

Arc-Based Directed Energy Deposition (DED-Arc) of 7xxx Series Al-Zn-Mg-Cu Alloys: A Review

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Abstract

Additive manufacturing (AM) of aluminium alloys has gained increasing relevance in high-performance sectors such as aerospace, defence and automotive. However, processing Al-Zn-Mg-Cu alloys (7xxx series) by fusion-based techniques remains challenging due to hot cracking, porosity, elemental vaporisation and oxide formation. Arc-based directed energy deposition (DED-Arc), also known as wire-arc additive manufacturing (WAAM), has recently emerged as a promising approach to overcome some of these limitations, particularly for large structural components. This review provides a comprehensive overview of recent progress on DED-Arc of 7xxx series alloys, with emphasis on microstructural evolution, defect formation mechanisms and resulting mechanical properties. Reported strategies to mitigate imperfections include advanced arc modes, hybrid laser-arc or ultrasonic assistance, active cooling, interlayer deformation and inoculant additions such as TiC, TiN, Zr and Sc. Studies also demonstrate the influence of post-processing heat treatments in enhancing mechanical strength and fatigue resistance. Research activity in this field has increased significantly in recent years, although investigations remain limited compared to other alloys. Addressing current challenges through

process optimisation, alloy design and qualification efforts will be critical to establish DED-Arc as an industrially viable route for high-performance aluminium components.

Keywords

Additive manufacturing; WAAM; Aluminium alloys; High Strength; Inoculant

1. Introduction

Additive manufacturing (AM) has become one of the most promising technologies in modern industry, introducing layer-by-layer manufacturing techniques that offer environmental benefits, cost efficiency and rapid prototyping capabilities [1]. Its applications span across high-performance sectors such as biomedical [2,3], construction [4,5], automotive [6,7], aerospace [8,9], defence [10] and marine industries [11,12]. AM can reduce production costs by up to 50% for high-strength alloys compared to traditional machining methods [13] and it enables the production of complex geometries with shorter time-to-market, on-demand manufacturing, increased customisation, minimised material waste and superior design flexibility [14,15].

As a result, significant research efforts have been dedicated to investigating the optimisation of this manufacturing technique, exploring its variants, understanding its intrinsic characteristics and addressing its challenges. Aluminium alloys, however, present unique difficulties when applied to fusion welding techniques. Specifically, the 7xxx series of aluminium alloys was long considered non-weldable [16]. Nevertheless, recent advancements in process parameters [17], equipment [18] and alloy composition [19] have partly overcome these limitations, opening new opportunities for the use of these high-strength alloys in welded structures. This review aims to provide a comprehensive overview of additive manufacturing of aluminium alloys using welding technologies, with a particular focus on arc based directed energy deposition (DED-Arc) of Al-Zn-Mg-Cu alloys, which is commonly employed in high-performance sectors such as aerospace, military and automotive industries. Based on a specific Scopus search, Figure 1 reveals that research on the additive manufacturing of Al-Zn-Mg-Cu alloys remained relatively limited until 2020, after which research efforts increased significantly, driven mainly by China, Germany and the United States, particularly in the context of the aerospace industry. Despite this positive trend, studies specifically utilising DED-Arc technologies remain very limited compared to other AM techniques. This highlights the significant untapped potential for further research on DED-Arc processing of Al-Zn-Mg-Cu alloys. This review aims to serve as a resource for future research, addressing existing gaps

and challenges, while contributing to the advancement of aluminium alloy-based additive manufacturing technologies and their industrial applications.

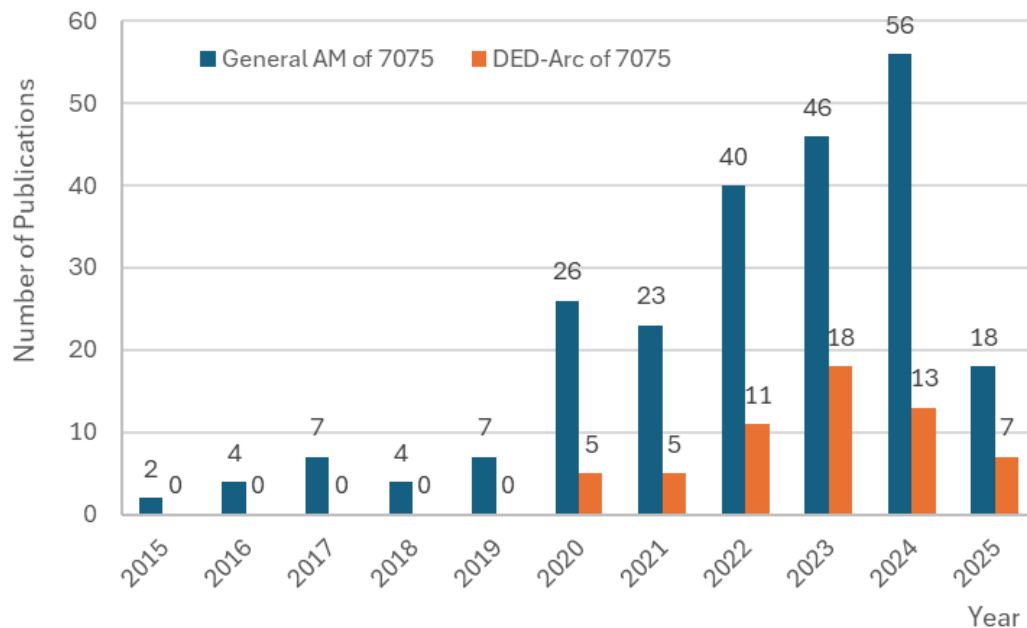


Figure 1 – Number of publications in the Scopus database regarding searches A (Additive Manufacturing + 7075 / Al-Zn-Mg-Cu / Al-Zn) and B (Wire and Arc Additive Manufacturing or DED-Arc + 7075 / Al-Zn-Mg-Cu / Al-Zn).

The most widely used AM processes for metals are Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) technologies. PBF-LB (laser beam) uses a high-powered laser to deposit metal powder layer by layer, making it ideal for producing complex, high-strength metal parts, particularly in industries like aerospace and medical applications. Similarly, PBF-EB (electron beam) operates with an electron beam in a vacuum, typically for materials such as titanium and is also well-suited for high-performance applications [20]. In DED technologies, metal powder or wire is fed into a focused energy source (laser, electron beam, or plasma arc), melted and deposited layer by layer upon solidification. These AM processes offer significant benefits, including enhanced design flexibility, reduced material waste and the ability to create complex geometries that would be difficult or impossible to achieve with traditional metal manufacturing techniques [21]. Figure 2 [22] outlines the differences between the mentioned metal AM techniques. PBF is generally preferred for producing metal parts with higher resolution and superior surface finish, offering greater detail but at the expense of slower build rates compared to DED. This is because DED utilises larger melt pools, created by its thermal heat sources. As a result, PBF is ideal for smaller parts with intricate features, while DED is more suited for producing medium to large parts where fine

details, dimensional accuracy and surface finish are less critical. The choice between powder and wire-based DED further influences the achievable part size.

A key economic factor in this comparison is the cost and utilisation efficiency of the feedstock material. Aluminium alloys used in PBF and in powder-fed DED processes are typically supplied as gas-atomised powders, which are significantly more expensive and reported in vendor catalogues at tens to hundreds of euros per kilogram [23], due to stringent requirements for particle shape, size distribution and purity. Wire-fed DED processes, on the other hand, utilise aluminium alloy wires costing approximately €20 to €40 per kilogram [24], making it a considerably more cost-effective option. Moreover, Wire-DED offers nearly 100% material utilisation, whereas powder-fed DED and PBF processes can lose over 15% of the feedstock during operation [25], further compounding material costs.

Therefore, while PBF offers unmatched resolution, the significantly lower material cost and higher efficiency of Wire-DED make it a compelling choice for producing large structural components in aluminium.

