F, Mehnen J, Williams SW, Colegrove P, Wang F (2012) Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. J Mater Process Technol 212(6): 1377–1386
16. F. Martina and S. Williams, “Wire + arc additive manufacturing vs. traditional machining from solid from solid: a cost comparison,” 2015
17. Sciaky Inc., “Electron beam additive manufacturing (EBAM) technology,” 2016. Available: http://www.sciaky.com/additive-manufacturing/electron-beam-additive-manufacturing-technology. [Accessed: 08-May-2018]
18. F. Vega, “Titanium additive manufacturing—a novel game changing technology,” in Titanium 2014 Conference, 2014, p. 24
19. S. Williams, “Large scale metal wire + arc additive manufacturing of structural engineering parts,” in 69th IIW annual assembly and international conference, 2016, p. 25
20. Suryakumar S, Karunakaran KP, Bernard A, Chandrasekhar U, Raghavender N, Sharma D (2011) Weld bead modeling and process optimization in hybrid layered manufacturing. Comput Aided Des 43(4):331–344
21. D. Ding, “Process planning for robotic wire and arc additive manufacturing,” University of Wollogong, 2015
22. “Fronius International GmbH.” Available: http://www.fronius.com. [Accessed: 08-May-2018]
23. Opderbecke T, Guiheux S (2009) TOPTIG: robotic TIG welding with integrated wire feeder. Weld Int 23(7):523–529
24. P. M. S. Almeida and S. Williams, “Innovative process model of Ti–6Al–4V additive layer manufacturing using cold metal transfer (CMT),” in Solid freeform fabrication symposium, 2010, pp. 25–36
25. “Aceros IMS.” Available: http://www.acerosims.com. [Accessed: 08-May-2018]
26. “Gefertec GmbH.” Available: http://www.gefertec.com/. [Accessed: 08-May-2018]