AA5083 (Al–Mg) plates produced by wire-and-arc additive manufacturing: effect of specimen orientation on microstructure and tensile properties

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Abstract

Among various additive manufacturing (AM) technologies, wire-and-arc additive manufacturing (WAAM) is one of the most suitable for the production of large-scale metallic components, also suggesting possible applications in the construction field. Several research activities have been devoted to the WAAM of steels and titanium alloys and, recently, the application of WAAM to aluminum alloys has also been explored. This paper presents the microstructural and mechanical characterization of WAAM plates produced using a commercial ER 5183 aluminum welding wire. The aim is to evaluate the possible anisotropic behavior under tensile stress of planar elements, considering three different extraction directions in relation to the deposition layer: longitudinal (L), transversal (T) and diagonal (D). Compositional, morphological, microstructural and fractographic analyses were carried out to relate the specific microstructural features induced by WAAM to the tensile properties. An anisotropic behavior was found in regard to the specimen orientation, with the lowest strength and ductility found on T specimens. Reasoning to this was found in the presence of microstructural discontinuities unfavorably oriented with regard to the tensile direction. The results of tensile tests also highlighted an overall good mechanical behavior, comparable to that of conventional AA5083-O sheets, suggesting future use in the realization of very complex geometries and optimized shapes for lightweight structural applications.

Keywords Directed energy deposition · Wire-and-arc additive manufacturing · Aluminum alloys · Tensile testing · Microstructure

1 Introduction

Among the various additive manufacturing (AM) techniques, one of the most suitable for producing large metal components for structural engineering purposes is the so-called wire-and-arc additive manufacturing (WAAM) [1]. WAAM is a direct energy deposition (DED) technology that derives from conventional welding processes and, as for the latter, it can be classified as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and plasma arc welding

(PAW), according to the heat source [2]. The main advantage of this AM-based technology lies upon the possibility to realize complex-shaped large-scale structural elements, with high deposition rates and still ensuring lower overall production costs, including that of feedstock material, if compared to other additively manufactured techniques for metals [3–5]. Furthermore, a wide range of materials can be processed by WAAM, such as steels [6–8], titanium [9, 10] and shape memory alloys [11–13]. Additive manufacturing of aluminum alloys has been extensively investigated considering AM process based on the fusion of a powder bed [14–16]; however, the application of WAAM technologies was also recently investigated. An extensive research effort has been devoted to GMAW and GTAW-based WAAM processes for aluminum alloys [17], also focusing on wrought Al–Mg alloys of the 5000 series [18–23]. The 5000 series of aluminum alloys offers an excellent combination of corrosion resistance, strength, toughness, weldability, and for

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these reasons, it is widely used in shipbuilding, automotive, aerospace and industrial sectors.

Aluminum alloys are also highly appreciated in the building sector for their high strength-to-weight ratio, very long in-service life, low maintenance, and contribution to the energy performance of buildings [24]. The low elastic modulus could be a main limit in the use of Al alloys in building, but it is well known that the global stiffness of structural elements can be improved by a proper design of cross sections characterized by high moment of inertia. This can be achieved by the use of complex-shaped extrudates, often made of the 6000 aluminum alloys series since the use of the 5000 series alloys is limited by their low extrudability. In this view, the WAAM process would help realizing optimized cross-section members of the 5000 series to guarantee a superior stiffness with a minimum amount of material, also gaining the advantage of the superior corrosion resistance of this series by comparison to the 6000 one [25].

Up to date, the research work on WAAM of 5000 series alloys (5083, 5183, 5087, 5356) has been focused on: (1) tensile behavior [18, 19, 21, 26]; (2) microstructural defects induced by the process [17–20]; and (3) possible anisotropic mechanical behavior induced by the process [18, 20, 21, 26].

From literature review, WAAM components made of the 5000 series alloys generally present quite evident microstructural defects and, in particular, large amount of internal gas porosity [17–20]. Indeed, gas porosity is considered one of the major issues concerning WAAM of aluminum alloys [27] and it is mainly ascribable to the large hydrogen solubility in molten aluminum. However, also the vaporization of low-melting alloy elements, such as Mg, should be taken into consideration [28–30]. The problem of gas entrapment can be mitigated by controlling the heat input during the process, for example by adopting the cold metal transfer (CMT) process, a variation of GMAW able to reduce heat input and, thus, hydrogen solubility. However, CMT is a patented process and requires specific equipment. Furthermore, preliminary results of the CMT applied to the Al–Mg alloys also show a significant porosity content [18, 21].

