Wire Arc Additive Manufacturing for Aluminum-Lithium Alloys

Subjects: Materials Science, Characterization & Testing
Contributor: Paula Rodríguez-González, Elisa María Ruiz-Navas, Elena Gordo

Out of all the metal additive manufacturing (AM) techniques, the directed energy deposition (DED) technique, and particularly the wire-based one, are of great interest due to their rapid production. In addition, they are recognized as being the fastest technique capable of producing fully functional structural parts, near-net-shape products with complex geometry and almost unlimited size. There are several wire-based systems, such as plasma arc welding and laser melting deposition, depending on the heat source. The main drawback is the lack of commercially available wire; for instance, the absence of high-strength aluminum alloy wires. Therefore, this entry covers conventional and innovative processes of wire production and includes a summary of the Al-Cu-Li alloys with the most industrial interest in order to foment and promote the selection of the most suitable wire compositions. The role of each alloying element is key for specific wire design in WAAM; this entry describes the role of each element (typically strengthening by age hardening, solid solution and grain size reduction) with special attention to lithium. At the same time, the defects in the WAAM part limit its applicability. For this reason, all the defects related to the WAAM process, together with those related to the chemical composition of the alloy, are mentioned. Finally, future developments are summarized, encompassing the most suitable techniques for Al-Cu-Li alloys, such as PMC (pulse multicontrol) and CMT (cold metal transfer).

Keywords: WAAM ; Al-Li alloys ; wire production ; DED (directed energy deposition)

1. Metal Additive Manufacturing Techniques

Additive manufacturing (AM) is defined as “a process of joining materials to make objects from 3D model data; it is usually layer upon layer, as opposed to subtractive and formative methods of manufacturing” [1]. The techniques in metal AM are divided into direct and indirect processes. The indirect processes require post-forming procedures, while the techniques included in direct AM methods use a high-power laser or electron beam as a heat source and the bonding mechanism is completely melted [2]. In addition, only two direct methods can produce metallic parts: directed energy deposition (DED) and powder bed fusion (PBF), and just one process can create an additively manufactured component from wire feedstock, direct energy deposition [3].

The aerospace industry is one of the major industries and essential players in the AM market [4] and is an impetus for innovation in aircraft materials and design structures. For instance, new aluminum-lithium alloys are being studied due to their low density, high specific modulus, and excellent fatigue, which help reduce aircraft weight and improve performance [5][6]. Therefore, the need for new production processes to obtain complex and lightweight parts combined with the application of new Al alloys has led to a growing interest in the design of new Al parts produced by AM.

Among all the AM processes, directed energy deposition (DED) and powder bed fusion are those most used in the industries for aluminum alloys. Powder-fusing systems are ideal for small and intricate parts with sophisticated and complex features, while wire-fusing systems with DED technology generally have high deposition rates but poor-quality surface finishes [7]. The advantages and disadvantages of using powder and wire in additive manufacturing are described below.

The main advantages of metallic wire are the full use of raw materials free of waste, and the easy handling and storage without any special conditions or requirements, except for a closed packing to keep the surface clean since the surface of metallic wire must be free of impurities. The main disadvantage is the lack of commercial wire with different compositions, as is the case with many high-strength aluminum alloys that are not commercially available as wire. Additionally, the chemical composition of the wire used cannot be modified, in contrast to powder feedstock, that can be mixed with alloying elements. Consequently, only a few compositions can be employed in the final part.

When powder is used in DED techniques, a high-quality one is required to avoid defects in the final part. Thus, high-quality powder is commonly used in order to achieve the nominal composition and reduce the concentration of interstitial elements, such as oxygen and nitrogen, especially those reactive with Ti and Al. However, some current studies use powder blending to tailor the final alloy composition, which provides great flexibility in alloy design [8]. Critical powder features are the packing density and flowability, which are related to the shape and size of the powder particles. The powder should spread evenly across a bed and form a gapless layer. Smooth and spherical particles flow more easily than irregular ones with a rough surface. The most commonly used methods for obtaining powders with these characteristics are gas atomization and plasma atomization.

2. Processes to Produce Metal Wires for AM

Production of wires is achieved by different techniques, such as casting, extrusion, and drawing. The most conventional process is casting, which uses ingots of metallic alloys. It is an elementary method that has been used for many years.

Drawing produces wires from rods, bars or plates. By means of a pulling force, the material goes through a die (a rigid tool with a wear-resistant surface), changing and reducing the cross-section. The process requires cleaning and lubrication before going through a die. Kabayama and Taguchi [9][10] defined the most important features of the drawing process as follows:

- Lubricant (friction coefficient, viscosity, surface treatment)
- Wire properties (yield stress, elastic modulus, strain rate, strain-hardening)
- Die geometry (reduction angle, bearing region length, reduction area, material).

The extrusion process is also an alternative for producing wires. Friction extrusion uses a heat source generated by the rotating friction between the raw material and the dies used in the process under load. When the material exhibits plastic behavior, it is forced to flow through the die.