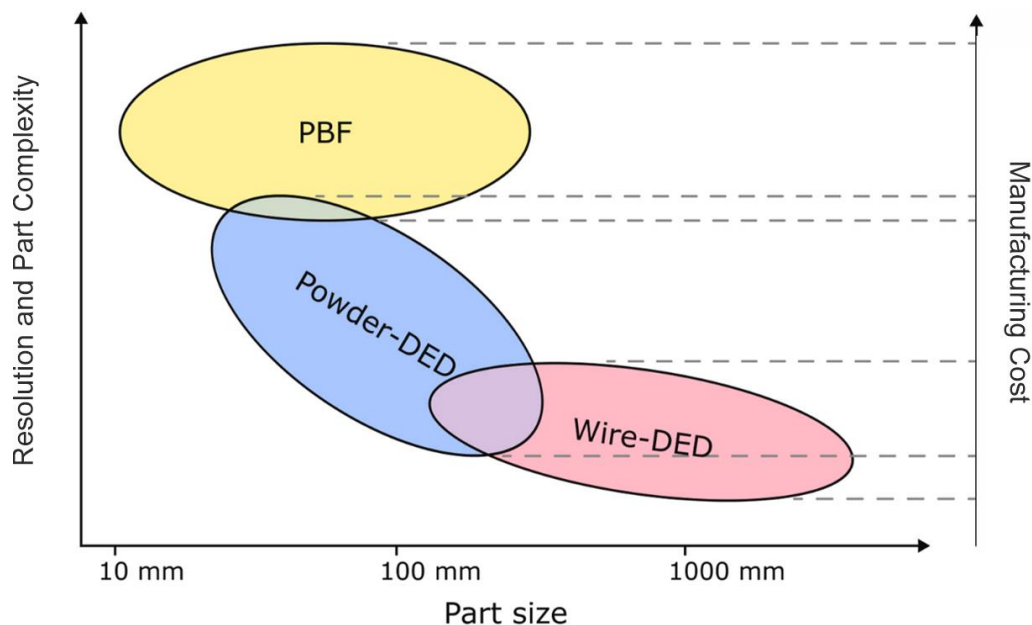


Figure 2 – AM process map considering resolution and part complexity, part size and per-unit printing cost (Adjusted from [22]).

DED-Arc, also referred to as WAAM, uses wire as feedstock material and is particularly advantageous for part repairs, coatings and large-scale component manufacturing [26]. It is based on welding processes to deposit material layer by layer, enabling the creation of three-dimensional (3D) parts [27]. The process involves feeding a metal wire into a melt pool generated by an electric arc between an electrode and the workpiece. As the melt pool solidifies,

successive layers are deposited, gradually building up the final part. DED-Arc presents several key advantages that make it a compelling option for various industrial applications. One of the primary benefits is its ability to produce large, high-strength components with significantly reduced material waste compared to traditional manufacturing methods [28]. Furthermore, DED-Arc supports a wide range of materials, including metals such as steel, titanium and aluminium alloys, making it versatile for industries like aerospace, automotive and construction. The process is also characterised by high deposition rates, enabling faster production times, particularly for large components, which improves cost-effectiveness, especially when manufacturing bulky parts that would otherwise be expensive using conventional methods [29]. Another significant advantage of DED-Arc is its ability to produce customised geometries, allowing for the creation of complex shapes that may be challenging or unfeasible (due to material losses) compared to traditional machining [28]. Additionally, DED-Arc has a lower energy consumption than other AM processes, resulting in lower material and process costs [30]. The ability to repair or modify existing components by adding material through DED-Arc further enhances its appeal for both manufacturing and maintenance applications [31]. These benefits, combined with its scalability, position DED-Arc as a promising and practical solution for producing durable, tailored parts across a variety of industries.

Despite its advantages, DED-Arc also presents certain challenges:

- generation of residual stresses and warping due to the high heat input during the deposition process, which may require additional post-processing steps, such as heat treatment, to correct or improve the as-built characteristics [32];
- geometric accuracy of parts produced by DED-Arc can be lower compared to other AM techniques (in particular when compared to PBF techniques), which may impact the final dimensions and functionality of the part;
- irregular surface finish, which may necessitate additional finishing processes, such as grinding or polishing, to achieve the desired quality [33];
- variations in cooling rates, directional heat dissipation and the cyclic layer-by-layer deposition method can result in inconsistent and heterogeneous material properties, potentially affecting the mechanical strength and fatigue resistance of the final part.

Some researchers have developed DED-Arc variants to minimise these challenges, such as the use of active cooling systems [34] and in-situ forging for grain refinement [35]. While DED-Arc excels in producing large components, it is less suitable for fine details and intricate features, which can be more effectively achieved using techniques like PBF-LB and PBF-EB. Finally, the need for post-processing to address surface finish, residual stresses and geometric inaccuracies can add time and cost to the overall manufacturing process, potentially reducing DED-Arc's efficiency for certain applications.

Figure 3 illustrates the most common anomalies observed in the DED-Arc process for different materials. Despite these challenges, ongoing research and technological advancements continue to enhance DED-Arc's capabilities, positioning it as a promising method for industries requiring large, high-performance components.

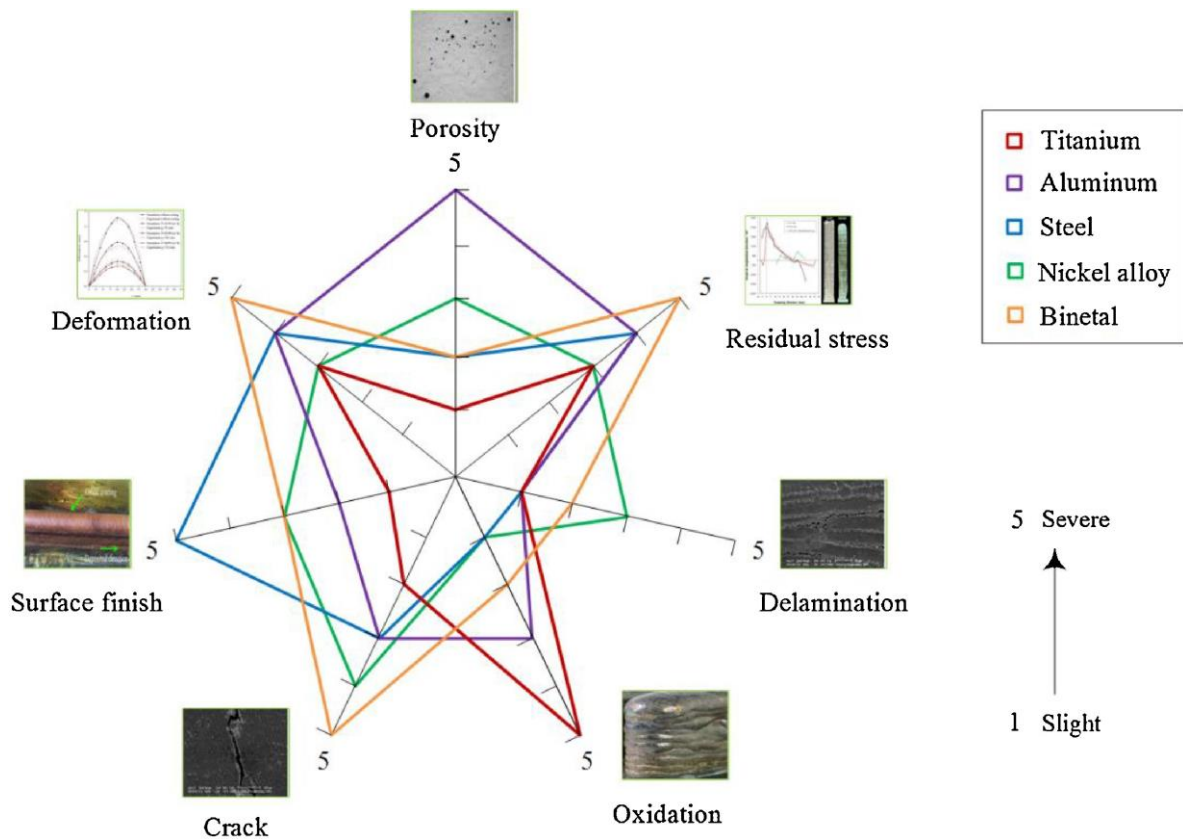


Figure 3 – Most common anomalies observed for DED-Arc of different metallic materials[36].