Regarding tensile properties, when considering two different directions of samples extraction (i.e., parallel and perpendicular) from WAAM plates, with regard to the deposition layer, literature results report an almost isotropic tensile behavior [18, 26, 31]. On the contrary, tests carried out on stainless steel WAAM plates show a highly anisotropic behavior [32–34]. Moreover, to the best of the authors knowledge, for Al alloys of the 5000 series, there are no data currently available on the tensile behavior of specimens extracted at 45° with regard to the deposition layer.

Based on the above, the focus of the present study is to investigate the influence of the deposition layer orientation on the tensile properties of AA5183 aluminum plates produced by GMAW-WAAM. To highlight a possible

anisotropic behavior, tensile tests have been carried out on specimens extracted from WAAM plates considering three orientations, being perpendicular (90°), parallel (0°) and diagonal (45°) to the deposition layer. Results of tensile tests are correlated with the results of extensive microstructural and fractographical analyses, aimed at relating the new production process to the specific induced microstructural features and consequently to the final mechanical properties and failure mechanisms. In addition, since surface quality is one of the major drawbacks of additively manufactured components, especially produced by WAAM, profilometric and morphological characterization of the as-printed surfaces was carried out. In fact, proper characterization of the inherent surface roughness of the printed outcomes is crucial to define the as-built mechanical properties [33, 35] for large-scale production and in situ fabrication (for which machining is unfeasible) as well as for their fatigue and corrosion behavior.

2 Experimental procedure

2.1 Material and process

The WAAM aluminum plates (380×380×4 mm³) analyzed in the present work were manufactured and supplied by the Dutch company MX3D [36]. The commercially available aluminum AlMg4.5Mn0.7 welding wire (ER 5183 according to AWS A5.10 designation [37]) supplied by *Oerlikon* [38] was used as feedstock material. GMAW-based process with a standard pulse signal was adopted to build the aluminum plates and the main process parameters are reported in Table 1. According to the scheme in Fig. 1, plates were built in the vertical (*z*) direction by overlapping individual layers of metallic material.

Table 1 Process parameters used for WAAM deposition (courtesy of MX3D [36])

Process parameters	Details	Value
Deposition power	Current	30–50 A
	Arc voltage	14–15 V
Speed	Welding speed	12–15 mm/s
	Wire feed rate	2–3 m/min
	Deposition rate	0.5–2 kg/h
Distance and angle	Layer height	0.5–2 mm
	Electrode to layer angle	90°
Wire	Wire grade	ER 5183
	Wire diameter	1.2 mm
Shield gas	Shield gas type	100% Ar
	Shield gas flow rate	10–20 L/min

Fig. 1 A representative WAAM aluminum plate ($380 \times 380 \times 4 \text{ mm}^3$) and schematic representation of samples extraction directions according to the building direction (z axis) and deposition layer (x axis); in the inset a detail of as-built surface where the deposition layer is highlighted

Chemical composition of WAAM plates was checked by means of quantitative analysis carried out by Glow Discharge Optical Emission Spectroscopy (GDOES, Spectra Analytik GDA-650).

2.2 Mechanical tests

Mechanical characterization of WAAM plates consisted of tensile and hardness tests. Flat dog-bone tensile specimens were machined from the AM plates considering three main directions, with regard to the deposition layer, as represented in Fig. 1: longitudinal (L), transversal (T) and diagonal (D) being parallel, perpendicular and inclined at 45° to the layer, respectively. For each plate, all three directions were tested, so the results of the mechanical characterization represented the overall mechanical performance of the WAAM plates. Tensile tests, performed at room temperature, were carried out on flat specimens, whose geometry and dimensions were chosen according to ISO 6892-1 [39] (gauge length of 160 mm, gauge width of 20 mm and nominal thickness of 4 mm according to ASTM E8/E8M-16a standard [40]) maintaining the as-built surface roughness of the WAAM plates (Fig. 2).

The tensile tests were performed according to ISO 6892-1 [39] on a Metrocom universal testing machine of 500 kN load capacity under displacement control with a loading rate of 2 MPa/s. Strain up to the yield point was measured by a

linear variable displacement transducer (LVDT) of 50 mm gauge length (Fig. 3).

