



Optimization of GMAW welding for additively manufactured aluminium alloys: insights into filler metal, shielding gas, and laser cleaning

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Received: 10 February 2025 / Accepted: 27 April 2025

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Abstract

Additive manufacturing (AM) of aluminium alloys enables complex geometries, reduced waste, and customization but poses challenges when welded with conventionally manufactured parts, primarily due to porosity issues. This study optimizes gas metal arc welding (GMAW), focusing on cold metal transfer (CMT), to join these components. Key factors include filler metal selection, shielding gas, and laser cleaning for surface preparation. Powder bed fusion-laser beam (PBF-LB) parts showed higher porosity than directed energy deposition-arc (DED-Arc) parts due to powder oxidation. ER 5356 (AlMg5Cr) filler metal and pure argon shielding gas improved weld quality, while laser cleaning reduced oxide layers and porosity. The findings highlight parameter optimization's importance in integrating AM and conventional methods for high-performance applications.

Keywords Additive manufacturing · Gas metal arc welding · Hybrid manufacturing · Laser cleaning · Pore belt region

1 Introduction

Additive manufacturing (AM) of aluminium alloys offers several advantages, including the ability to fabricate complex geometries that are difficult or impossible to achieve

with conventional manufacturing. This enables the design of lightweight, high-performance components with enhanced efficiency. By constructing parts layer by layer, AM minimizes material waste, contributing to both sustainability and cost-effectiveness. Additionally, AM enables rapid prototyping and on-demand production, significantly reducing lead times and allowing for greater customization. Aluminium's inherent properties—such as its excellent strength-to-weight ratio, superior corrosion resistance, and high thermal conductivity—make it especially well-suited for demanding applications in industries like aerospace, automotive, and other sectors requiring advanced material performance.

Despite these advantages, it is often not feasible to produce highly complex components entirely through AM, primarily due to financial or operational constraints. As such, integrating AM with conventional manufacturing processes remains critical. The ability to join conventionally and additively manufactured components is essential for bridging the gap between these technologies and realizing their full potential. However, despite the growing interest in AM, there remains a significant gap in knowledge concerning the joining of conventionally and additively manufactured parts.

Nunes et al. [1] conducted a comprehensive review of the weldability of additively manufactured aluminium alloy components. Their findings highlight that the primary

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challenge in this area lies in the application of fusion welding techniques to parts produced by the powder bed fusion-laser beam (PBF-LB) technique. In particular, they identified a porous region near the PBF-LB base material, termed the “pore belt region,” as a critical factor affecting weld quality. This region, as illustrated in Fig. 1, exhibits significant porosity, which complicates the use of conventional fusion welding techniques, such as arc welding, on PBF-LB produced parts. Fusion welding processes with higher energy density, such as laser and electron beam welding, also produce similar porosity, albeit with different distributions under identical welding conditions. The presence of the pore belt region has been observed by many researchers [2–19], and it significantly influences the mechanical properties of the final joint [1].

A key factor contributing to the formation of porosity is the energy density of the welding process. Arc welding, with its lower energy density compared to laser beam welding (LBW), produces a larger molten pool and greater heat dissipation into the surrounding material. This results in a longer solidification time, which allows gas bubbles to rise and coalesce, increasing the likelihood of porosity. In

contrast, solid-state welding processes, which operate with lower heat inputs, have been shown to produce high-quality welds without the presence of internal imperfections like porosity. Solid-state welding methods, such as friction stir welding, are more capable of minimizing porosity, as demonstrated by multiple studies [20–30].

While optimizing welding parameters can reduce porosity in fusion welding, it is unlikely that this issue can be entirely eliminated, especially in PBF-LB parts. Several factors influence the porosity levels in these joints, including the feedstock material used in the AM process [2]. A major difference between PBF-LB and directed energy deposition-arc (DED-Arc) processes is the form of the feedstock material. PBF-LB utilizes powder feedstock, which has a much higher surface area-to-volume ratio than the wire used in DED-Arc. This difference significantly impacts the porosity of the welds, as powders tend to produce higher porosity levels than wire-based feedstock due to humidity and the surface oxide layer. Griffiths et al. [3] demonstrated that welds of PBF-LB aluminium alloys can exhibit up to ten times higher porosity levels than those

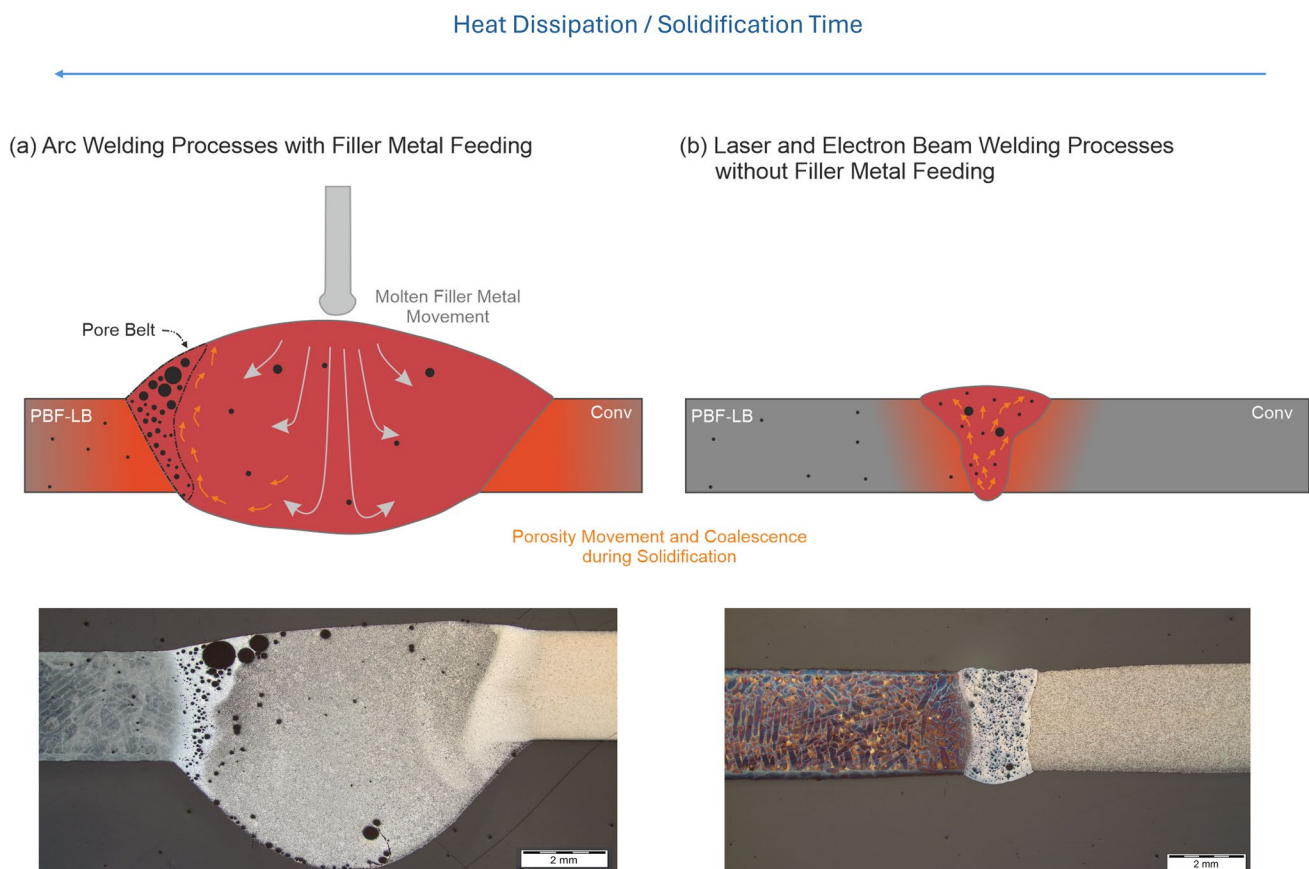


Fig. 1 Mechanism of pore movement and coalescence in the welds of PBF-LB manufactured Al alloys by arc welding **a**, and laser and electron beam **b** welding processes [1]

made with DED-Arc aluminium alloys, highlighting the influence of feedstock material on weld quality.