Researchers at the University of South Carolina (USC) obtained 2050 and 2195 aluminum wires. They used friction extrusion to obtain the preliminary rod, followed by drawing, giving the wires a length range between 1.7 and 2.3 m [11]. They also showed that 15 drawing steps can be needed to obtain the final wire with a 1.6 mm diameter. The 0.1 mm step size was used to reduce 2.7 mm starting diameters to 1.6 mm. Annealing and reannealing can alleviate work hardening caused by drawing to prevent wire breaking in the posterior drawing [12]. The purpose of this work was to design wires by wire arc additive manufacturing (WAAM) and explore the possibility of modifying the characteristics and initial compositions to obtain a specific final wire. This research concluded that post-extrusion drawing could improve the applicability of extruded wires in the following ways:

- Obtaining the desired diameter
- Improving surface finish
- Increasing the total length

Moreover, powder consolidation in the wires is possible. The direct extrusion of powders, which is a simple metal-forming process, is being developed to obtain preliminary rods. In the subsequent step, these rods can be drawn to obtain wires. Some studies have already been carried out for this purpose, obtaining high-strength Al alloy rods by direct extrusion processes [13][14].

Another process to produce wires from powders is the Conform™ process (**Figure 1**). Continuous extrusion or Conform™ is used to transform powders, particulates, or waste products, such as machining swarf, into a rod/wire, by means of severe plastic deformation processes. It is possible to obtain a diameter wire of < 5 mm by means of cold drawing with 100% of the material used.

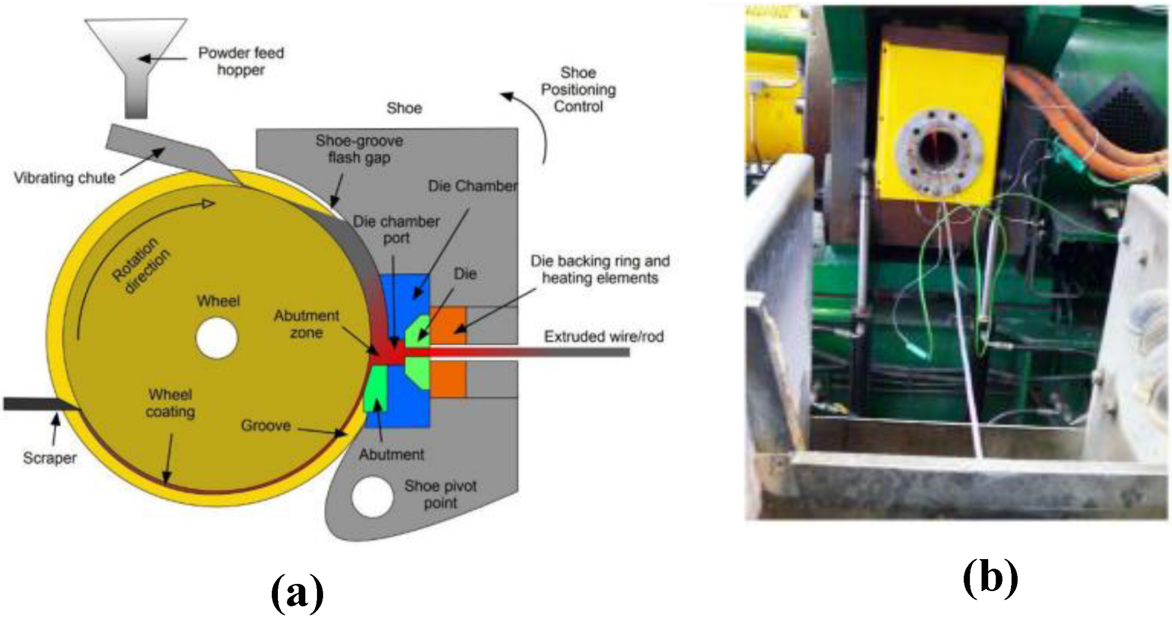

Figure 1. (**a**) Scheme of the Conform machine. (**b**) Extruded wire exiting from the Conform machine and entering the water trough for quenching [15].

WAAM, whose classification is explained below, has been established as a potential technology for the large-scale production of aluminum alloy parts; however, its application is currently limited by the porosity and low mechanical properties attained.

3. Classification of the WAAM Techniques and Their Characteristics

The classification of the WAAM techniques based on the type of welding technique used is shown in **Figure 2**: gas metal arc welding (GMAW), plasma arc welding (PAW), and non-consumable tungsten electrode welding (gas tungsten arc welding, GTAW) [16].

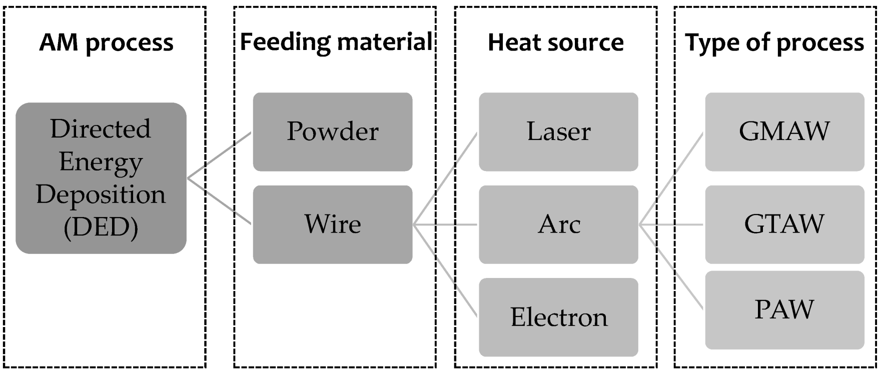

Figure 2. Classification of the DED process [3].