Four specimens for each extraction direction (L, T and D) were tested. Before testing, gauge length dimensions of each specimen were measured by means of digital caliper. Given the inherent surface roughness of the specimens (Fig. 1) due to the printing process, the values of cross-sectional area and thickness used to process the experimental results were taken from volume equivalency, by means of the Archimedes' principle, according to previous literature work on as-built WAAM specimens [32, 33]. The volume-equivalent average values of thickness t and cross-sectional area A of the gauge length were found equal to 4.10 mm and 81.45 mm^2 , respectively. The coefficient of variation of both thickness and cross-sectional area (based on the measures taken for the 12 specimens) is 0.02. Density of WAAM samples was determined by means of volume-based measures taken with a hydraulic scale according to the Archimedes' principle, which resulted to be on average equal to 2640 kg/m^3 , slightly below the typical value of conventionally manufactured

Fig. 3 Tensile test set-up

Fig. 2 Representative flat dog-bone specimen for tensile test (160 mm gauge length, 20 mm gauge width, 4 mm nominal thickness, according to ASTM E8/E8M-16a standard [37])

aluminum alloys for structural applications (2700 kg/m^3 , as suggested also in EN1999 [41]). The result, as will be later discussed, is related to the high porosity content evidenced by microstructural and fractographic analyses.

Elastic modulus (E), yielding stress (calculated as 0.2% proof stress) (YS), ultimate tensile strength (UTS) and elongation to failure ($A\%$) were evaluated from the engineering stress–strain curves. To evaluate the hardness of the WAAM plates, HV_1 Vickers tests (1 kg load, 15 s dwell time) were carried out on metallographic samples extracted from the grip region of tensile specimens and subsequently subjected to grinding and polishing procedures.

2.3 Samples characterization

Surface topography of WAAM plates was analyzed by means of a 3D Digital Microscope (Hirox KH-7700) with the aim of characterizing morphological features peculiar of the aluminum alloys WAAM plates. Waviness and roughness profiles, as well as R_a and R_z values, were evaluated according to the EN ISO 4287 standard [42] by means of a stylus profilometer (Hommelwerke T2000, $5 \mu\text{m}$ tip radius).

Phase composition was determined by X-ray diffraction (XRD, PANalytical Expert PRO with Xcelerator detector) operating at 40 kV and 40 mA. For XRD analysis, Cu-K α ($\lambda = 0.15406 \text{ nm}$) was used as radiation source and scans were carried out from 20° to 90° ($\theta - 2\theta$), with a 0.01° step size and a 10-s dwell time.

A comprehensive macro- and microstructural characterization was performed via Optical Microscopy (OM) and Field Emission Gun Scanning Electron Microscopy (FEG-SEM EDS), using both secondary and back-scattered electrons. According to the scheme reported in Fig. 4, samples for microstructural analyses were extracted from grip regions of L, D and T tensile specimens and the three principal cross sections (lying on x - z , x - y and z - y planes) were considered.

Standard grinding and polishing procedures (ASTM E3 [43]) were used for preparing metallographic samples and, to reveal specific microstructural features, chemical etching was carried out via 30 s immersion in the Keller's reagent (2.5 mL HNO_3 , 1.5 mL HCl , 1.0 mL HF and 95 mL distilled water [44]).

Fracture surfaces of the tensile specimens were first inspected by 3D Digital microscopy and then by FEG-SEM EDS microscopy, for both a general and more detailed characterization. To investigate the crack path, samples extracted close to the fracture surfaces were also subjected to metallographic preparation, as described above, and then analyzed by OM and FEG-SEM.

Fig. 4 Samples for microstructural analyses: schematic representation of samples extraction directions from L, D and T tensile specimens

3 Results and discussion

3.1 Chemical and morphological characterization

The results of chemical composition analysis, carried out by GD-OES, are reported in Table 2 and compared to the nominal composition of the ER5183 feedstock wire, as provided by the supplier [38], and to the nominal composition of AA5083 alloy [25], of which the ER5183 wire is the common filler material. Results show that, by comparison to the feedstock wire, WAAM plates exhibited a higher content of the main alloy element (Mg) and a lower presence of Mn; however, these values fall within the range of AA5083. It is worth noticing also that no trace of Si or Cu, nominally present in the wire and in the nominal composition of the AA5083 alloy, was detected on samples extracted from the as-built WAAM plates.