Various welding technologies are adapted for DED-Arc applications, each offering distinct characteristics based on material and part requirements. Welding processes are adapted for AM by incorporating a controlled wire feed system, precise thermal management and

advanced robotics or CNC systems to ensure accurate material deposition. The selection of a welding technology depends on factors such as the material being used, part size and the required mechanical properties. Each process offers trade-offs in terms of deposition rate, precision and surface quality and special features [37,38]. The most commonly used welding processes in DED-Arc include Gas Metal Arc Welding (GMAW) [39], Gas Tungsten Arc Welding (GTAW) [40] and Plasma Arc Welding (PAW) [41]. These techniques are summarised below and illustrated in Figure 4.

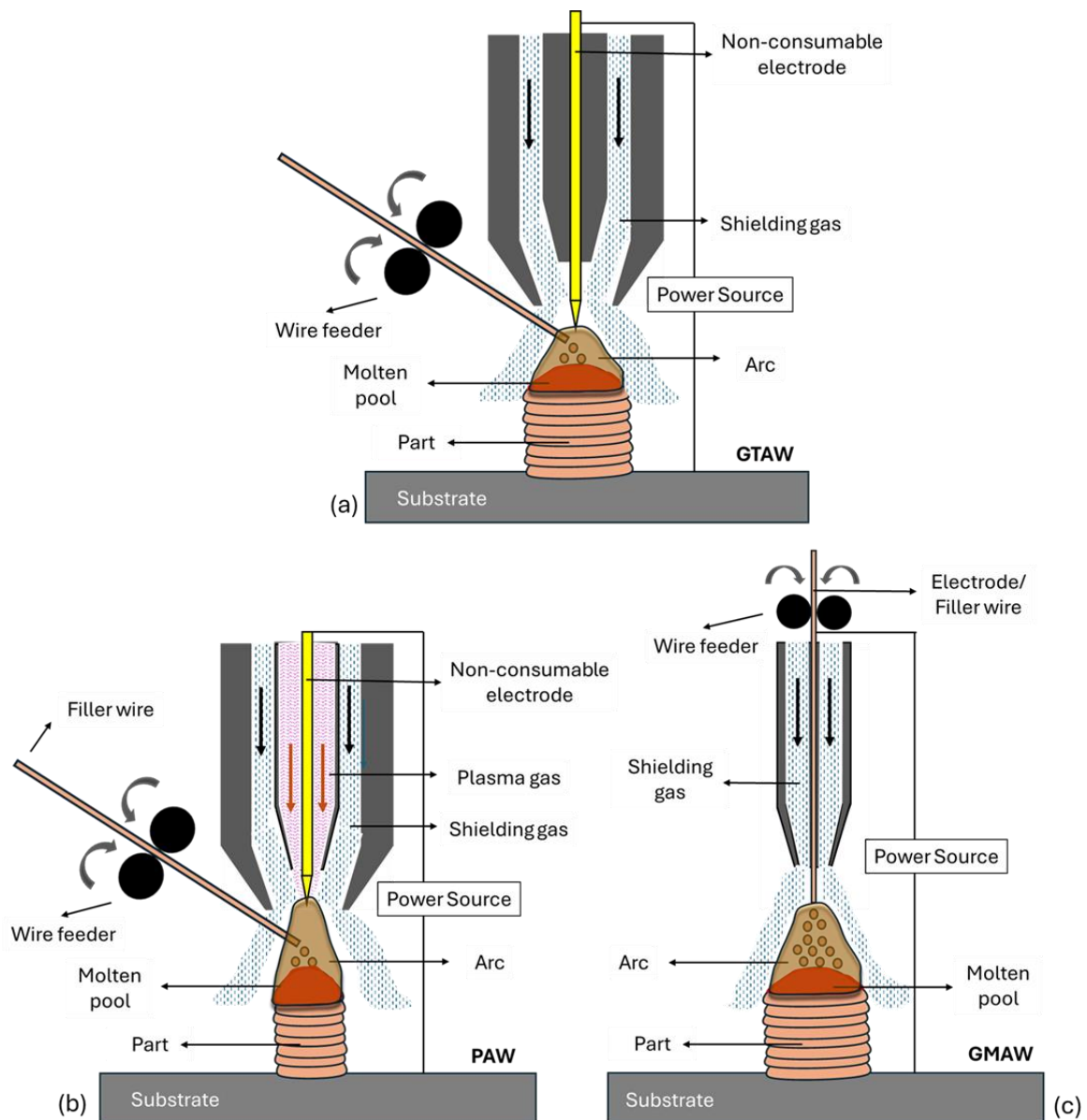


Figure 4 – Types of welding processes in DED-Arc: (a) GTAW; (b) PAW; (c); GMAW.

GTAW [42] and PAW [43] are common methods used in DED-Arc, especially for materials requiring higher precision and control, such as titanium and high-alloy steels. GTAW

and PAW produce clean, high-quality welds with minimal spatter, although they typically have a lower deposition rate than GMAW. This makes them ideal for applications where surface finish and mechanical properties are critical.

GMAW is the most widely employed in DED-Arc due to its high deposition rates and versatility. GMAW allows for continuous wire feed, making it well-suited for large-scale additive manufacturing. It is particularly advantageous for materials like steel and aluminium, providing relatively high production speeds [44]. GMAW is recognised for its higher energy efficiency, deposition rate, mechanical strength, material utilisation, part density, low porosity and reduced production time [45].

As welding technologies continue to advance, several electric arc based additive manufacturing systems have been developed following this trend. One notable example is the Cold Metal Transfer (CMT) based GMAW system, which operates with significantly lower heat delivered to the weld compared to conventional welding methods. The reduced heat input in CMT plays a crucial role in minimising thermal damage to the material, thereby enhancing the quality of the final product [46,47]. This characteristic has facilitated the effective use of CMT in the additive manufacturing of aluminium and its alloys. Various Al series, including the 2xxx, 5xxx and 6xxx series, have been investigated for their suitability in the CMT-based DED-Arc process [48–52]. However, the application of CMT to 7xxx series aluminium alloys remains limited due to inherent welding challenges. These challenges include the susceptibility to solidification cracking (hot cracking) and porosity during the welding process [53–55], the sensitivity to high interpass temperatures and thermal cycles, which can lead to undesirable geometric distortion [56–58] and the risk of over-aging during heat treatment, which results in precipitate instability and reduced material strength [55,59,60]. These factors have hindered the broader adoption of DED-Arc for 7xxx series aluminium alloys in aerospace applications. Nevertheless, ongoing research aims to overcome these limitations and expand the feasibility of arc-based AM for high-strength aluminium alloys for DED-Arc.

2. Aluminium 7xxx series Al-Zn-Mg-Cu alloys

Aluminium alloys are broadly classified into two main categories: wrought and cast alloys, based on their manufacturing processes. Currently, most aluminium alloys employed in structural applications belong to the wrought category. Heat-treatable alloys enhance their mechanical properties through thermal treatments, whereas non-heat-treatable alloys rely on work hardening for strength improvement. Additionally, aluminium alloys are classified according to their principal alloying elements. A comprehensive classification of aluminium

alloys, encompassing their strengthening mechanisms and key alloying elements, is presented in Figure 5.