GMAW generates an electric arc as the heat source between the consumable metal electrode and the workpiece. GMAW has two variants: metal inert gas (MIG) and metal active gas (MAG). It is ideal for producing parts on a large scale in short periods of time. These techniques basically consist of an electric arc established between the tip of a consumable wire and the part under the protection of an inert or active gas that protects the weld pool and the adjacent material. The deposition rate is 15–160 g/min [17], which is higher compared to GTAW and PAW.

GTAW and PAW generate an electric arc between the nonconsumable tungsten electrode and the workpiece. The difference with GMAW is that GTAW and PAW require a wire feed that is externally provided. The orientation and the wire feeding direction determine the characteristics and quality of the deposited material [7]. PAW and GTAW have features in common, such as a nonconsumable electrode to establish the electric arc and using an inert shielding gas without filler material [16][17]. However, PAW is a higher energy density process, where excellent stability is achieved due to the arc passing through an orifice between the cathode and anode. Consequently, the weld bead obtained by PAW tends to be narrow since it allows the welding speed to be controlled. The deposition rates are low, approximately 1 g/min, achieving a high-quality surface finish.

On the other hand, the deposition rate for the GTAW technique can be as high as 30 g/min, and the total wall width is thicker (4–15 mm) than the one obtained by PAW (2 mm). The beam's penetration is higher with PAW, causing the fusion of the previously deposited layers and compromising the wall's stability [17].

New techniques have been developed to improve the method according to the material used. A variation of the GMAW process, also known as a modified metal inert gas (MIG), is a cold metal transfer (CMT). CMT, known as the freezing process, compared to the other welding techniques [3], alternates cooling and heating based on a short circuit with high and low current and voltage. It applies noticeably less heat input than traditional GMAW and differs from the latter in its excellent control over penetration, a high wire melting efficiency, and a high deposition rate. Another variant is GMAW in tandem. A tandem uses two independent welding systems, synchrony, and two wires. The energy input and deposition rates are higher.

4. Overview of WAAM

In 1925, Baker [18] carried out studies using an electric arc as a heat source and metal wire as feedstock, but the earliest research into WAAM dates back to 1926, when Baker patented "the use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers" [19]. Baker used a new technique to build a 3D object using welding, the oldest known attempt to use welding technology in additive manufacturing. The same year, Eschholz [20] used an electric arc to deposit metal to create a variety of ornamentation using only a single layer and identified the primary process variables, such as arc current, depth of penetration, travel speed, substrate material, bead width, and height.

In 1935, an electric arc was covered beneath a bed of granulated flux known as SAW (submerged arc welding). The process patented by Jones, Kennedy, and Rothermund [21] required a continuously fed consumable solid or tubular (metal-cored) electrode. In 1947, 20 years later, Carpenter et al. [22] patented the method for metal coating of metal pipes by electric fusion. This invention was used in the production of magnesium retorts, having a carbon steel base clad with a high chromium, high nickel steel alloy coating of one-half inch and a base metal thickness of one inch.

Numerous patents were accepted as the first steps in wire and arc additive manufacturing. In 1950, a process for additive manufacturing with wire deposition was described by Muller Albert et al. [23]. In 1971, Ujiie (Mitsubishi) fabricated a pressure vessel using SAW, electroslag, and TIG, and also employed different wires to provide functionally graded walls. In 1983, Kussmaul [24] used shape welding to manufacture high-quality, large, nuclear structural steel parts with a deposition rate of 80 kg/h and a total weight of 79 tons [25].

In recent years, WAAM techniques have progressed, incorporating post-processing such as heat treatment of parts and research into corrosion behavior. In addition, the integration of rapid prototyping using CMI-WAAM allows bimetallic materials to be obtained and memory alloys to be shaped.

Recent studies have also focused on increasing the deposition rate. Project development by Stewart Williams at Cranfield University has made considerable contributions to the fields of aluminum and WAAM [26][27][28]. The researchers developed the WAAM process capable of creating the most significant part, a six-meter-long, 300-kg, double-sided spar created from aerospace-grade aluminum [29].

5. Overview of Al-Cu-Li Alloys

5.1. Introduction to Al-Li Alloys

The most widely used aluminum alloys in the aerospace industry are the precipitation-hardening Al-Cu alloys (2xxx series) and Al-Zn alloys (7xxx series) due to their high strength-to-weight ratio. Al-Cu-Li alloys are lightweight and ideal for reducing weight and achieving lighter and stronger parts [30]. However, Al-Cu-Li alloys are expensive compared to other aluminum alloys, with a cost that is three to five times higher than the others.