As concerning morphological characterization, it can be inferred that the surface of WAAM plates is characterized by a high roughness and a marked waviness, inherent of the process itself that consists of subsequent deposition of thick (1–2 mm) layers of molten material [45]. Evidence can be found in the representative waviness profile measured by a stylus profilometer along the building direction (z axis) on the surface of WAAM plates (Fig. 5a), where it is possible to recognize a cyclic repetition of peaks and valleys, consistent with the layer deposition thickness (0.5–2 mm, Table 1), being the maximum distance between the highest peak and the lowest valley

Table 2 Chemical composition of WAAM aluminum plates (mean value and standard deviation) measured by GD-OES, compared to the nominal composition of the feedstock wire ER5183 provided by the supplier and AA5083 alloy [25]

	Elements (wt%)								
	Al	Mg	Mn	Fe	Zn	Ti	Cr	Si	Cu
WAAM plates									
Mean	Bal	4.876	0.614	0.097	0.032	0.086	0.042	–	–
SD		±0.047	±0.013	±0.003	±0.002	±0.003	±0.001		
Wire	Bal	4.5	0.8	0.1	–	0.1	0.1	0.3	0.1
AA5083	Bal	4.0–4.9	0.4–1.0	0.4	0.25	0.15	0.05–0.25	0.4	0.1

Where a specific range is not reported, value has to be considered as maximum admissible content

Fig. 5 Profilometric analyses of WAAM plates surface: **a** representative waviness profile along building direction (z axis), **b** corresponding roughness profile

(total height of waviness profile) equal to 357 μm . The corresponding roughness profile is reported in Fig. 5b and reveals a poor surface finishing, characterized by $R_a = 21 \mu\text{m}$ and $R_z = 94 \mu\text{m}$. The high surface roughness can be ascribable to the deposition process, consisting of the subsequent formation of melt pools to realize the single layer, as highlighted by 3D digital micrographs reported in Fig. 6. Figure 6a shows the typical surface of WAAM plates, where both the deposited layers (whose

boundaries are highlighted by yellow dashed lines) and melt pools (highlighted by red dashed lines) can be recognized. In some cases, typical defects of conventional welding process, also reported for WAAM components, were detected on plates surfaces (x – z plane) [44, 45]. For example, Fig. 6b shows a collapsed melt pool, while spatters, consisting of metal droplets ejected from the liquid pool and then solidified in spherical shape, can be seen in Fig. 6c.

Fig. 6 3D digital micrographs of WAAM plates surface (x - z plane): **a** typical surface where dashed yellow lines highlight deposition layers boundaries while red ones highlight melt pools boundaries, **b**

collapsed melt pool underlined by white dashed line, **c** spatters, indicated by white arrows

3.2 Phase composition

The results of X-ray diffraction analyses performed on L, D and T samples are reported in Fig. 7. In the general view of spectra (Fig. 7a), only the α -Al phase can be appreciated. By focusing on the low intensities, in the range of $2\theta = 20^\circ$ – 60° (Fig. 7b), for all three directions, few small peaks can be recognized, that can be attributed to second phases, i.e., intermetallic compounds. In Al–Mg–Mn alloys, main intermetallic compounds are Mg-rich and Fe-rich [46–48] such as Al_3Mg_2 , Al_5Mg_8 , and $\text{Al}_6(\text{Fe},\text{Mn})$. Similar spectra were presented by [49], who studied the effect of Fe and Mn addition to the Al–5Mg–Mn alloy solidified in near-rapid cooling conditions, and by [18] who investigated the AA5183 alloy processed by CMT WAAM. They evidenced the presence of $\text{Al}_6(\text{Fe},\text{Mn})$ and Al_5Mg_8 with peaks located in the range $2\theta = 35^\circ$ – 43° thus, as also supported by FEG-SEM analyses later discussed, low intensity peaks in Fig. 7b can be reasonably attributed to these intermetallic compounds.