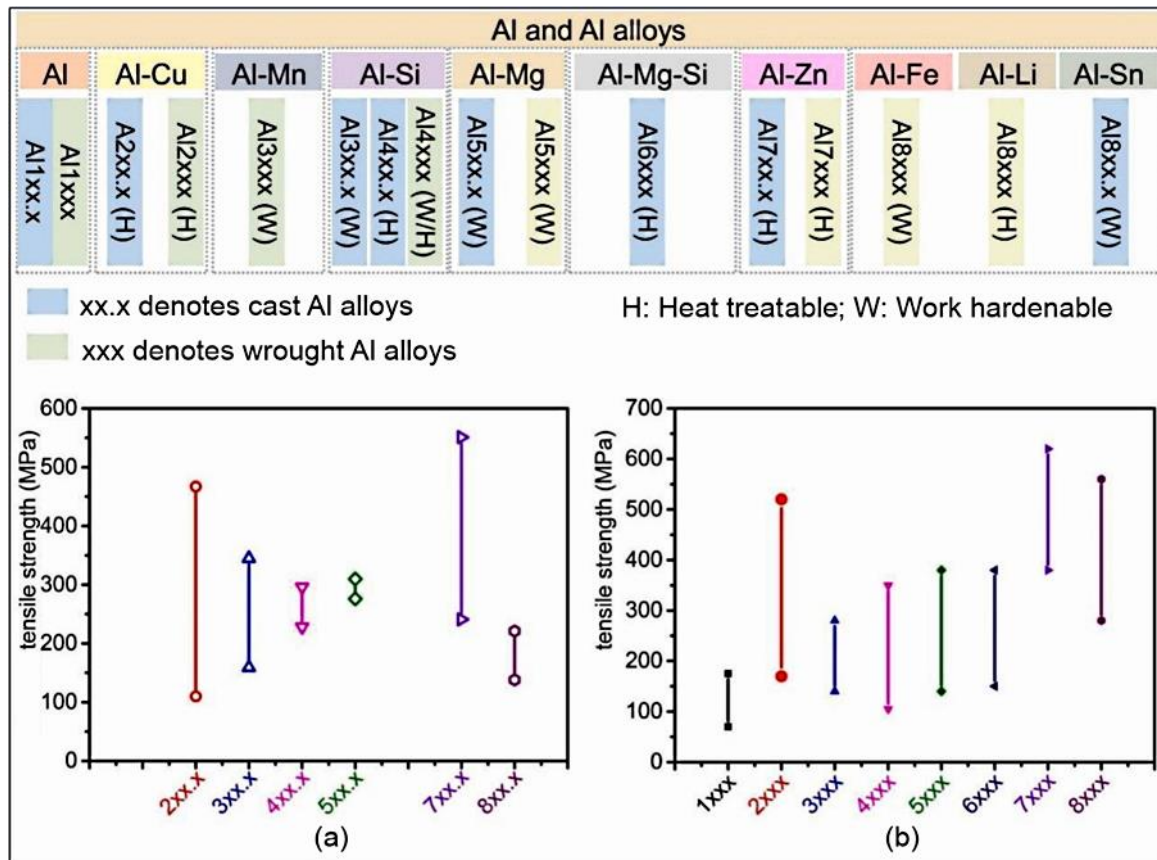


Figure 5 – Aluminium alloys, strengthening mechanism, main alloying element and heat treatability. Adapted from [61].

The increasing utilisation of aluminium alloys across multiple industries is driven by their unique combination of desirable properties, including low density (2.6 to 2.9 g/cm³), excellent corrosion resistance and a high strength-to-weight ratio. Furthermore, their superior recyclability has positioned them as a sustainable material, aligning with the growing demand for environmentally friendly solutions [62]. In aerospace, automotive and construction industries, aluminium alloys contribute significantly to advancements in fuel efficiency, structural performance and durability [63]. Their versatility in manufacturing and fabrication, combined with outstanding thermal (120 – 235 W/mK) and electrical (30% – 60% IACS) conductivity, has led to widespread adoption across applications ranging from transportation to electronics [64]. Ongoing advancements in alloy composition and processing techniques continue to enhance their performance, further solidifying aluminium alloys as a cost-effective and high-performance alternative to conventional materials. Figure 6 illustrates the comparative mechanical properties of several aluminium alloys.

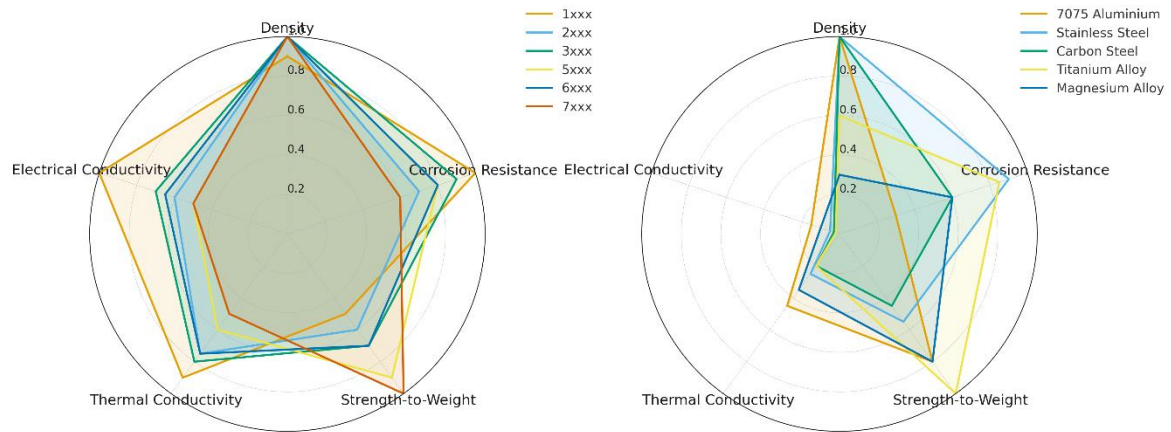


Figure 6 - Normalised comparison, including density, corrosion resistance, strength-to-weight ratio, thermal and electrical conductivity, of: (left) across aluminium alloy series and (right) across different metallic materials grades.

The evolution of aircraft structural materials has progressed significantly, from early designs such as the Boeing 747 to contemporary aircrafts like the Boeing 777 and Airbus A380 [65]. Despite the integration of advanced composite materials, aluminium alloys remain predominant, accounting for more than 70% of the structural composition in modern commercial aircrafts [66]. In military aviation, aluminium alloys continue to play a critical role, comprising more than 35% of the structural materials used in most military aircrafts [67]. This sustained reliance on aluminium alloys is largely attributed to their ability to reduce weight while maintaining structural integrity, a crucial factor in both commercial and defence aviation. The most used aluminium alloys in aerospace applications belong to the 2xxx, 5xxx and 7xxx series. The 2xxx series, including alloy 2024, is recognised for its high strength and excellent fatigue resistance, making it well-suited for fuselage and wing structures. The 5xxx series, exemplified by alloy 5052, is favoured for aircraft skins and fuel tanks due to its superior corrosion resistance and moderate strength [65]. Meanwhile, the 7xxx series, particularly alloy 7075, offers exceptional strength and is extensively utilised in critical structural components such as wing spars and landing gear. These alloys play an indispensable role in modern airframe construction, where performance, longevity and safety are paramount. Continued advancements in alloy development and optimisation are crucial for enhancing the efficiency and performance of both commercial and military aircraft [63,68–71].

Heat treatment is a critical step in optimising the mechanical performance of 7xxx series Al alloys, significantly enhancing their strength and hardness [72]. The full-strength potential of Al-Zn-Mg-Cu alloys is realised through a series of heat treatment processes, typically comprising three stages: solution heat treatment, quenching and age hardening. These processes control the precipitation of secondary phases, enabling the material to achieve the

desired mechanical properties [73]. The precipitation is primarily influenced by the aging process, which involves the precipitation and growth of fine η' -phase precipitates (a semi-coherent, metastable precursor of the equilibrium MgZn_2 phase) originating from Zn and Mg Guinier–Preston (GP) zones [74]. The addition of copper enhances the aging kinetics by increasing supersaturation levels, potentially through the nucleation of the Al_2CuMg (S-phase) [75–79]. Considering the heat treatment methodologies, various tempers (with different temperature and time of heat treatment as well as deformation level) are found in literature, including T6 [80,81], T651 [82,83], T73 [84,85], T7351[86] and T76 [87]. The T6 temper, the most widely used post-processing treatment, involves solution heat treatment at 470–495°C for 1–2 hours, followed by rapid water quenching [80,81]. This creates a supersaturated solid solution of alloying elements within the aluminium matrix. Subsequently, artificial aging at 120–180°C for 3–8 hours facilitates the precipitation of strengthening phases (η'), significantly increasing hardness and strength [88]. The T651 temper includes an additional stress-relief step achieved through stretching before aging, improving stability in high-stress applications. In contrast, the T73 temper undergoes an extended aging process to enhance resistance to stress corrosion cracking, making it ideal for applications requiring high durability. Despite the variety of established heat treatments, specific modifications are occasionally employed to improve the resulting material properties or achieve similar outcomes with added benefits, such as cost and time savings [89].