Research into Al-Cu-Li alloys began in the U.S. and Germany in the early 1920s. Although this research was interrupted for many years, in 1980, researchers developed the second generation of Al-Cu-Li alloys [31]. These alloys clearly have improved mechanical properties compared to the first-generation ones. However, the properties still could not meet most aircraft specifications in terms of thermal stability, corrosion resistance, isotropy, and weldability. The third generation of Al-Li alloys was then developed to overcome these issues [30], and some of them were finally used in the aerospace industry. For instance, AA2060 and AA2050 alloys present excellent properties, such as thermal stability, corrosion resistance, and high specific strength [32].

5.2. Al-Cu-Li Alloys and Their Applications

Despite the fact that the development of third-generation alloys has led to new applications in the aerospace industry, their high cost has not allowed them to be fully exploited and implemented in new applications.

Conventional aluminum alloys, such as 2024 and 7055, are still widely used. The most common aluminum alloys for aerospace are 2014, 2024, 5052, 6061, 7050, 7068, 7075, 2219, 6063, and 7475. However, the alloys that are being employed for additive manufacturing techniques are mainly 2524, 7055, 7150, and AA2024, which are currently employed in the Boeing 777.

Nevertheless, some Al-Li alloys, such as 8090, have been proposed to replace AA2014, AA7010, AA2024, and AA7075 in various locations of the EH101 helicopters for structural and nonstructural applications. In particular, in floor installations, brackets, stiffeners, longerons, bulkheads, tail cone skins, flying control structures, door rails, and seat tracks [33]. AA8090 has also been evaluated for cryogenic fuel tanks.

According to Al-Cu-Li alloys, **Figure 3** shows the most used Al-Cu-Li alloys. The compositions can be found in the Aluminum Association, revised in 2018 [34]. These alloys can be divided into two main groups: high-copper and low-lithium, and low-copper and high-lithium.

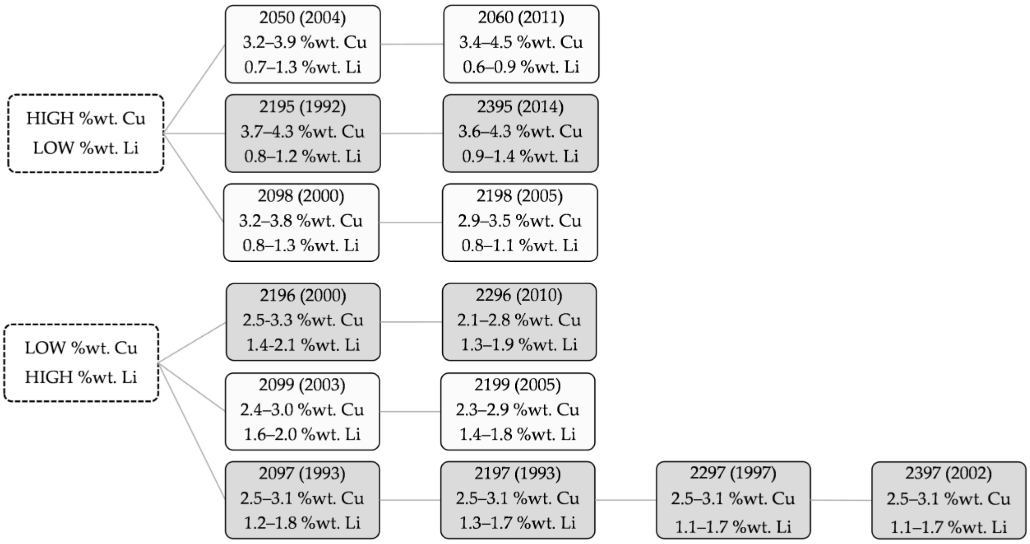

Figure 3. Scheme of the most used Al-Cu-Li alloys.

5.3. Influence of the Main Alloying Elements

The addition of lithium reduces the density of the alloy substantially while increasing its strength more than any other element added. Each increment of 1 wt.% of lithium decreases the density by 3% and increases the elastic modulus (E) by approximately 6% [35][36][37]. Approximately 14–16 at.% (4.7 wt.%) of Li can be wholly dissolved in solid Al at 600 °C [38].

In addition, the low atomic weight of Li (6.94 g/mol) gives it the highest heat capacity compared to any other metal (in terms of J/kg·K). These properties and its relatively good thermal conductivity make Li an appealing high-temperature heat transfer material [38]. It can be a disadvantage because aluminum also presents high thermal conductivity, making it challenging in some undercooling processes.

Al-Li precipitates tend to nucleate heterogeneously on grain boundaries in slowly cooled and overheated alloys. The precipitates sequence can be described as a solid solution α + δ’ + δ → α + δ where δ is the equilibrium phase (AlLi) and δ’ metastable phase (Al_3Li). They can also easily nucleate homogeneously in the matrix, forming spherical precipitates, thanks to their low interfacial energy with the matrix (approximately 14 MJ/m^2) and low precipitation activation energy [39].

The addition of copper improves strength and hardness and reduces corrosion resistance. During aging, the precipitates, solute-rich domains produce the strengthening effect in the alloy. These areas are fully coherent with the matrix, but the atomic spacings are different enough to distort the crystal lattice without discontinuity in the matrix. When the movement of dislocations is obstructed, an increase in strength is attained. Al-Cu systems follow this sequence during heating, where GP corresponds to Guinier–Preston zones [40]:

Super saturated solid solution → Cu clustering → G.P.1 → G.P. 2 (θ’’) → θ’ → θ θ'' is an intermediate precipitate, with a tetragonal structure, which maintains coherency with the Al matrix. When θ' appears, the strengthening is reduced. Further heating causes the transformation from θ' to θ, an equilibrium precipitate, with the composition Al_2Cu.