3.3 Microstructural characterization

Microstructure of L, D and T samples was first studied by light microscopy (OM) along three main directions, in accordance with Fig. 4, thus allowing assembling the three-dimensional reconstructions shown in Fig. 8. As it can be noticed from this figure, microstructural features such as layer boundaries (yellow dashed lines) and melt pool boundaries (red dashed lines) were differently oriented with reference to the tensile test direction (black arrows) in L, D and T samples and this should lead to a different mechanical response. Extensive macro- (greater than $100\ \mu\text{m}$) and micro-porosity (of about a few of tens of micrometers) were detected in all samples, being the latter one mainly located in correspondence of interlayer regions and melt pool borders, as showed in Fig. 9a. Porosity located in the region adjacent to layer boundaries was also found by other researchers in Al–Mg alloys processed by WAAM [18–21, 31] and it is considered one of the major issues in processing aluminum

Fig. 7 XRD analysis: **a** whole spectra and **b** detail of low peaks in the 20° – 60° portion for longitudinal (L), diagonal (D) and transverse (T) samples

Fig. 8 3D microstructural reconstructions by optical micrographs of longitudinal (L), diagonal (D) and transverse (T) samples. Black arrows indicate tensile direction, yellow dashed lines highlight layer boundaries and red dashed lines highlight melt pool boundaries

Fig. 9 Micrographs of a representative samples showing: **a** porosity and cracks in the interlayer region (yellow dashed line identifies layer boundary, red dashed line indicates a melt pool boundary), **b** detail of cracks

alloys with this technology [2, 27]. Such porosities are commonly spherical in shape, as in the present study, thus suggesting gas entrapment, ascribable to the shielding gas and especially to the hydrogen content, whose solubility in solid aluminum is much smaller than that in the molten state [27, 50]. The hydrogen content is probably derived from surface contamination of melt pool or feedstock wire, such as moisture that reacted with molten aluminum during the process [2]. Consequently, the phenomena can be reduced by a careful storage and handling of the feedstock material and protection of melt region. Microcracks in the interlayer region were also evidenced (Fig. 9b), mainly located in the area subjected to re-heating by the deposition of the subsequent layer. Intergranular cracks were already reported in the literature by Horgar et al. [20] for the WAAM processed AA5183 and they were attributed to the hot cracking phenomenon. It is well known that hot cracking is mainly related to the alloy composition that indirectly refers to the

amount of eutectic present at solidification and, for this reason, this is the main welding problem of the AA5083 alloy, not readily eliminated by simple change in welding procedures [51, 52]. Some studies [53, 54] evidenced the positive effect of titanium (Ti)–boron (B), scandium (Sc), erbium (Er) and zirconium (Zr) additions on mitigating the hot cracking tendency, due to the induced grain refinement. It should be also mentioned that WAAM, even if it is not the AM process with the highest cooling rate, yet results in a very fine microstructure; thus, microcracks are presumably mainly related to porosity content rather than hot cracking. As shown in Fig. 9b, in fact, cracks tend to connect micro-porosities present in the interlayer region.

The analysis at the optical microscope revealed the presence of two main phases: a light one, being the primary α -Al phase, and a dark one corresponding to secondary phases, such as intermetallic compounds (Fig. 10a). Second phases were already detected by XRD analyses (Fig. 7) and

Fig. 10 Microstructural analyses: **a** optical micrographs of an interlayer region, **b** FEG-SEM micrographs showing the two different types of intermetallic compounds (indicated by white arrows), **c** and **d** FEG-SEM EDS analysis of intermetallic compounds

attributed to Fe- and Mg-rich intermetallic phases. In the reason of the high cooling rate that the material experiences during WAAM process [45, 55], these secondary phases were extremely fine [49] and, in addition, they were uniformly distributed in the Al matrix, as already observed by [18]. FEG-SEM analyses (Fig. 10b) evidenced two different types of intermetallic compounds, that have been further investigated by EDS spectroscopy (Fig. 10c, d). In accordance with XRD results, gray equiaxed particles (Fig. 10c) mainly contain Al, Mg and Mn and, thus, were consistent with the Al_5Mg_8 phase, while bright vermicular particles (Fig. 10d), in the reason of the presence of Fe, could be identified as $\text{Al}_6(\text{MnFe})$. It should be noticed that Si was not detected by the mass spectrometric analysis, while EDS revealed a small amount of Si in correspondence of some intermetallic compounds. A possible explanation is that the Si, present in a very low content, segregated in these secondary phases.