In aerospace and defence industries, manufacturing precision of high-end materials is crucial due to the elevated costs (materials and processes), lightweight requirements of the parts and high structural performance demand. Additionally, residual stresses from these operations can influence the fatigue behaviour. It is known that aerospace industry focuses primarily on cost, weight and performance. These factors are strongly influenced by the Buy-to-Fly (BtF) ratio, which is the ratio of the weight of the purchased raw material and the weight of the final part. Aerospace is characterised by one of the highest BtF ratios among industries, with parts reaching the 12:1 proportion (it means that for 12 weight units of material, only one is assembled on the aircraft) [90]. With this in mind, additive manufacturing is becoming an increasingly viable technique for producing 7xxx series Al-Zn-Mg-Cu alloy components. The adoption of AM in high-end applications enhances the efficiency (reduces BtF ratios) by optimising material usage while maintaining high strength-to-weight ratios [91,92]. Despite these advantages, large-scale structural components such as fuselages and wing ribs are still predominantly manufactured through conventional forging and machining processes, which result in substantial material waste and limited design flexibility. Consequently, there is a

growing demand for near-net-shape manufacturing approaches that align with cost control requirements and structural manufacturing adaptability [93].

3. AM characteristics of 7xxx series Al alloys

3.1 Common imperfections

DED-Arc of 7xxx series Al alloys requires special attention to the following intrinsic challenges:

1. **Elemental vaporisation** - Some alloying elements have a high tendency to evaporate due to their low boiling temperature (specifically Zn and Mg). The elemental vaporisation causes elemental losses compared to the raw wire material, which can contribute negatively to mechanical strength [94]. Studies on AM of 7xxx series Al alloys have measured a Zn loss of up to 30.8% [95] for PBF-LB and up to 44.7% for DED-Arc [96,97].
2. **Formation of oxide impurities** - Between layers, formation of oxide impurities is a common issue during multilayer deposition. These oxides, which adhere loosely to the substrate (or previously deposited layer), are typically porous and possess a high specific surface area, making them susceptible to absorbing moisture, particles and contaminants from the surrounding environment [98]. Moreover, the random distribution of oxide impurities and spattering caused by evaporation destabilise the cathode spots, adversely affecting process stability [99].
3. **Hydrogen-induced porosity** - Hydrogen solubility in liquid aluminium alloys is significantly higher than in the solid state, limiting the escape of hydrogen bubbles during rapid solidification and leading to hydrogen-induced porosity [100]. The risk of porosity is further exacerbated by the presence of moisture or lubricants on the wire or substrate, which can introduce additional hydrogen into the melt pool [101].
4. **Hot cracking (solidification and liquation cracking)** - The wide solidification range of 7xxx alloys, combined with high thermal gradients, makes them particularly prone to hot cracking. Both types of cracks can significantly compromise the mechanical integrity and are among the most challenging imperfections to control in DED-Arc of 7xxx alloys [102].
5. **Geometric inaccuracies and distortion** - The repeated thermal cycling inherent to DED-Arc processes can lead to high residual stresses and/or geometric distortions, warping and dimensional inaccuracies. These issues are particularly pronounced in

high-strength alloys like the 7xxx series, where thermal stresses can exceed the material's yield strength, causing permanent deformation [103].

6. **Lack of fusion and incomplete layer bonding** - Inappropriate process parameters or improper interlayer cleaning can result in lack of fusion between layers, leading to weak interfaces and potential delamination under mechanical loading [104].

These imperfections, elemental vaporisation, porosity, oxide inclusions, hot cracking, residual stresses and geometric distortion and lack of fusion, collectively undermine the mechanical performance, reliability and dimensional accuracy of DED-Arc fabricated 7xxx series aluminium components [105–107]. Figure 7 depicts some common imperfections observed during DED-Arc of Al-Zn-Mg-Cu alloys. Consequently, ongoing research is focused on process optimisation, advanced monitoring and microstructural control to mitigate these issues and unlock the full potential of DED-Arc for high-performance Al-Zn-Mg-Cu alloys.

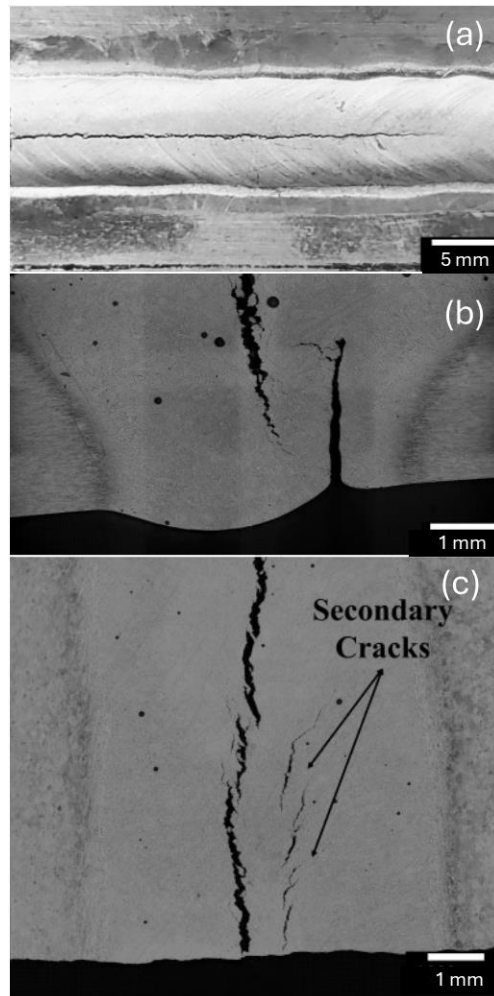


Figure 7 – Common imperfections in GTAW-based DED-Arc processing of ER7075 Al alloy. (a), (b) and (c) solidification crack and (b) and (c) porosity. Adapted from [108].

3.3 Microstructure

The distinguishing feature of 7xxx aluminium alloys lies in their precipitation behaviour, primarily governed by the high concentrations of Zn, Mg and Cu. These alloying elements promote the development of η' (MgZn_2) precipitates as the predominant strengthening phase, which, when finely dispersed throughout the aluminium matrix, impart remarkable strength and toughness [109,110]. This precipitation pathway contrasts with that of other series, such as 2xxx and 6xxx alloys, where strengthening is achieved through phases like Al_2Cu or Mg_2Si , respectively, often resulting in a more heterogeneous distribution of precipitates. Another notable characteristic of 7xxx alloys is their pronounced quench sensitivity, requiring precise control of cooling rates and thermal treatments to achieve the optimal morphology and fraction of η' precipitates [109]. These microstructural attributes are central to the superior mechanical

performance of 7xxx alloys and explain their frequent selection for demanding structural applications.

While traditional welding and DED-Arc techniques share similarities in terms of equipment and processing environment, their thermal cyclic processing conditions differ significantly which consequently modifies the resulting microstructure. Key factor influencing this microstructure is the recurrent thermal cycles in DED-Arc that is an intrinsic repeated heat treatment [111]. Due to their pronounced tendency for hot cracking, Al–Zn–Mg–Cu alloys have been extensively studied for DED-Arc, focusing on compositional adjustments and microstructural optimization.