The addition of magnesium increases strength due to solid solution strengthening. Additions greater than 1.6 wt.% Mg in Al-Cu alloys promote the formation of the metastable, incoherent S' (Al_2CuMg) phase near grain boundaries [41].

The addition of silver and Mg stimulates the nucleation of a fine and uniform dispersion of T1 phase [42]. However, it is essential to take into account that adding elements, such as Ag, makes the alloy more expensive.

The addition of manganese promotes the formation of precipitates of the $Al_{20}Cu_2Mn_3$ phase, which controls grain size and texture during the thermomechanical processing [43]. This helps improve creep resistance and damage tolerance in fracture toughness and fatigue.

Titanium interacts with the Al matrix to form Al_3Ti intermetallic, strengthening in addition to conventional precipitation hardening (such as in the θ' (Al_2Cu) phase). A study shows that adding 0.6% Ti to an Al-Cu-Mg-Ag alloy promotes the precipitation of finer and denser θ' (Al_2Cu) phase. It also promotes the formation of the intermetallic phase Al_3Ti. In contrast, if the addition of Ti is increased to 1.1%, no improvements are observed; the results reveal that a high volume of Al_3Ti phase is likely detrimental to strengthening [44].

Furthermore, it is widely used as a grain refiner. In particular, and regarding the WAAM techniques, Wang, L. et al. [45] studied the Al-Mg alloy for WAAM, using ER5356 as the filling wire and adding Ti powder between layers as a grain refiner. This study reports that the Al3Ti phase provides heterogeneous nucleation cores. The addition of Ti powder during WAAM can promote effective transformation from columnar to equiaxed grains at the interlayer interface. The ultimate tensile strength and elongation increase by 20.25 MPa and 3.13% in the horizontal direction, and by 25.89 MPa and 6.97% in the vertical direction. This study highlights the addition of Ti as a grain refiner as an excellent strategy to obtain isotropic and improved mechanical properties in the WAAM technique.

The addition of zirconium promotes the formation of coherent dispersoid β' (Al_3Zr) and θ' and T1 phases and reduces the solubilities of lithium and magnesium in Al alloys [46]. Zr inhibits recrystallization and grain growth at elevated temperatures [47].

The small additions of Scandium act as a core for the formation of very refined grain microstructures. At the same time, its influence has led to the development of a new alloy, Scalmalloy (AlMgSc), developed by the Airbus Group Innovations [48]. The addition of Sc results in high mechanical properties, good ductility, and specific resistance.

6. General Welding Problems for Aluminum Alloys

The most relevant concerns related to aluminum alloys applied to additive manufacturing techniques are: the oxidation of the material surface due to the formation of Al_2O_3, the solidification shrinkage (compared to ferrous metallic materials) due to the wide solidification temperature range, the high coefficient of thermal expansion (CTE), which leads to cracking phenomena due to high solidification stresses and shrinkage, high reflectivity, high thermal conductivity (which leads to rapid dissipation of heat from the scanned area and requires greater source heat), and the high solubility of hydrogen in liquid aluminum (which leads to pore formation) [49].

7. Suitable WAAM Techniques for Al-Cu-Li Alloys

There is scant use of WAAM in Al-Cu-Li alloys. The first research study carried out focused on post-WAAM treatments to improve properties, such as removing porosity and increasing strength. However, other problems, such as the surface oxide film (alumina), which has a higher melting point than Al, cannot be addressed by those post-treatments. For this purpose, the most recent studies have focused on a variant of the WAAM technique that works with alternating current (AC).

AC mode allows the current waveform (frequency and balance) to be modified. In one half of the cycle, the electrode will be negative (with the base plate positive), and in the next half, the electrode tip will be positive (with the base plate negative). The balance represents the relationship between the penetration (EN, electrode negative) and cleaning action (EP, electrode positive) in the percentage of the cycle. The AC mode is necessary for Al-Li alloys since it allows both actions to be worked on: cleaning the oxide layer and heating a weld bead [50]. During the cleaning, the electrons remove the oxide layer from the aluminum surface, and the shielding gas prevents new oxide from being formed during the welding process.

VP-GTAW (variable polarity gas tungsten arc welding) was applied successfully on an Al-Cu-Li alloy, in particular 2050 wire, and a thin straight wall was deposited [51]. The results showed that the inner layers consisted of refined, equiaxed grains, compared to the interlayers, which consisted of coarse, columnar grains. The secondary phases were θ (Al_2Cu) and δ' (Al_3Li) phases, which were dispersed along the grain boundaries after post-deposited heat treatment. The mechanical properties, such as microhardness, in the heat-treated sample were 141HV, which showed an increase of 98.6% compared to that of the deposited one (71HV), and 55% compared to that of the wire (91HV).