The powder production method also plays a crucial role in the porosity levels of PBF-LB parts. Powders for PBF-LB are typically produced through gas atomization, which tends to produce powders with higher porosity compared to powders produced by water or centrifugal atomization. The rapid solidification and cooling rates inherent to the gas atomization process result in fine, porous powders [31]. Moreover, the reuse of powder in the PBF-LB process can exacerbate porosity issues. As powder particles are handled and stored, they often develop an oxide layer on their surface. Repeated reuse of the powder can lead to thicker oxide layers, which, in turn, can reduce laser absorption, impairing the quality of the laser-melted material. Fedina et al. [32] reported that reused AlSi10Mg powder exhibited a significant reduction of up to 15% in laser absorbance. Lower laser absorbance results in incomplete melting of powder particles, leading to unmelted regions and voids within the final part, which contribute to increased porosity.

Another factor contributing to porosity is the control of the inert atmosphere in commercial PBF-LB systems [33]. Most systems regulate the atmosphere based on oxygen content rather than creating a vacuum and filling the chamber with argon. This method can lead to hydrogen accumulation within the chamber, which may be absorbed by the deposited material, further exacerbating porosity issues.

To date, only two studies have focused on the GMAW of PBF-LB aluminium alloy parts, specifically Wu et al. [34] and Isilak et al. [35]. Wu et al. [34] investigated the selection of filler metal for welding AlSi7Mg parts produced by PBF-LB, selecting between ER4047 and ER5356. They utilized cold metal transfer (CMT) as a variant of the GMAW process, which, in addition to its widespread use in DED-Arc processes, is particularly well-suited for welding thin aluminium alloy sheets. CMT offers several advantages, including low thermal input, high gap-bridging ability, low dilution, and minimal spatter formation [36, 37]. Wu et al. [34] found a reduction in porosity, a decrease in microsegregation, and an enhanced effect of solid solution strengthening of silicon (Si) in the α -Al matrix when using ER5356 filler metal. The improved mechanical properties, including higher hardness and ultimate tensile strength (UTS), can be primarily attributed to the reduced porosity, refined grain structure, increased solid solution strengthening, and the altered morphology of the Si phase.

A similar approach was explored by Isilak et al. [35], who compared the performance of ER5356, ER4047, and ER4043 filler metals in the lap joint welding of PBF-LB AlSi10Mg parts. While their results suggested that ER4047 was the optimal filler metal due to its satisfactory mechanical properties and high weldability, the joints welded with

ER5356 exhibited significantly improved mechanical and metallurgical properties.

Building on these findings, the present work focuses on optimizing the gas metal arc welding (GMAW) process using the cold metal transfer (CMT) variant. In addition to comparing and selecting two different filler metal alloys, this study also evaluates the influence of various shielding gas mixtures and the innovative use of laser cleaning to enhance the quality of fusion welds in additively manufactured PBF-LB aluminium alloy parts.

Laser cleaning treatment is introduced as a novel preparatory technique for GMAW of additively manufactured aluminium alloy components. The effectiveness of laser cleaning in removing oxide layers and its impact on weld quality are discussed, with a particular focus on its potential to reduce porosity and improve the performance of welded joints. The approach aims to enhance the weld integrity and mechanical performance of AM aluminium components, particularly in applications where material strength and durability are critical.

The integration of advanced preparatory techniques, such as laser cleaning, with optimized GMAW processes holds a significant promise for addressing the challenges associated with welding of additively manufactured aluminium alloy components. By systematically evaluating the effects of filler metal selection, shielding gas mixtures, and surface preparation methods, this study aims to provide a comprehensive framework for improving weld quality and mechanical performance. These advancements are critical for expanding the applicability of AM aluminium alloys in high-performance industries, bridging the gap between additive and conventional manufacturing, and unlocking the full potential of these innovative materials.

2 Materials and methods

The following section presents the welding experiments, organized into three distinct groups. The complete design of experiments (DOE) is provided in Table 2. Three materials were welded: cold rolled EN AW-5083 H111 (AlMg5), PBF-LB AlSi10Mg, and DED-Arc ER 5183 (AlMg4.5Mn). The chemical composition provided by the certificates of the three selected materials is given in Table 1.

The first group focuses on the selection of the filler metal. These experiments involve a comparative analysis based on the filler metal alloy and its manufacturing quality by comparing two filler metals (ER5183 and ER5356) produced by two different manufacturers. The welding is conducted between conventionally manufactured and additively manufactured (PBF-LB) aluminium alloys, as shown in Table 1. Manufacturer B refers to MIGAL.CO [38]. After identifying

Table 1 Chemical composition of conventionally manufactured EN AW-5083, DED-Arc manufactured ER 5183, and PBF-LB manufactured AlSi10Mg Al-alloys

Manufacturing process	Chemical composition in wt%										
	Al	Cu	Fe	Mg	Mn	Ni	Si	Cr	Ti	Zn	Zr
Conv—Cold Rolled EN AW-5083 H111 [AlMg5]	bal	0.05	0.36	4.7	0.7	–	0.19	0.11	0.02	0.01	–
DED-Arc ER 5183 [AlMg4.5Mn]	bal	–	–	4.3–5.2	0.5–1.0	–	–	0.05–0.25	< 0.15	–	–
PBF-LB AlSi10Mg	bal	< 0.01	0.16	0.34	< 0.01	0.02	9.91	–	< 0.01	< 0.01	< 0.01

Table 2 Full design of experiments proposed for the three steps of welding optimization based on filler metal selection, shielding gas selection, and evaluation of laser cleaning prior to the welding

	Sample	Material A	Material B	Filler metal	Cleaning method	Shielding gas
Filler Metal Selection (ER 5183 vs ER 5356 & Manufacturer A vs Manufacturer B)	C–C 01	Conv EN AW-5083	Conv EN AW-5083	ER 5183 (Manuf. A)	Brushed	Ar
	C–C 02	Conv EN AW-5083	Conv EN AW-5083	ER 5183 (Manuf. B)	Brushed	Ar
	C–P 03	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5183 (Manuf. A)	Brushed	Ar
	C–P 04	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5183 (Manuf. B)	Brushed	Ar
	C–C 05	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. A)	Brushed	Ar
	C–C 06	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. B)	Brushed	Ar
	C–P 07	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. A)	Brushed	Ar
	C–P 08	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. B)	Brushed	Ar
Shielding Gas Mixture (Ar vs Ar 30% He)	C–C 06	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. B)	Brushed	Ar
	C–C 09	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. B)	Brushed	Ar 30% He
	C–P 08	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. B)	Brushed	Ar
	C–P 10	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. B)	Brushed	Ar 30% He
Laser Cleaning (Brushed vs LC)	C–C 06	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. B)	Brushed	Ar
	C–C 11	Conv EN AW-5083	Conv EN AW-5083	ER 5356 (Manuf. B)	Laser Cleaning	Ar
	C–P 08	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. B)	Brushed	Ar
	C–P 12	Conv EN AW-5083	PBF-LB AlSi10Mg	ER 5356 (Manuf. B)	Laser Cleaning	Ar
	C–D 13	Conv EN AW-5083	DED-Arc ER 5183	ER 5356 (Manuf. B)	Brushed	Ar
	C–D 14	Conv EN AW-5083	DED-Arc ER 5183	ER 5356 (Manuf. B)	Laser Cleaning	Ar

the optimal filler metal, a similar approach was employed to select the appropriate shielding gas mixture.

Given the challenges posed by weldability and the high sensitivity to porosity, the initial two sets of experiments are conducted on welds between conventionally manufactured materials, which served as a reference. Additionally, experiments are performed on welds between conventionally manufactured parts and those produced via PBF-LB additive manufacturing, with the goal of optimizing welding parameters and conditions.