3.3.1 Hot cracking mechanisms

Hot cracking in 7xxx series aluminium alloys during DED-Arc primarily arises from two mechanisms: solidification cracking and liquation cracking. Solidification cracking occurs during the final stages of solidification in the fusion zone, where the segregation of alloying elements leads to the formation of low-melting-point eutectic phases at the interdendritic regions. The rapid thermal gradients and shrinkage stresses, result in the formation of cracks along grain boundaries [112,113]. In contrast, liquation cracking is associated with the intense thermal cycling inherent to DED-Arc, which causes partial melting of grain boundary regions in the heat-affected and partially melted zones adjacent to the fusion zone. Repeated heating and cooling can remelt these susceptible grain boundary films and upon re-solidification under tensile stress, intergranular cracks may propagate [114]. In [115], a custom-made wire manufactured with adjusted elemental composition (Al-5.66Zn-2.76 Mg-1.26Cu-0.14Fe) was investigated, yielding high-quality billets with minimal contamination. Their study produced crack-free specimens with low porosity (~0.36%). The as-deposited microstructure revealed micro-segregations that could later be dissolved via solution post-weld heat treatment, allowing hardening phases to precipitate [115]. This process resulted in nearly doubling the microhardness compared to the as-built material.

3.3.2 Grain morphology and spatial distribution

The grain morphology is also a topic that requires attention in DED-Arc of Al-Zn-Mg-Cu alloys. Wang et al. [116] fabricated structures in which the resulting microstructure comprised of both columnar and equiaxed grains, with coarse equiaxed grains at the top and

columnar dendrites at the bottom of the walls. EBSD analysis revealed average grain sizes of 108.2, 97.0 and 97.3 μm for the upper, middle and lower regions of the structure, respectively. They concluded that the intrinsic repeated heat treatment in DED-Arc influenced grain refinement, with variations depending on the peak temperature and processing duration. Their characterisation revealed a complex network of precipitate phases (η and η') and nanoscale second-phase precipitates.

Morais et al. [117] analysed a novel Al–Zn–Mg–Cu alloy with improved processability, resulting in a DED-Arc built component with high mechanical strength. The microstructure consisted of equiaxed and elongated grains, with smaller equiaxed grains in interlayer regions. However, the produced parts exhibited dispersed porosity, with variations in pore content along the sample's height, lower at the bottom and higher at the top. A similar trend was observed for the grain size, increasing with height due to rising temperature.

Dong et al. [93] reported that Al-Zn-Mg-Cu alloys produced by DED-Arc exhibit a microstructure composed of columnar grains and twinned dendrites. They emphasised that cross-sectional observations can be misleading, since grains that appear equiaxed may actually represent the transverse view of longitudinally oriented columnar grains, as illustrated in Figure 8 (a–d). The columnar grains grow with a slight upward tilt, following the deposition direction. During deposition, two distinct regions can form within the same layer: the lower part (LP) and the upper part (UP) (Figure 8 (e)). This difference arises from their origins, UP grains nucleate at the start of a deposition layer, whereas LP grains originate from the fusion boundary between the penultimate and final layers.

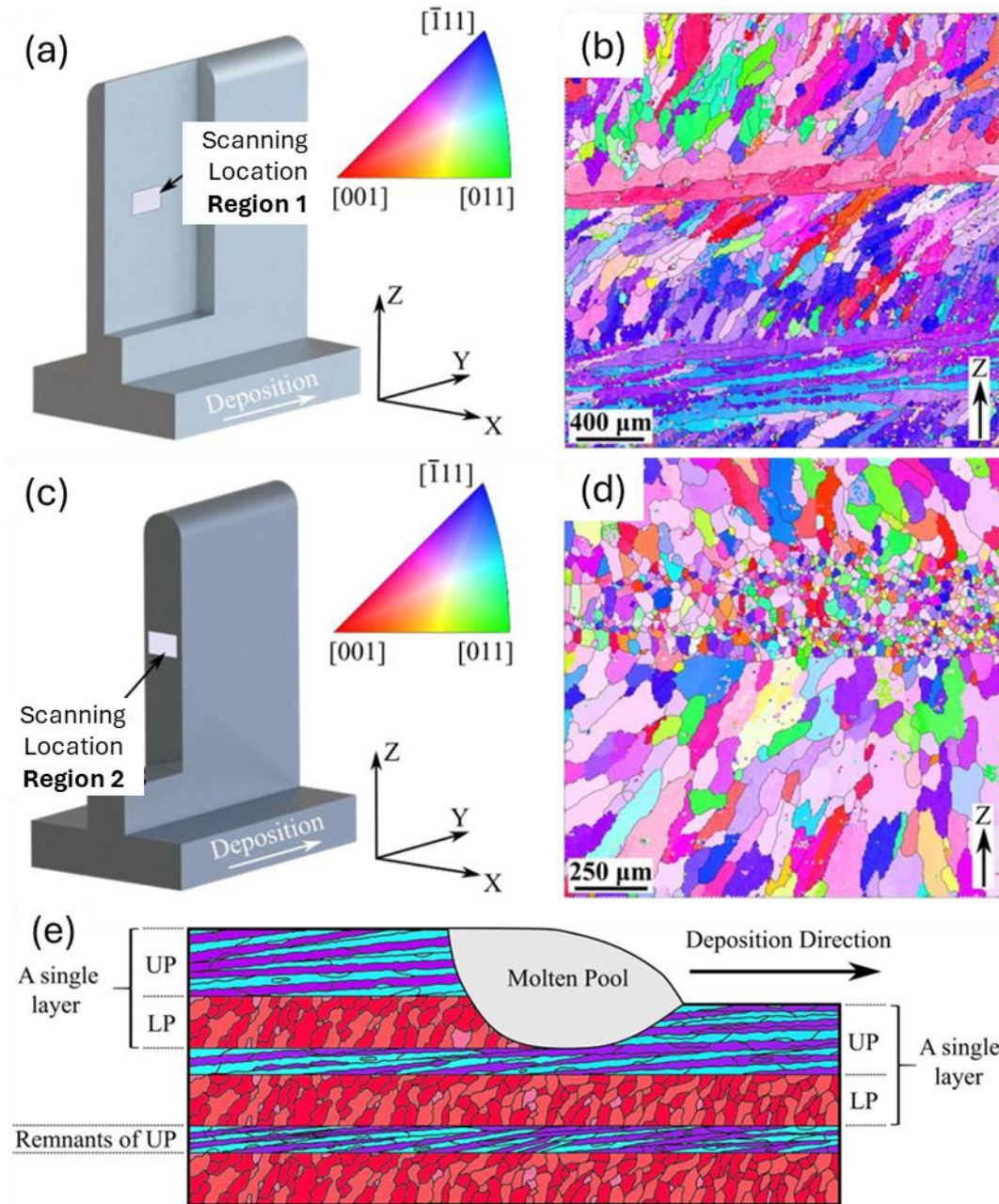


Figure 8 - EBSD orientation maps of cross-sectional samples: Scanning locations of (a) region 1 and (c) region 2; Orientation maps with reconstructed grain boundaries of (b) region 2 and (d) region 1. (e) Formation mechanism for the grain morphology at the upper (UP) and lower (LP) part of a single layer. Adapted from [93].

Cai et al. [109] examined the effects of deposition parameters on Al–Zn–Mg–Cu thin-wall components. Lower deposition rates increased temperature gradients but did not refine grains, while higher speeds induced remelting, leading to grain refinement via Al_3Zr precipitation and reduced twin dendrite growth. They found that increasing the deposition rate initially reduced and then increased porosity, while twinned dendrites showed an inverse trend.