Other variants of GMAW, such as cold metal transfer (CMT), are of particular interest for Al-Cu-Li alloys: CMT-P, CMT-ADV, and CMT-PADV. The CMT-P refers to pulsing recurrent, in which the high pulse current results in a higher heat input compared to the conventional CMT-ADV. The advanced path involves a polarity reversal in the short circuit; and the combination of both is CMT-PADV and pulse-advanced. CMT-PADV, developed by Fronius [17], greatly improves porosity due to the control of the polarity and the pulse cycles [52]. The most significant characteristics are the low thermal heat input, the high deposition rate, and the low spatter, which have been shown to eliminate gas pores due to an oxide cleaning effect.

To evaluate the applicability of the alloy to WAAM techniques, it is necessary to carry out numerous weldability tests. No alloy should be discarded due to its chemical composition or the possibility of the evaporation of elements with low vapor pressure, such as Li or Zn.

The combined effect of CMT, interlayer rolling, and heat treatment on the porosity and oxide cleaning surfaces of aluminum alloy by WAAM is an area of interest for many researchers. The interlayer rolling contributes to reducing porosity and greatly influences the grain structure. When rolling is applied, depending on the load, precipitates break into smaller sizes. After heat treatment, a uniform distribution of refined, smaller grains is attained. For the 2024 alloy, a preliminary study by Fixter et al. [53] showed that, with adequate control of porosity and subsequent heat treatment, the tensile properties could be improved through the WAAM process to levels comparable to those of the standard wrought products. By rolling each added layer, the interpass deformation was found to lead to further refinement in grain size and improved ductility.

New pulse technologies, such as PMC (pulse multicontrol) and PMC mix, are based on pulse-controlled spray arcs optimized by tight control algorithms. The company Fronius has managed to modify the power source platform (TPS) to obtain better welding results. Process stability is improved, heat input is reduced compared to MIG, and there is almost no spatter. Consistently, good penetration is guaranteed, there is less undercutting, and it is possible to weld more quickly and more cost-effectively. PMC Mix technology combines this pulse-controlled transfer to cycles controlled short-circuit, generating a colder phase and reducing the heat input even more [54][55].

Gomes et al. [54] also compared the PMC and CMT techniques for Al alloys. The porosity was smaller than 175 µm in diameter and was dispersed in both cases. Samples by PMC and PMC mix showed a pore fraction of 0.21% and 0.80%, respectively, much lower compared to those by CMT and CMT-P techniques, which showed 0.54% and 1.16%, respectively. These results are particularly interesting for Al-Cu-Li alloys. Regarding mechanical properties, nearly isotropic properties were obtained with a difference of 13 MPa higher in the longitudinal direction of the deposition. Therefore, the small pore fractions and the regularity of the deposits obtained with PMC and PMC Mix, compared with CMT and Pulsed-MIG, point to the benefits of these techniques.

Synchro-feed welding [56] is the most advanced technology and produces a high-quality and high-speed weld without requiring a post-weld cleanup. It incorporates a driven wire feeder within the torch body, advancing the welding wire forward to create an arc. It then retracts the wire while synchronizing with a specialized weld current waveform that extinguishes the arc to make consistent droplet transfer with virtually zero weld spatter. This way, it combines a speedy wire feed control and ultra-low spatters with ultra-low heat input and ultra-low smut. Finally, it results in a very neat, precise weld laid down at a rate of up to 100 inches (254 cm) per minute using a welding current of up to 300 amps [56].

Another improvement was found by Zhang et al. [57] y means of the workpiece vibrating in combination with the VP-CMT technique. The most conclusive results were the refined grain and the homogenized grain distribution with increased vibration. The average grain size decreased due to the over-threshold bending stresses induced by workpiece vibration, breaking the dendrite arms and evolving into more nuclei. In this way, the workpiece vibration was able to significantly reduce the porosity from 6.66% to 1.52% and improve the mechanical properties; the workpiece vibration induced the molten pool stirring, which removed the fine grain zone of the interlayers and the pore defects [57]. Therefore, the combination of vibration and WAAM techniques will help to significantly reduce porosity in Al-Cu-Li alloys.