By using the advanced dynamic wire feed of the CMT variant, model TPS5000 from Fronius, the welding parameters played an important role in optimizing the results. After selecting the optimal filler metal and shielding gas mixtures, the laser cleaning technique is applied prior to welding to enhance the final weld quality and improve the overall achievable results of GMAW for additively manufactured PBF-LB aluminium alloy components. As proof

of concept for welding additively manufactured aluminium alloy components, the optimized technique is also applied to joints between conventionally manufactured parts and those produced via directed energy deposition using electric arc (DED-Arc), demonstrating their applicability and consistency across different additively manufactured material classes.

The laser source used in the experiments was provided by P-Laser Industrial Laser Cleaning [39], with the QF-100 model featuring a focal diameter of 75–85 μm , a wavelength of 1064 nm, a typical power of 100 W, a pulse duration of 100 ns, and a nominal pulse frequency of 100 kHz. The laser cleaning treatment is carried out in all areas in contact with the weld pool; therefore, the top, bottom, and side surfaces of the sheets are to be welded (Table 2).

The various sections of the design of experiments (DOE) will be further illustrated and discussed in their respective parts of the manuscript, with a focus on

evaluation, analysis, and conclusions. All welds were evaluated through metallographic examination using an optical microscope and tensile testing. For internal examinations, cross-sectional samples were etched with hydrofluoric acid (HF) for 10 s, which were then analyzed using the Olympus MX51 optical microscope with Stream Enterprise image analysis software.

Mechanical characterization was performed by extracting samples perpendicular to the weld direction for tensile testing. In order to show its repeatability, three tensile tests were carried out for each welding condition. Both sample extraction and tensile testing followed the procedures outlined in EN ISO 15614–2:2015 [40]. The Instron 8872 servo-hydraulic fatigue testing system, with a force capacity of 25 kN, was used to perform the tensile tests.

Due to the limited availability of additively manufactured parts relative to the extensive design of experiments (DOE) proposed, the joint design shown in Fig. 2 was used. That figure also illustrates the tensile test geometry.

In order to perform a deep analysis on the quality of the filler metals used in the experiments, the surface roughness and the chemical composition were analyzed using the JEOL JSM-7600 F Analytical Ultrahigh Resolution TFEF field emission scanning electron microscope (SEM) equipped with an Oxford Inca Energy Dispersive X-ray Spectroscopy (EDX) system for compositional analysis.

3 Results

3.1 Base materials characterization

The microstructures of the three selected materials exhibit distinct characteristics, which can be attributed to the varying thermal cycles involved in their respective manufacturing processes. The microstructures on vertical and horizontal cross sections are presented in Fig. 3. Due to these differences in microstructure and chemical composition, the mechanical properties of the materials also vary. The average ultimate tensile strengths of conventional EN AW-5083, DED-Arc ER 5183, and PBF-LB AlSi10Mg parts are 311 MPa, 288 MPa, and 436 MPa, respectively.

In PBF-LB, the aluminium alloy microstructure is characterized by very fine grains due to extremely high cooling rates. The grains are often cellular or columnar, typically aligned along the build direction. Some porosity (such as gas pores) and micro segregation can also occur. In DED-Arc, the observed microstructure consists of fully equiaxed grains, with no visible columnar features. This equiaxed grain structure may result from relatively low thermal gradients and significant melt pool convection. In cold rolling, the aluminium alloy experiences plastic deformation, producing elongated, deformed grains aligned with the rolling direction. There is a high dislocation density, and if a subsequent annealing step is applied, the structure can transform into a fine equiaxed grain microstructure due to recrystallization.

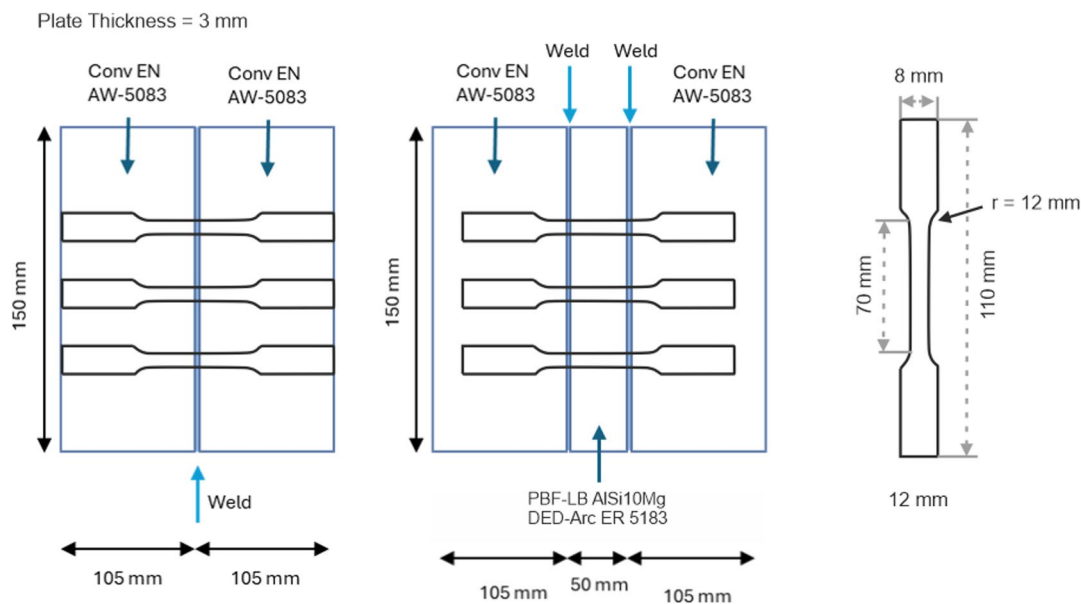


Fig. 2 Joint design for welding plates by GMAW, highlighting the extracted samples for tensile testing