3.3.3 Grain refinement strategies

Given the metallurgical challenges, microstructure optimisation is essential for enhancing the mechanical properties via grain refinement (Hall-Petch relationship), eliminating imperfections and expanding DED-Arc applicability to high-strength alloys. A strategy for grain refinement in Al-Zn-Mg-Cu alloys is the introduction of heterogeneous particles to modify nucleation and grain growth. The most common particles added to 7xxx series aluminium alloys during DED-Arc are ceramic-based reinforcements such as titanium nitride (TiN), titanium carbide (TiC) and other carbides or nitrides, as well as alloying elements like zirconium (Zr) and scandium (Sc) [118,119]. TiN and TiC particles primarily act as heterogeneous nucleation sites to promote grain refinement and enhance mechanical properties. Both TiN and TiC are stable, high-melting-point ceramic particles that remain solid in the melt pool, facilitating the formation of finer, equiaxed grains and reducing the tendency for hot cracking [120]. In contrast, Zr and Sc function primarily through precipitation strengthening and recrystallisation inhibition. These elements form fine, coherent Al₃Zr and Al₃Sc precipitates during solidification and subsequent heat treatment, which effectively pin grain boundaries and prevent grain coarsening or recrystallisation during thermal cycling [121].

Qin et al. [122] used a GTAW-based DED-Arc system with simultaneous Al-Mg-0.35Sc and Al-Zn-Mg-Cu wire feeding to produce Al-Zn-Mg-Cu-0.15Sc parts, studying the impact of Sc addition on microstructural development and mechanical properties. Oropeza et al. [55] employed TiC nanoparticle-enhanced welding wires to successfully deposit a six-layer 7075 structure, demonstrating the potential of nanoparticle treatments in addressing solidification challenges in fusion-based manufacturing. Wang et al. [123] fabricated 7075 alloy structures using TiB₂ nanoparticle-reinforced welding wire with ultrasonically assisted (UA) wire-arc DED, while Yuan et al. [124] introduced TiN particles into the melt pool of DED-Arc processed Al-Zn-Mg-Cu alloys, promoting grain refinement. Their studies showed a complete transformation in grain structure, with coarse columnar grains replaced by equiaxed grains, which promotes more uniform and isotropic mechanical properties as well as improved resistance to cracking and deformation [125]. Figure 9 illustrates the reduction in grain size with increasing TiN particles concentration, highlighting the beneficial effect of this technique.

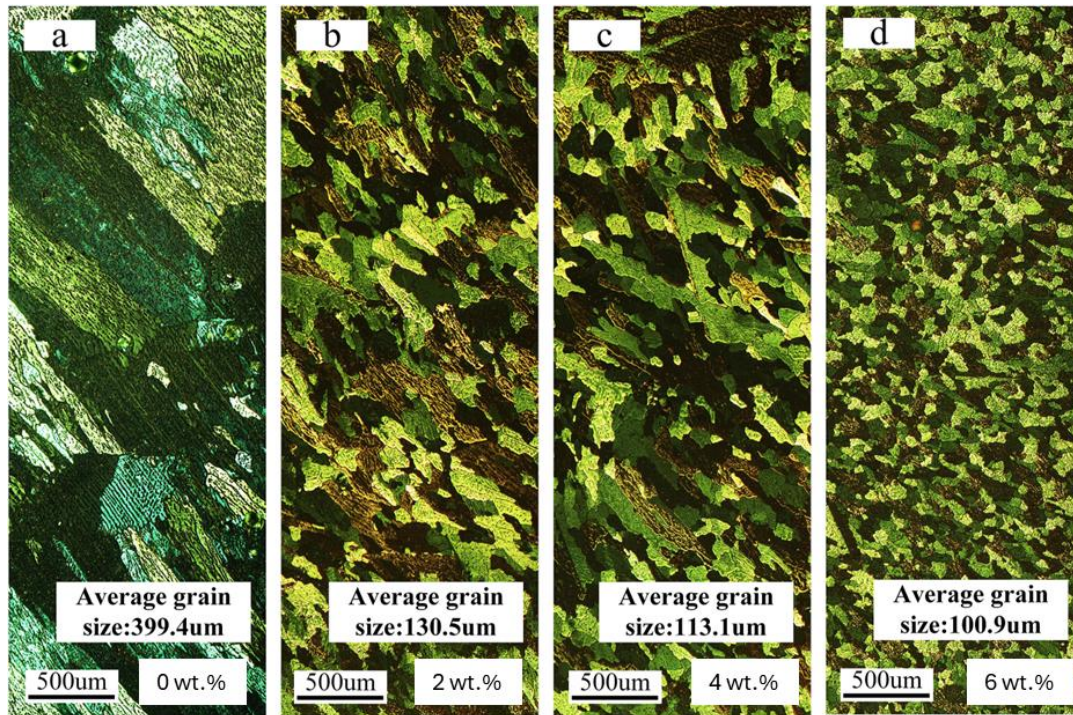


Figure 9 - Micrographs of cross sections of DED-Arc deposits of ER7075 at various concentrations of TiN particles: (a) 0 wt.%; (b) 2 wt.%; (c) 4 wt.%; (d) 6 wt.%. Adapted from [124]

The average grain size reduced considerably due to heterogeneous nucleation of Al_3Ti particles, which also inhibited grain growth. This refinement significantly improved the mechanical properties, reduced the texture intensity by 87.6% and altered the grain orientation from uniaxial to multi-axial. Wang et al. [126] studied the influence of the TiC content on the microstructure and mechanical properties of DED-Arc processed 7075 Al alloy. Their findings, shown in Figure 10, indicated that TiC additions refined the grain structure, reducing the grain size by 77.8%, 78.5% and 83.7% for TiC contents of 0.27 wt%, 0.48 wt% and 0.70 wt%, respectively. TiC also transformed coarse $\alpha\text{-Al} + \eta\text{-MgZn}_2$ eutectics into finer, more uniformly distributed particles. However, for TiC contents above 0.48 wt%, these particles tended to aggregate along grain boundaries.

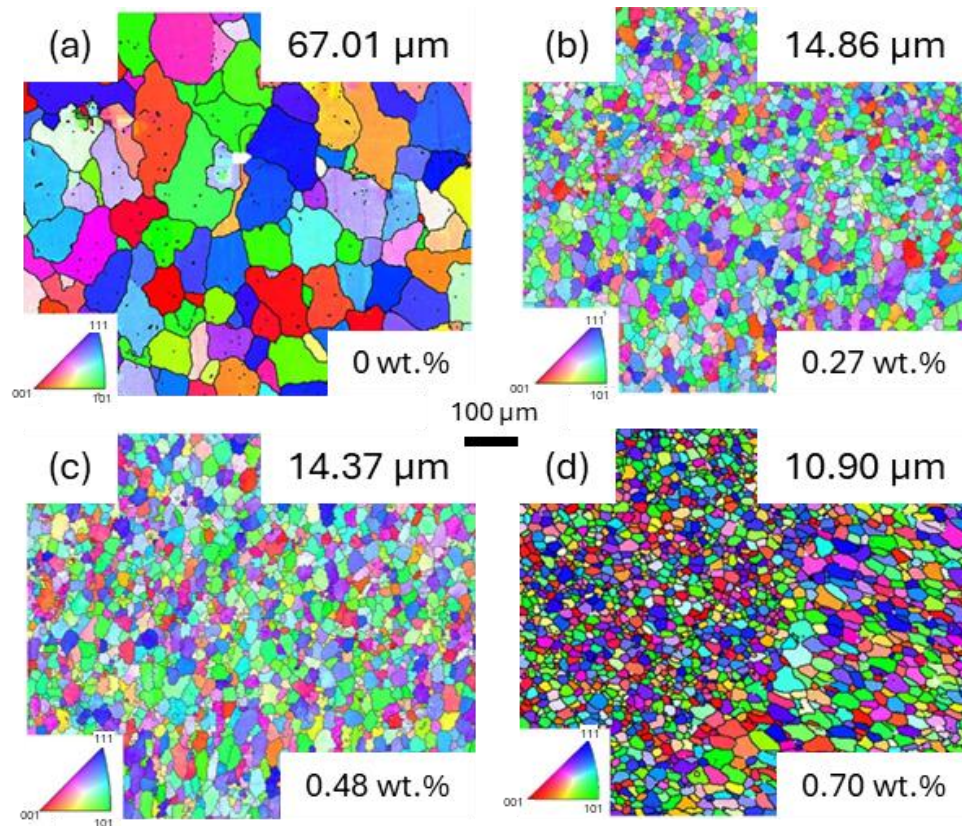


Figure 10 – EBSD results of Al 7075 samples with different TiC contents: (a) 0 wt%; (b) 0.27 wt%; (c) 0.48 wt%; (d) 0.70 wt%. Adapted from [126].