References

1. ASTM F2792-1; Standard Terminology for Additive Manufacturing Technologies. ASTM International: West Conshohocken, PA, USA, 2012.
2. Guo, N.; Leu, M.C. Additive manufacturing: Technology, applications and research needs. Front. Mech. Eng. 2013, 8, 215–243.
3. Derekar, K.S. A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. Mater. Sci. Technol. 2018, 34, 895–916.
4. Altıparmak, S.; Yardley, V.; Shi, Z.; Lin, J. Challenges in Additive Manufacturing of High-Strength Aluminium Alloys and Current Developments in Hybrid Additive Manufacturing. Int. J. Light. Mater. Manuf. 2020, 4, 246–261.
5. Zhang, X.; Liang, E. Metal additive manufacturing in aircraft: Current application, opportunities and challenges. IOP Conf. Series Mater. Sci. Eng. 2019, 493, 012032.
6. Boţilă, L. Considerations regarding aluminum alloys used in the aeronautic/aerospace industry and use of wire arc additive manufacturing WAAM for their industrial applications. Weld. Mater. Test. 2020, 4, 1–16.
7. Ding, D.; Pan, Z.; Cuiuri, D.; Li, H. Wire-feed additive manufacturing of metal components: Technologies, developments and future interests. Int. J. Adv. Manuf. Technol. 2015, 81, 465–481.
8. Ramosena, L.A.; Dzogbewu, T.C.; Preez, W. Direct Metal Laser Sintering of the Ti6Al4V Alloy from a Powder Blend. Materials 2022, 15, 8193.
9. Kabayama, L.K.; Taguchi, S.P.; Martínez, G.A.S. The influence of die geometry on stress distribution by experimental and FEM simulation on electrolytic copper wiredrawing. Mater. Res. 2009, 12, 281–285.
10. Ikumapayi, O.M.; Ojolo, S.J.; Afolalu, S.A. Experimental and Theoretical Investigation of Tensile Stress Distribution During Aluminium Wire Drawing. Eur. Sci. J. 2015, 11, 86–102.
11. Tang, W.; Reynolds, A.P. Production of wire via friction extrusion of aluminum alloy machining chips. J. Mater. Process. Technol. 2010, 210, 2231–2237.
12. Li, X. Study of Friction Extrusion and Consolidation. Ph.D. Thesis, University of South Carolina, Columbia, SC, USA, 2016.
13. Taleghani, M.A.J.; Navas, E.M.R.; Torralba, J.M. Microstructural and mechanical characterisation of 7075 aluminium alloy consolidated from a premixed powder by cold compaction and hot extrusion. Mater. Des. 2014, 55, 674–682.
14. Rodríguez-González, P.; Ruiz-Navas, E.M.; Gordo, E. Effect of heat treatment prior to direct hot-extrusion processing of Al–Cu–Li alloy. Metals 2022, 12, 1046.
15. BThomas, M.; Derguti, F.; Jackson, M. Continuous extrusion of a commercially pure titanium powder via the Conform process. Mater. Sci. Technol. 2016, 33, 899–903.
16. Li, J.L.Z.; Alkahari, M.R.; Rosli, N.A.B.; Hasan, R.; Sudin, M.N.; bin Ramli, F.R. Review of Wire Arc Additive Manufacturing for 3D Metal Printing. Int. J. Autom. Technol. 2019, 13, 346–353.
17. Rodrigues, T.A.; Duarte, V.; Miranda, R.M.; Santos, T.G.; Oliveira, J.P. Current Status and Perspectives on Wire and Arc Additive Manufacturing (WAAM). Materials 2019, 12, 1121.
18. US423647A; Method of Making Decorative Articles. Baker Ralph: Perth, Australia, 1925.
19. Baker. The Use of an Electric Arc as a Heat Source to Generate 3D Objects Depositing Molten Metal in Superimposed Layers; Baker: Chicago, IL, USA, 1926.
20. US1533239A; Ornamental Arc Welding. CBS Corp.: New York, NY, USA, 1925.
21. US44142A; Electric Welding. Union Carbide Corp.: Houston, TX, USA, 1935.
22. Carpenter, O.; Kerr, H. Method and apparatus for metal coating metal pipes by electric fusion. United States Patent US2427350A, 1943.
23. US2504868A; Electric Arc Welding. Airco Inc.: Punta Gorda, FL, USA, 1950.
24. Kussmaul, K.; Schoch, F.W.; Luckow, H. High-quality large components shape welded by a SAW process. Weld. J. 1983, 62, 17–24.