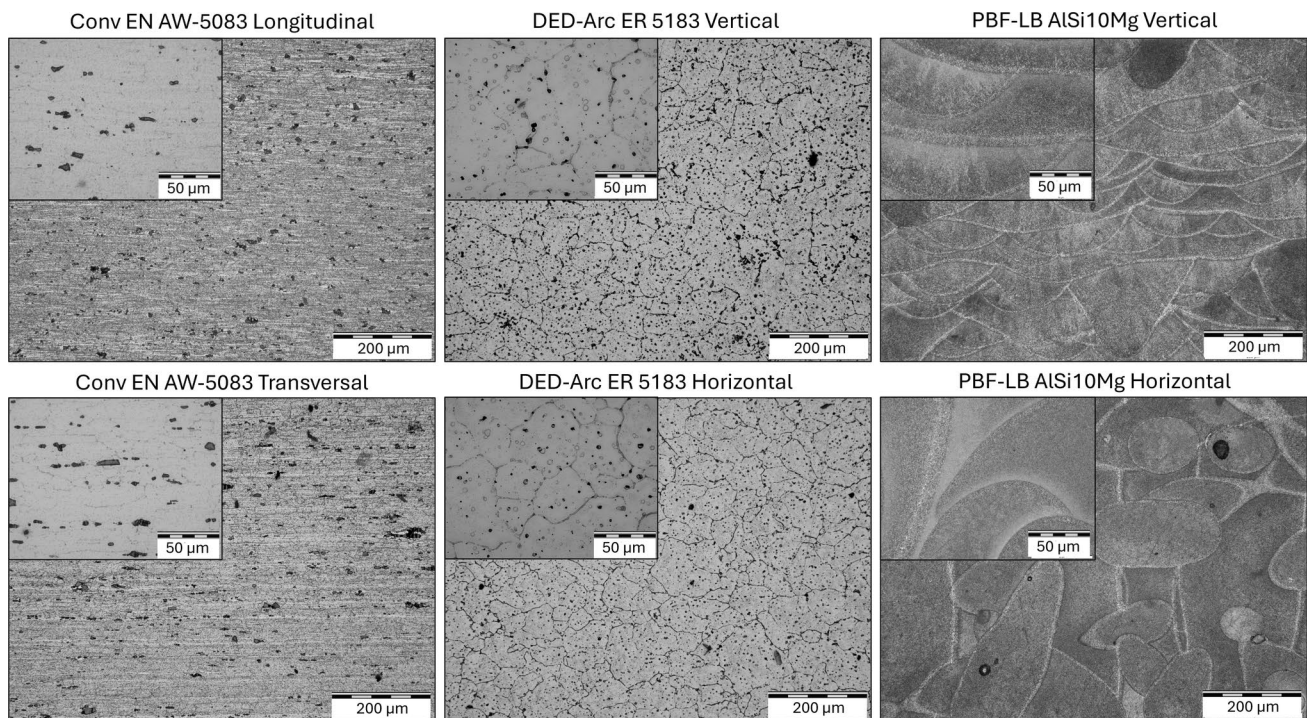


Fig. 3 Microstructures of conventionally (Conv) manufactured EN AW-5083, DED-Arc manufactured ER 5183, and PBF-LB manufactured AlSi10Mg parts in vertical and horizontal directions

The four different filler metals were analyzed using SEM and EDX to detect any anomalies in their chemical composition and surface roughness, as shown in Fig. 4.

In addition to the notably lower surface roughness of the two filler metals produced by Manufacturer B, the chemical composition of both alloys from this manufacturer also demonstrates greater consistency between the outer surface and the inner core. The main difference between the two wires is in their Mg content. The difference in Mg content between the inner core and the outer surface is 0.2–0.3% for Manufacturer A and identical (at the precision of the EDX analysis) for Manufacturer B.

3.2 Filler metal selection based on alloy and manufacturing quality

The quality of the filler wire used in GMAW plays a critical role in determining the overall quality of the weld, particularly when working with materials like aluminium alloys, which are highly sensitive to impurities and process conditions. For aluminium alloys, key factors such as wire surface roughness and chemical composition significantly influence the welding process, weld integrity, and final mechanical properties. These factors are especially important when welding parts produced by AM, where previous studies have demonstrated an exceptionally high sensitivity to porosity [1].

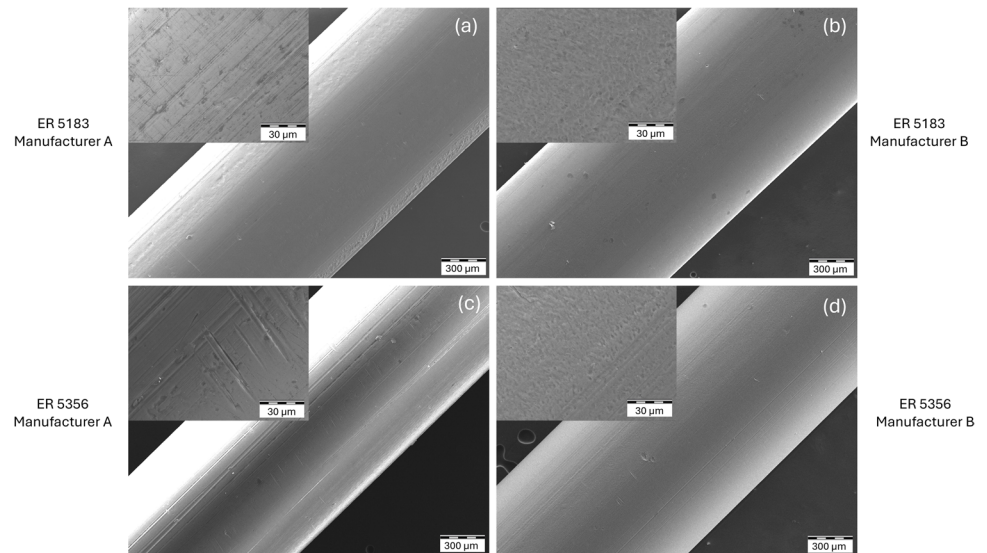
In GMAW, the filler wire electrode is melted to form a weld pool, which subsequently melts the base metal. The surface roughness of the wire, referring to the microscopic texture of the wire's surface, can influence the heat transfer and material deposition from the filler metal to the weld pool, as well as the behaviour of the arc [41]. A similar observation was made by several authors regarding the use of filler wire in DED-Arc techniques for AM of aluminium alloys [42–45]. The macrographs of the cross-sectional welds, along with their corresponding porosity levels, are presented in Fig. 5a.

As indicated by the evaluation of the cross-sections, welds made with the two filler metals from Manufacturer B exhibited lower porosity levels compared to those made with the filler metals from Manufacturer A. Similarly, welds using ER5356 consistently showed lower porosity levels compared to those made with ER5183. Specifically, the use of ER5356 from Manufacturer B compared to the worst-case scenario with ER5183 from Manufacturer A led to a reduction in porosity of 84% and 24% in the welds between conventional-to-conventional materials and between conventional-to-PBF-LB materials, respectively. The same conclusion regarding the selection of filler metals is reinforced by the tensile testing results, as shown in Fig. 6a.

Due to the differing strength properties of the materials, specific strength requirements for each material combination were established in accordance with the EN ISO

Fig. 4 SEM analysis of the four filler metals selected for the optimization experiments.

a ER5183 Manufacturer A.
b ER5183 Manufacturer B.
c ER5356 Manufacturer A.
(ad) ER5356 Manufacturer B,
 and EDX analysis of the four selected filler metals based on the chemical composition of their respective external surfaces and core regions



Chemical Composition Analysis - EDX

		Al	Mg	Mn
ER 5153 Manuf A	Surface	94.0 ± 0.1 %	5.2 ± 0.1 %	0.8 ± 0.1 %
	Inner	94.4 ± 0.1 %	4.9 ± 0.1 %	0.7 ± 0.1 %
ER 5153 Manuf B	Surface	93.8 ± 0.1 %	5.4 ± 0.1 %	0.7 ± 0.1 %
	Inner	94.0 ± 0.1 %	5.4 ± 0.1 %	0.7 ± 0.1 %
ER 5356 Manuf A	Surface	94.7 ± 0.1 %	5.3 ± 0.1 %	-
	Inner	94.9 ± 0.1 %	5.1 ± 0.1 %	-
ER 5356 Manuf B	Surface	95.0 ± 0.1 %	5.0 ± 0.1 %	-
	Inner	95.0 ± 0.1 %	5.0 ± 0.1 %	-

15614–2:2005 standard [46]. This standard stipulates that the tensile strength of the welded test specimens must be equal to or exceed the minimum specified strength of the base material. For dissimilar metal joints, the tensile strength should be at least equal to the minimum specified tensile strength of the base material with the lowest strength, in this case, conventionally manufactured EN AW-5083 [AlMg4.5Mn0.7] which belongs to group 22.4 (ISO/TR 15608:2017 [47]).