3.4 Tensile and hardness data

Vickers hardness measurements HV_1 were performed on metallographic samples and, by referring to Fig. 4, they were conducted on the three main directions considered (x - z , z - y and x - y plane) to determine the overall hardness of samples. Hardness values in the range 79–84 HV_1 were measured in all the

investigated samples, that can be considered comparable values when taking into account the standard deviations (Table 3). The resulting hardness is consistent and even higher than the values reported in literature for similar alloys processed by WAAM [19, 20]. The measured hardness is higher than nominal value reported for conventional AA5083-O sheets, equal to 75 HB that can be conventionally compared to 75 HV [25]. Following the Hall–Petch relationship, the increase in hardness is mainly due to the very fine microstructure resulting from WAAM process.

Figure 11 shows the whole engineering stress–strain curves for specimens L (Fig. 11a), T (Fig. 11b) and D (Fig. 11c). The curves showed in general a quite uniform stress–strain behavior within each specimen orientation, also evidenced in the low standard deviations presented in Table 4. All directions presented a first elastic branch, followed by a post-yielding hardening behavior. Specimen 1D did not reach full rupture but only partial, but given that the trend registered was in line with the other

Table 3 Hardness measurements carried out on samples: mean values and standard deviations

Samples	HV_1
L	84 ± 4
D	81 ± 3
T	79 ± 4

Fig. 11 Stress–strain curves for tensile tests: **a** longitudinal (L); **b** diagonal D; **c** transversal (T) specimens

tests carried out on specimens with the same orientation, it has been taken under consideration as well. Therefore, it should be noted that for this specimen, the values of UTS and $A_{\%}$ have been taken at the failure point corresponding to its partial rupture. It is worth noticing that all three orientations evidenced the phenomenon of serrated yielding or serrated flow, also known as the Portevin–Le Chatelier (PLC) effect, as reported also by [20] for the same WAAM processed AA5083 alloy. This phenomenon is due to plastic deformation instability and can be observed in the stress–strain curves of many metal alloys as repetitive steps, called yielding teeth or serrated yielding [56]. The PLC effect is associated with diffusion of solute atoms occurring at higher rate than speeds of dislocations and is a well-known issue concerning Al–Mg alloys as well as the 5083 alloy [56–58], but it has also been associated with preferential crystallographic orientations [59].

This suggests that the serrated yielding observed in the stress–strain curves of the WAAM specimens is an intrinsic property of the specific alloy but can be also related to the additive process.

The main tensile properties in terms of Young’s modulus (E), yield stress (YS), ultimate tensile strength (UTS), elongation to failure ($A_{\%}$) and strength ratio (YS/UTS) are reported in Table 4, for the three specimen orientations. As far as the influence of orientation is concerned, specimens oriented longitudinally (L) presented the highest values of ultimate tensile strength, up to 300 MPa; whereas, those oriented transversally (T) presented the lowest values, of around 200 MPa. These latter ones also showed the lowest values of elongation to failure, of about 7%, which is less than half of the average value for both orientations L and D. Young’s modulus values ranged from 66 to 86 GPa, being the lowest for specimens D and the highest for specimens

Table 4 Summary of tensile tests results (in bold: mean values and standard deviations)

Specimen ID	E (GPa)	YS (MPa)	UTS (MPa)	A _g (%)	YS/UTS
1-L	86	144	304	18	0.47
2-L	75	143	295	17	0.48
3-L	88	145	292	22	0.50
4-L	71	141	290	21	0.49
μ	80 ± 8	143 ± 1	295 ± 5	20 ± 2	0.48 ± 0.01
1-D	64	115	265	16	0.43
2-D	66	131	266	17	0.49
3-D	66	132	259	15	0.51
4-D	68	129	261	16	0.50
μ	66 ± 1	127 ± 7	263 ± 3	16 ± 1	0.48 ± 0.03
1-T	93	125	218	6	0.57
2-T	82	119	206	6	0.58
3-T	63	121	217	7	0.56
4-T	105	127	221	9	0.57
μ	86 ± 15	123 ± 3	215 ± 6	7 ± 1	0.57 ± 0.01

Table 5 Comparison of tensile tests results

	E (%)	YS (%)	UTS (%)	A _g (%)
(D-L)/L	− 18	− 14	− 11	− 18
(T-L)/L	+ 7	− 15	− 27	− 64
(T-D)/D	+ 31	− 1	− 18	− 56

T. Values of strength ratio (YS/UTS) ranged from 0.48 (for both L and D) to 0.57 (for T), further evidencing the influence of orientation on tensile strength values.