25. Yan, L. Wire and Arc Additive Manufacture (WAAM) Reusable Tooling Investigation. Ph.D. Thesis, Cranfield University, Bedford, UK, 2012.
26. Gornyakov, V.; Sun, Y.; Ding, J.; Williams, S. Modelling and optimising hybrid process of wire arc additive manufacturing and high-pressure rolling. Mater. Des. 2022, 223, 111121.
27. Chen, X.; Wang, C.; Ding, J.; Bridgeman, P.; Williams, S. A three-dimensional wire-feeding model for heat and metal transfer, fluid flow, and bead shape in wire plasma arc additive manufacturing. J. Manuf. Process. 2022, 83, 300–312.
28. Eimer, E.; Williams, S.; Ding, J.; Ganguly, S.; Chehab, B. Mechanical performances of the interface between the substrate and deposited material in aluminium wire Direct Energy Deposition. Mater. Des. 2023, 225, 111594.
29. Cranfield University. Is This the Largest Metal 3D Part Ever Made? 2016. Available online: https://www.cranfield.ac.uk/press/news-2016/is-this-the-largest-metal--3d-part-ever-made (accessed on 28 December 2022).
30. Rioja, R.J.; Liu, J. The evolution of Al-Li base products for aerospace and space applications. Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 2012, 43, 3325–3337.
31. Skrabec, Q.R. Aluminum in America: A History; McFarland, Incorporated, Publishers: Jefferson, North Carolina, 2017.
32. Jawalkar, C.S.; Kant, S. A Review on use of Aluminium Alloys in Aircraft Components. I-Manag. J. Mater. Sci. 2015, 3, 33–38.
33. El-Aty, A.A.; Xu, Y.; Zhang, S.; Ma, Y.; Chen, D. Abd, Experimental investigation of tensile properties and anisotropy of 1420, 8090 and 2060 Al-Li alloys sheet undergoing different strain rates and fibre orientation: A comparative study. Procedia Eng. 2017, 207, 13–18.
34. Alloys, W.A. International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys Use of the Information; The Aluminum Association, Inc.: Arlington County, VA, USA, 2018. Available online: www.aluminum.org (accessed on 28 December 2022).
35. Schlatter, S. Improvements of Mechanical Properties in Aluminum-Lithium Alloys; Sagina Valley State University: University Center, MI, USA, 2013; pp. 31–46.
36. Molian, P.A.; Srivatsan, T.S. Weldability of aluminium-lithium alloy 2090 using laser welding. J. Mater. Sci. 1990, 25, 3347–3358.
37. Davis, J.R. Aluminum and Aluminum Alloys; ASM International: Almere, The Netherlands, 1993.
38. Russell, A.M.; Lee, K.L. Structure-Property Relations in Nonferrous Metals; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005.
39. Sanders, T.H. Aluminum-Lithium Alloys; Metallurgical Society of AIME: Warrendale, PA, USA, 1981; p. 388.
40. Campbell, F.C. Manufacturing Technology for Aerospace Structural Materials; Elsevier Science: Amsterdam, The Netherlands, 2011.
41. Ion, J. Laser Processing of Engineering Materials: Principles, Procedure and Industrial Application; Elsevier Science: Amsterdam, The Netherlands, 2005.
42. Polmear, I.; Chester, R. Abnormal age hardening in an Al-Cu-Mg alloy containing silver and lithium. Scr. Met. 1989, 23, 1213–1221.
43. Giummarra, C.; Thomas, B.; Rioja, R. New Aluminum alloys for aerospace applications. In Proceedings of the Light Metals Technology Conference, 2007; Volume 2007.
44. Xiao, D.; Wang, J.; Ding, D. Effect of titanium additions on mechanical properties of Al-Cu-Mg-Ag alloy. Mater. Sci. Technol. 2004, 20, 1199–1204.
45. Wang, L.; Suo, Y.; Liang, Z.; Wang, D.; Wang, Q. Effect of titanium powder on microstructure and mechanical properties of wire + arc additively manufactured Al-Mg alloy. Mater. Lett. 2019, 241, 231–234.
46. Abbaschian, R.; Reed-Hill, R.E. Physical Metallurgy Principles; Cengage Learning: Boston, MA, USA, 2008.
47. Safyari, M.; Moshtaghi, M.; Hojo, T.; Akiyama, E. Mechanisms of hydrogen embrittlement in high-strength aluminum alloys containing coherent or incoherent dispersoids. Corros. Sci. 2021, 194, 109895.
48. Airbus-Group, Scalmalloy-RP. 2014. Available online: http://www.technology-licensing.com/etl/int/en/What-we-offer/Technologies-for-licensing/Metallics-and-related-manufacturing-technologies/Scalmalloy-RP.html (accessed on 28 December 2022).
49. Ding, Y.; Muñiz-Lerma, J.; Trask, M.; Chou, S.; Walker, A.; Brochu, M. Microstructure and mechanical property considerations in additive manufacturing of aluminum alloys. MRS Bull. 2016, 41, 745–751.

50. Sarrafi, R.; Kovacevic, R. Cathodic cleaning of oxides from aluminum surface by variable-polarity arc. 2010; Volume 89, pp. 1S–10S.

51. Zhong, H.; Qi, B.; Cong, B.; Qi, Z.; Sun, H. Microstructure and Mechanical Properties of Wire + Arc Additively Manufactured 2050 Al–Li Alloy Wall Deposits. Chin. J. Mech. Eng. 2019, 32, 92.

52. Wang, H.; Jiang, W.; Ouyang, J.-H.; Kovacevic, R. Rapid prototyping of 4043 Al-alloy parts by VP-GTAW. J. Mater. Process. Technol. 2004, 148, 93–102.

53. Fixter, J.; Gu, J.; Ding, J.; Williams, S.W.; Prangnell, P.B. Preliminary investigation into the suitability of 2xxx alloys for Wire-Arc Additive Manufacturing. Mater. Sci. Forum 2016, 877, 611–616.

54. Gomes, B.F.; Morais, P.J.; Ferreira, V.; Pinto, M.; De Almeida, L.H. Wire-arc additive manufacturing of Al-Mg alloy using CMT and PMC technologies. MATEC Web Conf. 2018, 233, 00031.

55. Fronius. Pulse Multi Control: Fronius Has Its Finger on the Pulse os Controlled and Fast Welding. Welding Processes—PMC. 2018. Available online: https://www.fronius.com/en/welding-technology/our-expertise/welding-processes/pmc (accessed on 28 December 2022).

56. DAIHEN Corporation. Synchro-Feed. 2015 OTC Daihen Inc. Synchro-feed GMAW Robotic Welding. Available online: https://www.daihen-usa.com/product/synchrofeed-technology/ (accessed on 28 December 2022).

57. Zhang, C.; Gao, M.; Zeng, X. Workpiece vibration augmented wire arc additive manufacturing of high strength aluminum alloy. J. Mater. Process. Technol. 2019, 271, 85–92.