In Fig. 6a, b, c and in Fig. 8, the columns with dashed filling represent weld conditions where the acceptance criteria were not met, while the solid columns correspond to tests that achieved satisfactory results. Welds made with filler wires from Manufacturer B consistently achieved higher ultimate tensile strengths compared to those made with filler wires from Manufacturer A. Although the presence of porosity, particularly in the pore belt region, still limits the overall weld quality, the

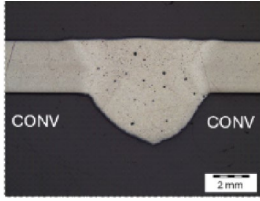
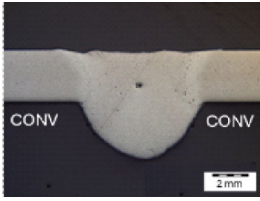
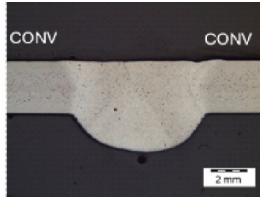
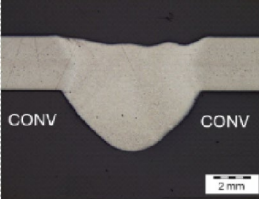
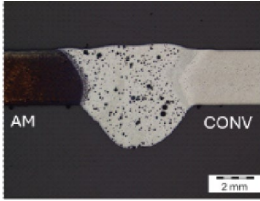
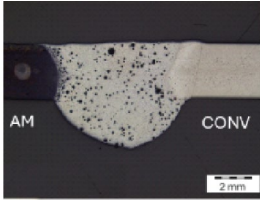
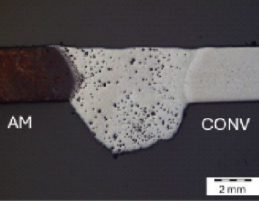
influence of the filler metal alloy and its quality on weld performance is evident. Specifically, the use of ER5356 as the filler metal resulted in a 15% increase in tensile strength for welds between conventionally and PBF-LB additive manufactured parts.

Based on the quality of the filler metal, macrographic inspection, and ultimate tensile strength results, ER5356 produced by Manufacturer B was selected for the subsequent stages of the proposed experiments.

3.3 Shielding gas mixture

The choice of shielding gas is a critical factor in welding aluminium alloys, as it significantly influences weld quality, heat input, and arc characteristics. Pure argon (Ar) is commonly used due to its excellent arc stability, ease of arc initiation, and ability to produce clean, smooth weld beads with minimal spatter. The relatively low ionization energy

a) Filler Metal Selection Based on Alloy and Manufacturing Quality

	Filler Metal			
	ER5183 Manuf. A.	ER5183 Manuf. B	ER5356 Manuf. A	ER5356 Manuf. B
Conv EN AW-5083 + Conv EN AW-5083				
Weld Area	33.4 mm ²	34.6 mm ²	33.4 mm ²	35.3 mm ²
Porosity Level	0.3%	0.2%	0.2%	0.1%
Max Pore Diameter	160 µm	226 µm	110 µm	30 µm
Conv EN AW-5083 + PBF-LB AlSi10Mg				
Weld Area	32.7 mm ²	29.9 mm ²	35.2 mm ²	31.0 mm ²
Porosity Level	5.7%	4.9%	5.6%	4.4%
Max Pore Diameter	479 µm	250 µm	340 µm	210 µm

b) Shielding Gas

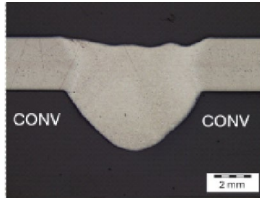
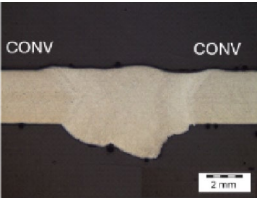
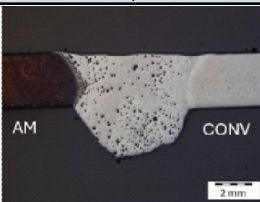
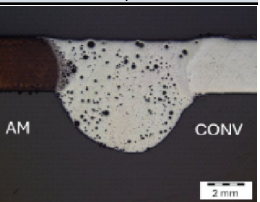
	Shielding Gas	
	Ar	Ar 30% He
Conv EN AW-5083 + Conv EN AW-5083		
Weld Area	35.3 mm ²	32.1 mm ²
Porosity Level	0.1%	0.2%
Max Pore Diameter	30 µm	10 µm
Conv EN AW-5083 + PBF-LB AlSi10Mg		
Weld Area	31.0 mm ²	39.3 mm ²
Porosity Level	4.4%	5.3%
Max Pore Diameter	210 µm	375 µm

Fig. 5 Cross-sections of GMAW welded joints between conventionally, PBF-LB, and DED-Arc manufactured aluminium alloy parts focused on: **a** filler metal selection based on alloy and manufacturing quality, **b** shielding gas mixture, and **c** cleaning method prior to the welding

of argon results in a cooler arc plasma compared to helium, making it particularly suitable for welding thinner aluminium sections, where excessive heat can lead to distortion or burn-through. With pure argon, the arc temperature typically

remains moderate, which allows for precise control of the weld pool and minimizes the risk of oxidation [48].

In contrast, using a mixture of argon and helium (Ar + He) as shielding gas increases both the energy and

c) Cleaning Method

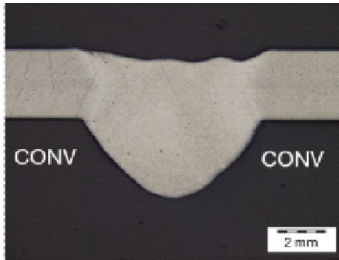
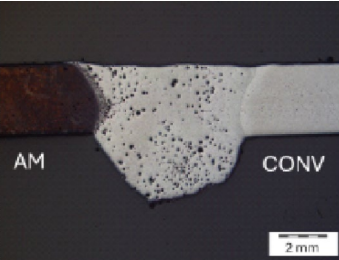
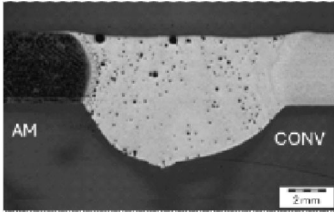
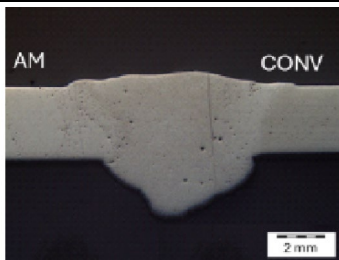
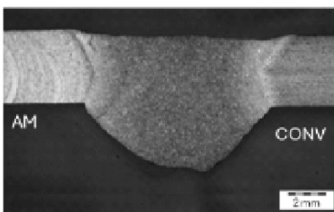
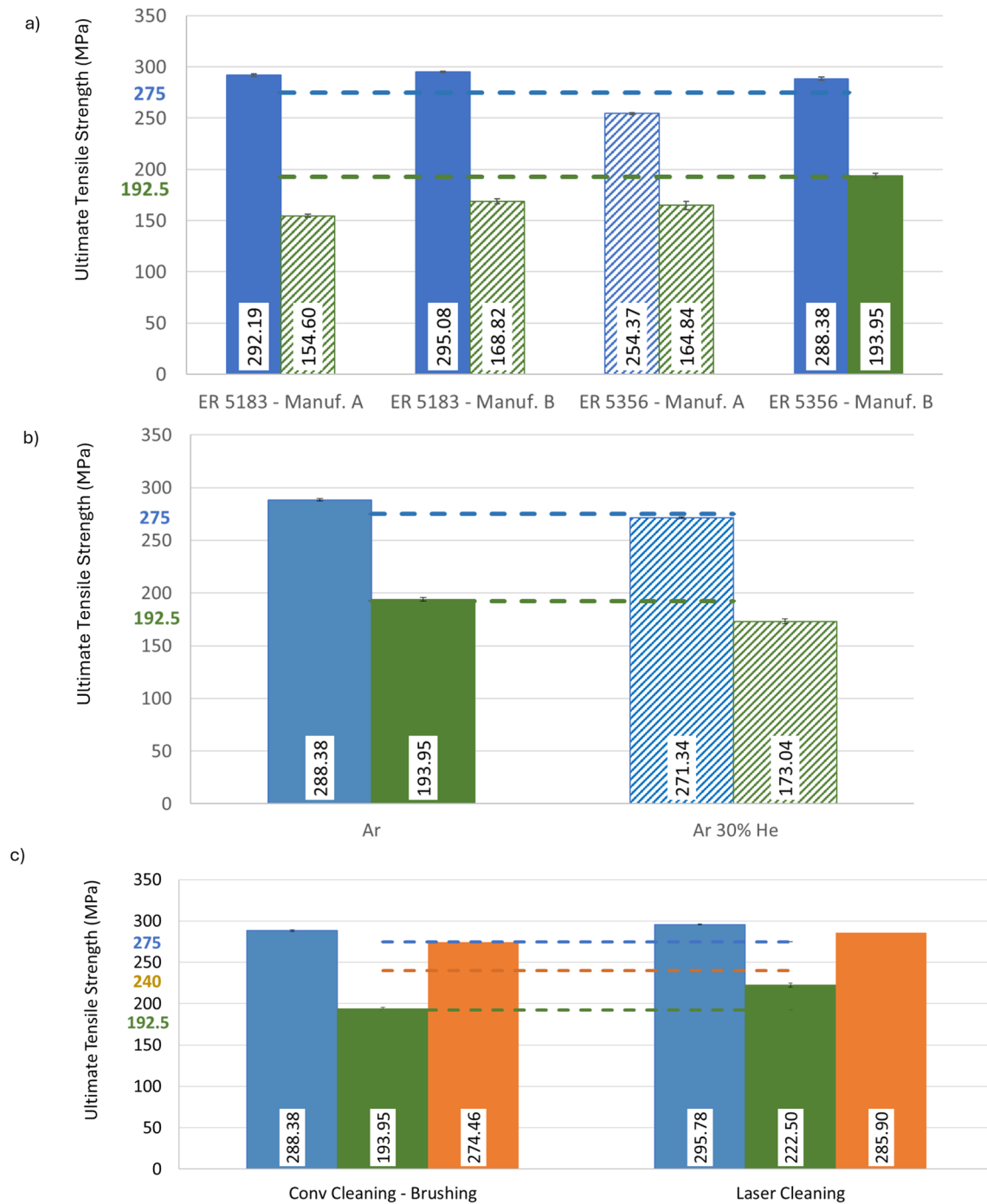
	Cleaning Method	
	Conv Brushing Cleaning	Laser Cleaning
Conv EN AW-5083 + Conv EN AW-5083		
Weld Area	35.3 mm ²	39.0 mm ²
Porosity Level	0.1%	0.1%
Max Pore Diameter	30 µm	10 µm
Conv EN AW-5083 + PBF-LB AlSi10Mg		
Weld Area	31.0 mm ²	40.7 mm ²
Porosity Level	4.4%	3.4%
Max Pore Diameter	210 µm	470 µm
Conv EN AW-5083 + DED-Arc ER5183		
Weld Area	34.9 mm ²	40.3 mm ²
Porosity Level	0.3%	0.1%
Max Pore Diameter	110 µm	10 µm