The values of the mechanical properties reported in Table 4 indicated overall a quite anisotropic behavior of WAAM aluminum alloy specimens, further confirmed in the ratios presented in Table 5. In fact, the anisotropic trend for yield stress, ultimate tensile strength and elongation to failure is evidenced by the relative differences among the three tested directions. Specifically, T specimens showed the lowest values, with a drop of approximately 27% in the ultimate strength and 64% in the elongation by comparison to L specimens, and 18 and 56%, respectively, if compared with D specimens. The mechanical behavior on T directions was further investigated by analyzing fracture surfaces and, as will be later discussed, was strongly related to the microstructural defects.

The bar charts of Fig. 12 provide a graphical comparison of the three different orientations tested for each investigated tensile property. In particular, the trends showed a marked anisotropic behavior mainly for both ultimate tensile strength and elongation to failure values (Fig. 12c, d), for which in both cases, the highest value is for orientation L and the lowest for T. A similar trend can be observed for

yield stress (Fig. 12b), although the difference among the three orientations is slightly lower. Young's modulus values presented instead a different trend, since specimens L and T exhibited similar values while specimens D showed the lowest one. However, by taking into account the high standard deviations registered for specimens D and L, the values can be considered almost comparable for all directions.

The different mechanical response of the three orientations will be explained when analyzing the results of fracture surfaces characterization, reported in the next section.

A summary of results found in the literature for the additively manufactured aluminum alloys of the 5000 series is presented in Table 6, including reference values from ASM Handbook [25]. It is worth noticing that only L and T specimens were generally considered in the literature, while no data are reported on specimens D, with 45° orientation to the deposition layer.

By comparing the results of the present study with the outcomes of previous experiments on similar WAAM processed aluminum alloys, it can be noticed that in general yield stress and ultimate tensile strength values are in line with the results of the present work. However, greater values of elongation to failure for specimens T were presented in literature than values obtained in the present campaign. It is worth mentioning that only one reference [20] declared values of Young's modulus, and for L specimens only, which resulted on average in line with the experimental results reported in the present study.

It is worth noting that the values of tensile strength and elongation measured on L specimens were higher than those reported for the conventionally manufactured thin (1.2–6.3 mm) sheets of the 5083-O alloy. D specimens exhibited values on average in line or slightly lower than the standard requirements. On the other hand, T specimens differed from the values of the standard alloy especially with regard to the ultimate tensile strength (215 MPa vs 275 MPa) and elongation to failure (7% vs 16%).

3.5 Fracture surfaces

To study the main fracture mechanisms occurred during tensile tests, fracture area have been investigated both at low and high magnification. Low magnification analyses of the lateral view of the fracture area (Fig. 13a–c) suggested that, in case of D and T samples, fracture occurred along a boundary layer; while in case of L samples, fracture crossed over the layers. The same was confirmed by metallographic analyses carried out on polished sections of fracture surfaces, where it can be clearly seen that fracture path followed the boundary between two consecutive layers for samples D and T. The behavior can be explained by referring to microstructural analyses (Sect. 3.3), that revealed defects, such as

Fig. 12 Results of the tensile tests on longitudinal (L), diagonal (D) and transversal (T) specimens cut from WAAM plates according to the scheme in Fig. 1: **a** Young's modulus; **b** yield stress; **c** ultimate tensile strength; **d** elongation to failure

Table 6 Overview of tensile properties of WAAM-produced aluminum alloys of the 5000 series from literature review

	Alloy	Specimen orientation	E (GPa)	YS (MPa)	UTS (MPa)	A _g (%)	References
<i>Present study</i>							
WAAM	5183	L	80	143	295	20	/
		D	66	123	263	16	
		T	86	122	215	7	
<i>Literature review</i>							
WAAM	5356	L	/	115	268	28	[31]
		T	/	115	254	17	
	5183	L	73	145	293	/	[20]
	5183	L	/	/	293	/	
	5087	T	/	/	281	/	[18]
		L	/	142	291	22.4	
		Al5–3.1Mg–2.0Si	L	/	77	176	11
	T	/	77	170	11		
	Al-Mg6	L	/	/	315	/	[21]
		T	/	/	265	/	
<i>Reference values</i>							
Sheet (thickness 1.2–6.3 mm)	5083-O	/	70	125	275	16	[25]

Fig. 13 3D digital analyses of fracture region (x - z plane): **a–c** lateral view for sample L, D and T, respectively; **d–f** corresponding metallographic cross sections. Deposition layers are defined by yellow dashed lines

porosities and cracks, mainly located in correspondence of interlayer regions.