Fig. 5 (continued)

temperature of the arc. Helium, with its higher ionization potential and thermal conductivity, generates a hotter and more intense plasma, improving heat transfer and arc stability. This elevated arc temperature enhances penetration and heat distribution, which is particularly beneficial when welding thicker aluminium sections or alloys with high thermal conductivity. Additionally, the higher arc temperature allows for faster travel speeds and reduces the risk of incomplete fusion. However, the increased energy can make the weld

pool more difficult to control, and the higher cost of helium, along with more challenging arc initiation, must also be taken into account. As a result, the combination of argon and helium offers a balanced solution, providing a stable arc and improved heat transfer for a wide range of aluminium welding applications [48]. Helium-argon mixtures are preferred for semiautomatic welding with aluminium-alloy electrodes in the 5XXX series and when increased heat input is desirable to achieve lower porosity levels [46].

Conv EN AW-5083 + Conv EN AW-5083 Conv EN AW-5083 + PBF-LB AlSi10Mg Conv EN AW-5083 + DED-Arc ER 5183
 -EN ISO 15614-2:2015 Requirement 1 -EN ISO 15614-2:2015 Requirement 2 -EN ISO 15614-2:2015 Requirement 3



Solid Columns = Approved EN ISO 15614-2:2005

Non-solid Columns = Not Approved EN ISO 15614-2:2005

Conv EN AW-5083 + Conv EN AW-5083 = EN ISO 15614-2:2005 Requirement 1

Conv EN AW-5083 + PBF-LB AlSi10Mg = EN ISO 15614-2:2005 Requirement 2

Conv EN AW-5083 + WAAM ER 5183 = EN ISO 15614-2:2005 Requirement 3

Fig. 6 Tensile testing results of welded joints between conventionally PBF-LB and DED-Arc manufactured parts with conventional brushing cleaning and with laser cleaning prior to welding

To evaluate the effect of different shielding gas mixtures on the welding of AM aluminium alloys, two shielding gas mixtures—pure argon and argon with 30% helium (Ar + 30% He)—were tested for welding joints between conventionally manufactured and PBF-LB additively manufactured aluminium alloys, as detailed in Table 1.

The macrographs of the cross-sectional welds, along with their corresponding porosity levels, are presented in Fig. 5b.

While the use of helium-enriched gas mixtures can offer benefits in aluminium welding, this study observed increased instability and porosity levels when using an Ar 30% He mixture. In the welds between conventionally and PBF-LB additively manufactured parts, the porosity level increased by 21% with the enriched gas mixture. This adverse effect is likely due to the relatively thin sheet thickness, which demands more stable welding conditions and reduced heat input to achieve optimal results and welding properties [45].

Consistent with the observations from the weld cross sections, the mechanical properties were also negatively affected by the use of the Ar 30% He mixture. The ultimate tensile strength values, as shown in Fig. 6b, further illustrate this reduction in weld performance. Therefore, the original shielding gas, Ar, was selected for the next phase of experiments.

3.4 Laser cleaning

Additively manufactured aluminium alloy components present unique welding challenges due to the inherent formation of surface oxide layers and other contaminants that can compromise weld quality. Aluminium naturally forms a thin oxide layer (Al_2O_3) upon exposure to air, which inhibits fusion and is known to contribute to porosity within the weld [49]. These issues can weaken the weld, diminishing its mechanical properties and limiting the performance of the component in demanding applications.

Laser cleaning offers a promising pre-welding treatment for AM aluminium alloys, enabling the precise and controlled removal of the oxide layer without introducing contaminants or damaging the underlying surface [50]. By using laser cleaning to remove this oxide layer prior to welding, the degree of porosity in the weld can be reduced [51], resulting in a stronger bond between the additively manufactured aluminium parts and the filler material. Although this technique remains still innovative for welding additively manufactured aluminium alloy parts, the expected benefits include improved mechanical properties and enhanced overall weld quality.

Laser cleaning modifies the surface roughness of a metal part through the process of ablation, where the intense, focused energy of the laser removes contaminants, oxides, or coatings from the surface by vaporizing or ejecting them. As the laser interacts with the material, it can also induce

localized melting or microstructural changes, leading to a redistribution of surface features [52]. Depending on factors such as laser intensity, pulse duration, and material properties, this ablation process can either increase or decrease surface roughness, as it may expose underlying textures or generate new microtopographies [53].

Using the optimized filler metal (ER 5356 from Manufacturer B) and argon (Ar) as the shielding gas, both conventionally produced EN AW-5083 and additively manufactured PBF-LB AlSi10Mg parts were subjected to laser cleaning prior to GMAW welding.

To assess the effectiveness of laser cleaning, a comparative study was also conducted between conventional brush cleaning and laser cleaning for the welding of additively manufactured DED-Arc ER 5183 parts. These additional experiments serve as proof of concept for the application of the optimized welding parameters and conditions to aluminium parts produced via different additive manufacturing processes. Table 1 provides an overview of the experiments carried out to evaluate the impact of the laser cleaning technique on GMAW welding of AM aluminium alloy parts. Laser cleaning resulted in an increase in surface roughness for all three materials investigated. The corresponding surface roughness values are provided in Fig. 7.

From a chemical composition perspective, the primary objective of laser cleaning is to reduce the oxide layer on the material surface prior to welding. To assess this effect, the samples were analyzed using SEM and EDX. The SEM analysis in Fig. 7a, c, and e reveals the increase in surface roughness previously discussed. The EDX analysis in Fig. 7b, d, and f shows a significant reduction in the oxygen content on the material surface following laser cleaning across all three selected materials. Although EDX is not quantitative in oxygen detection, the result underscores the qualitative trends in the effectiveness of the laser cleaning technique in removing oxide layers.

It is important to note that, due to sample extraction and preparation procedures, SEM and EDX analyses were performed one day after the laser cleaning process. In contrast, the actual welding was carried out within seconds following the laser cleaning. Therefore, one can reasonably expect even more favourable results, with a more complete oxide removal, than those observed in the post-cleaning analyses presented in Fig. 7.

The macrographs of the cross-sectional welds for the three selected materials, along with their corresponding porosity levels, are presented in Fig. 5c. These macrographs and porosity levels clearly demonstrate the benefits of laser cleaning across all three material combinations. The removal, or at least the visible reduction, of the oxide layer facilitates the escape of gas pores to the atmosphere during solidification, resulting in a significant reduction in porosity. Specifically, the porosity of the welds between

Material	Before Laser Cleaning		After Laser Cleaning	
	Ra (μm)	Rz (μm)	Ra (μm)	Rz (μm)
Conventional AW EN-5083	$0.3 \pm 0.0 \mu\text{m}$	$2.0 \pm 0.1 \mu\text{m}$	$4.1 \pm 0.2 \mu\text{m}$	$31.1 \pm 1.3 \mu\text{m}$
PBF-LB AlSi10Mg	$6.6 \pm 0.4 \mu\text{m}$	$46.2 \pm 3.2 \mu\text{m}$	$7.5 \pm 0.4 \mu\text{m}$	$51.2 \pm 3.1 \mu\text{m}$
DED-Arc ER 5183	$2.1 \pm 0.0 \mu\text{m}$	$12.6 \pm 0.2 \mu\text{m}$	$6.3 \pm 0.7 \mu\text{m}$	$40.0 \pm 5.3 \mu\text{m}$

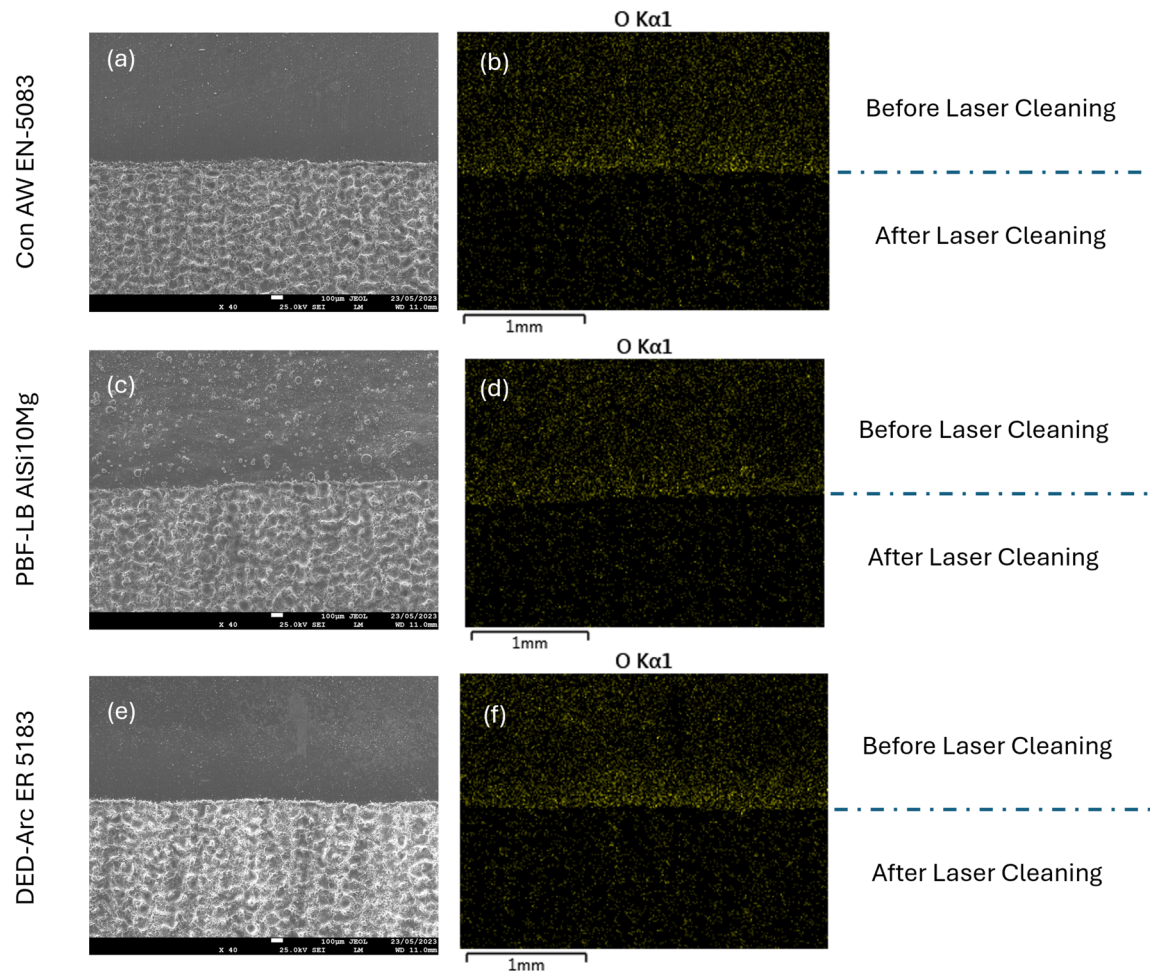
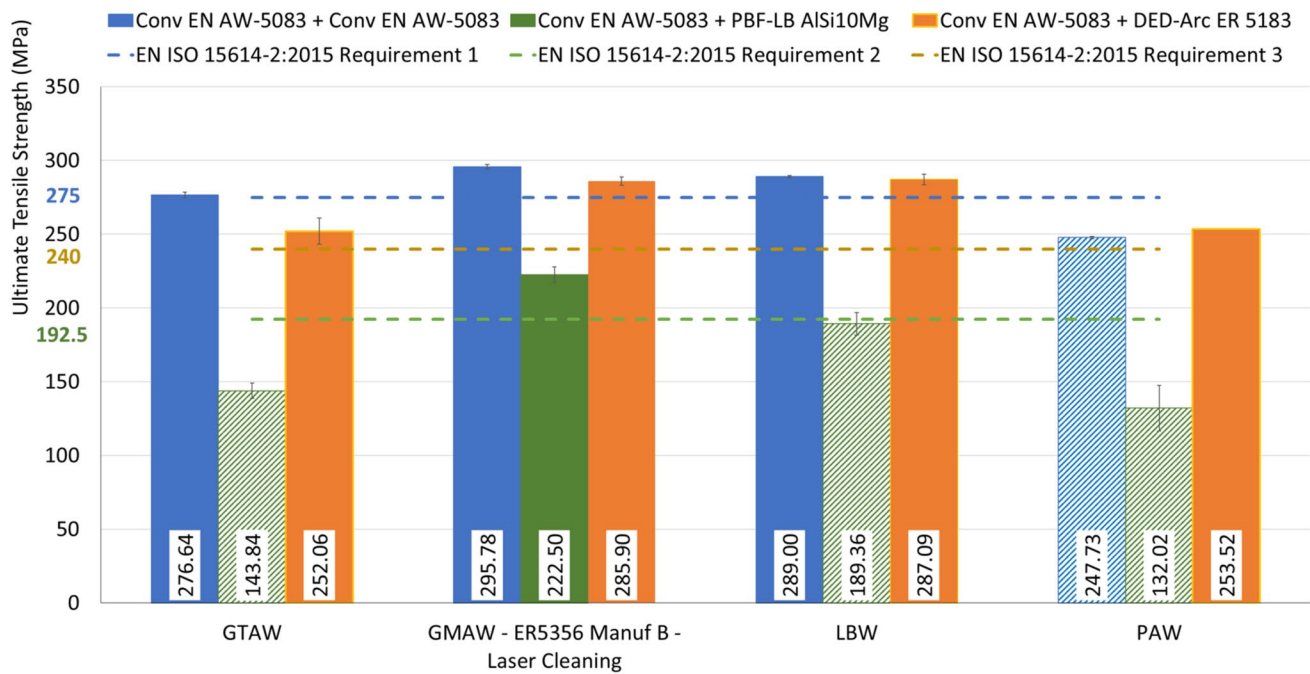