This result was confirmed also by low magnification FEG-SEM investigation (Fig. 14a–c), that evidenced an extensive porosity on fracture surfaces, especially in case of samples T where pores strongly prevailed. The shape of pores on L and T surfaces was almost spherical (Fig. 14d, f); while on D surfaces, it was quite elongated (Fig. 14e). The dimensions of these defects in some case reached 100 μm , but for the most part, they lied in the size range 10–50 μm . During tensile tests, and more in general when a load is applied, microcracks can generate from pores and eventually result in macrocracks, thus reducing the overall mechanical strength of the material [18]. So, if defects are unfavorably aligned with regard to the direction of the applied load, i.e., perpendicularly to the tensile load as for samples T, they can be detrimental for the mechanical strength of the component. With reference to the mechanical tests results (Fig. 12), samples T showed indeed the lowest mechanical properties, in particular in terms of ultimate strength and elongation, while L ones the highest one. Thus, it could be inferred that the orientation of the deposition layer, that determined also the orientation of defects (pores and cracks), in regard to the tensile direction (Fig. 8), played an important role in determining the mechanical response of WAAM aluminum parts. Based on these results, in accordance with the outcomes reported in literature (Table 6), it is preferable to align the

deposition layer with the tensile direction, as for sample L. Mechanical properties of D samples ranged in between those of L and T ones, so this suggests that orienting the layer at 45° to the tensile direction is preferable than 90°.

Observation at higher magnification of the fracture surfaces evidenced the presence of dimples in all tested samples, typical of a ductile fracture (Fig. 15). Dimples were very fine (lower than 10 μm) and equiaxed on samples L (Fig. 15a), coarser but still equiaxed on T samples (Fig. 15b), while slightly elongated on D samples, due to the effect of shear stresses (Fig. 15c). As highlighted in Fig. 15d, e, very small particles (about 1 μm) were found inside dimples. EDS analyses revealed, by comparison with the aluminum matrix, an enrichment of Mg and Fe, respectively, consistent with the intermetallic compounds evidenced by microstructural characterization (Sect. 3.3).

4 Conclusions

In the present work, the assessment of morphological, mechanical and microstructural features of aluminum plates produced by wire-and-arc additive manufacturing (WAAM) using an ER5183 wire was carried out. Aiming to a comprehensive characterization of the WAAM plates, all the analyses were performed on specimens extracted along the parallel (L), diagonal (D) and perpendicular (T)

Fig. 14 FEG-SEM analyses of fracture surfaces (x - y plane): **a–c** low magnification micrographs for samples L, D and T; **d–f** corresponding high magnification details of surfaces

direction, in regard to the deposition layer. Based on the experimental results, the following conclusions can be drawn:

- Chemical composition of WAAM plates complied with the standards for AA5183.
- The deposition process resulted in a layered structure comprised of successive solidified melt pools and the final microstructure of WAAM plates was composed by α -Al phase and fine Fe- and Mg-based intermetallic particles homogeneously distributed in the aluminum matrix.
- Microstructural discontinuities (gas porosity and microcracks) were evidenced by microstructural analyses, especially located in the interlayer regions of all specimens. A consistent porosity was also evidenced on all fracture surfaces and, reasonably, it was the main responsible for the tensile behavior of the WAAM specimens.
- Results of tensile tests evidenced an anisotropic behavior, according to L, D and T orientation. L direction exhibited the highest tensile properties, overcoming values of conventional AA5083-O sheets. Similar values of the conventional alloy were registered for D direction. T direction, instead, was characterized by the lowest mechanical properties.
- The anisotropic tensile behavior was related to the alignment of the deposition layer in relation to the tensile direction, taking into account that microstructural discontinuities were mainly found in the interlayer area. Indeed, specimens T, whose layers are perpendicular to the loading direction, exhibited the lowest mechanical properties while L specimens, whose layers are parallel, the highest ones.

Fig. 15 High magnification FEG-SEM analyses of fracture surfaces: **a–c** dimples morphology for samples L, D and T; **d, e** semi-quantitative FEG-SEM EDS analyses of particles inside of dimples

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing interest.

Availability of data and material Data supporting the findings of this study are available from the corresponding author, [L. T.], upon reasonable request.

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