Fig. 7 Laser cleaning influence on the surface roughness of conventional AW EN-5083, PBF-LB AlSi10Mg, and DED-Arc ER 5183 materials, and SEM and EDX analysis, respectively, of **a, b** conventional AW EN-5083, **c, d** PBF-LB AlSi10Mg, and **e, f** DED-Arc ER 5183 materials

conventional parts, between conventional and PBF-LB parts, and between conventional and DED-Arc parts is reduced by 76%, 22%, and 56%, respectively, when laser cleaning is used to prepare the surfaces prior to welding.

These improvements in porosity are reflected in the mechanical properties, with the reduction in porosity leading to higher ultimate tensile strength values. As shown in Fig. 6c, the application of laser cleaning results in a notable enhancement in weld performance, further supporting its effectiveness as a pre-welding treatment.

When compared to other fusion welding techniques reported in previous studies [60] and shown in Fig. 8, it is observed that GMAW, when applied with the optimized welding parameters and conditions, is the only method capable of achieving satisfactory results across all three material combinations, in accordance with the EN ISO 15614–2:2005 standard [46]. It is worth mentioning that the GTAW, LBW, and PAW were performed on plates conventionally cleaned by brushing. While LBW was performed autogenously, GTAW and PAW used ER 5356 from



Solid Columns = Approved EN ISO 15614-2:2005

Non-solid Columns = Not Approved EN ISO 15614-2:2005

Conv EN AW-5083 + Conv EN AW-5083 = EN ISO 15614-2:2005 Requirement 1

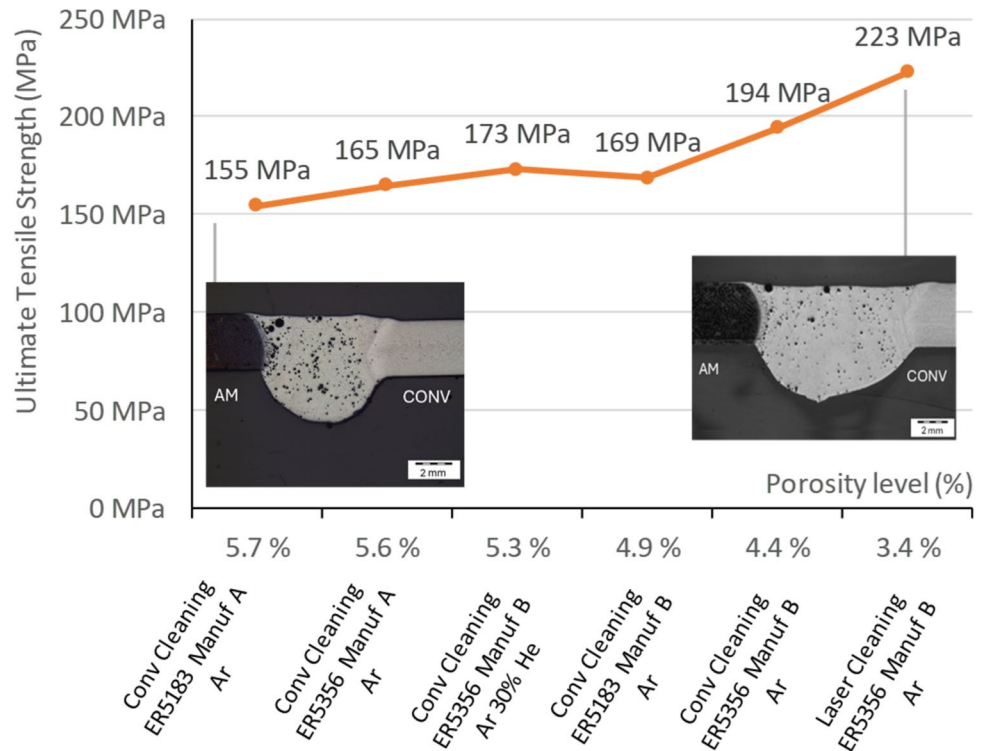
Conv EN AW-5083 + PBF-LB AlSi10Mg = EN ISO 15614-2:2005 Requirement 2

Conv EN AW-5083 + WAAM ER 5183 = EN ISO 15614-2:2005 Requirement 3

Fig. 8 Tensile testing results of GMAW-optimized welded joints between conventionally, PBF-LB, and DED-Arc manufactured parts with laser cleaning prior to the welding, compared to welds between

the same materials by GTAW, LBW, and PAW (complementary data extracted from [54])

Fig. 9 Correlation between porosity level and ultimate tensile strength of the welds between conventional and PBF-LB manufactured aluminium alloy parts



manufacturer A as filler metal in 2.4 mm and 1.2 mm in diameter, respectively.

As observed in the different experiments conducted, there is a direct and clear relationship between porosity level and mechanical properties. In Fig. 9, the different conditions are compared, highlighting the worst (conventional cleaning, ER5183 manufacturer A, Ar) and optimal conditions (laser cleaning, ER5356 manufacturer B, Ar) for the joining of PBF-LB Al alloy parts. A reduction of 40% in the porosity level led to an increase in 44% of the ultimate tensile strength.

The obtained results highlight the critical importance of selecting the appropriate filler metal and shielding gas mixture, as well as employing advanced techniques such as laser cleaning, to achieve the highest possible weld quality in the joining of additively manufactured aluminium alloy components.

4 Final considerations and conclusion

This study systematically explored the challenges and optimization strategies for welding additively manufactured (AM) aluminium alloy components with conventionally manufactured parts, with a focus on the GMAW process using the CMT variant. The findings underscore the critical impact of material properties, welding parameters, and preparatory techniques on weld quality.

Key observations include the significant influence of feedstock characteristics, with PBF-LB components showing heightened sensitivity to porosity compared to DED-Arc due to factors like powder oxidation and inert gas contamination. Optimizing filler metal selection revealed ER 5356, particularly from Manufacturer B, as the most effective choice, achieving enhanced mechanical properties through reduced porosity and improved microstructure. Shielding gas analysis highlighted the superior performance of pure argon for thin aluminium parts, where stability and controlled heat input are paramount. The optimized processing path allows overpassing the requirements of EN ISO 15614-2:2005 standard [44].

The incorporation of laser cleaning prior to welding proved transformative, reducing surface oxides, mitigating porosity, and improving ultimate tensile strength across all evaluated material combinations. This technique demonstrated a clear advantage over traditional methods, underscoring its potential to enhance weld integrity and performance.

Overall, this research provides critical insights into the integration of AM and conventional manufacturing processes through optimized welding. The demonstrated approaches pave the way for broader industrial applications of hybrid manufacturing technologies, enabling high-quality, reliable joints in demanding engineering contexts. Further studies are encouraged to expand on these findings, exploring additional AM processes, materials, and welding techniques to address emerging challenges in the field.

Funding The presented results and discussions on the weldability of additively manufactured aluminium alloys were achieved during the COAMWELD project: “Advanced metal components through optimal combination of additive manufacturing and welding techniques” funded by VLAIO (Flanders Innovation & Entrepreneurship) under Grant Agreement HBC.2020.2994.

Declarations

Conflict of interest The authors declare no competing interests.

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