Grain refinement effectively mitigates hot cracking in 7xxx series aluminium alloys by promoting a transition from crack-susceptible columnar grains to finer, equiaxed microstructures. This refined grain structure enhances strain accommodation during solidification and disrupts the continuity of crack-prone grain boundaries. Studies confirm that additions of grain refiners (e.g., Sc, TiB₂, or nanoparticles) significantly reduce hot cracking susceptibility while improving mechanical properties [102,127].

Several studies have explored other methods for grain refinement like interlayer deformation techniques. Qie et al. [128] combined DED-Arc with interlayer friction stir processing (FSP) in Al-Zn-Mg-Cu alloys, achieving finer grains and improved tensile properties, although at the cost of deposition efficiency. In-situ interlayer hot-forging [129] has been used for different materials in DED-Arc and could be a possible solution for improving the grain morphology (less oriented and finer grains), enhance the mechanical properties and reduce the internal imperfections such as porosities.

Despite considerable progress in the DED-Arc of aluminium alloys, persistent challenges in producing defect-free structures and achieving optimal microstructures continue to limit the

full realisation of this technology's potential. Overcoming these barriers will require sustained, focused research into advanced grain refinement strategies, precise optimisation of deposition parameters and the integration of hybrid manufacturing techniques. Addressing these critical issues is essential, not only for minimising imperfections such as hot cracking and porosity, but also for unlocking superior mechanical performance and reliability. Ultimately, such advancements will be pivotal in establishing DED-Arc as a robust, industrially viable solution for fabricating aluminium alloy components for demanding applications.

3.2 Process optimisation

Process optimisation plays a critical role in the successful DED-Arc of 7xxx series aluminium alloys, which are inherently prone to hot cracking, porosity and microstructural heterogeneity due to their complex thermal and metallurgical behaviour. The high thermal conductivity and wide solidification range of these alloys make them especially sensitive to deposition parameters such as current, travel speed, interlayer temperature and cooling rate. Fine-tuning these parameters is essential to control heat input and thermal gradients, which directly influence grain morphology, segregation behaviour and imperfection formation [130]. For instance, optimised travel speeds can enhance remelting and promote grain refinement, while tailored interlayer dwell times can mitigate residual stress accumulation and improve fusion between layers [131]. Furthermore, the integration of process enhancements such as interlayer deformation, ultrasonic stirring or in-situ alloying, requires precise synchronisation with thermal cycles to be effective [132].

Cong et al. [133] investigated the influence of different arc modes on the microstructure and porosity of aluminium alloys produced via DED-Arc additive manufacturing. Their study revealed that porosity was significantly reduced when employing the CMT pulsed advanced (CMT PADV) mode, which also facilitated the formation of fine equiaxed grains with lower porosity, as depicted in Figure 11, where standard CMT, CMT-P (pulse) and CMT PADV were compared for a DED-Arc produced Al-6.3%Cu alloy. The CMT PADV mode features a mixed droplet transfer mechanism, combining short-circuiting (typical of standard CMT) and spray transfer (seen in pulse or advanced modes).

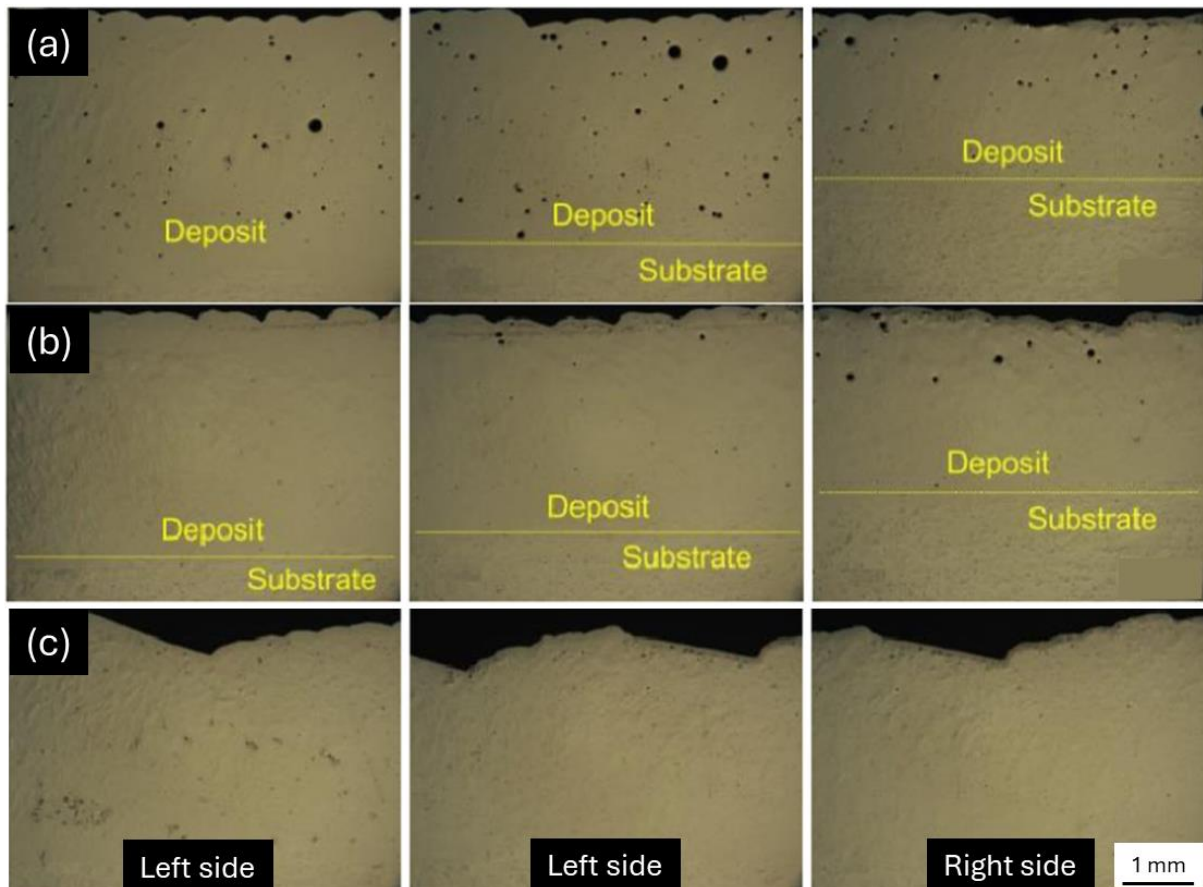


Figure 11 - Optical micrographs showing porosity of Al-6.3%Cu alloy with (a) CMT process; (b) CMT-Pulse process; (c) CMT-Pulse Advanced process. Adapted from [133].

This is achieved by periodic switching of current polarity between direct current electrode positive (EP) and electrode negative (EN) phases within each cycle [134]. The ratio of EP to EN phases is a key parameter, with prior studies demonstrating its impact on both microstructure and mechanical properties [135]. The ratio is calculated based on the EP and EN periods from a typical electrical waveform, as illustrated in Figure 12. For instance, Wang et al. [136] examined how the EP to EN ratio influences the dimensional accuracy of thin-walled 7075 aluminium alloy components produced via DED-Arc, finding that a higher ratio enhances process stability. Guo et al. [99] explored the effects of varying the EP to EN ratio on the forming arc stability and oxide behaviour of 7075 aluminium alloy in oscillating laser-enhanced DED-Arc (OLA-DED). Their results indicate that when the EP to EN ratio decreases, the forming stability deteriorates and oxide impurities accumulate on the surface. They concluded that an EP to EN ratio of 1 represents the threshold for stable process.

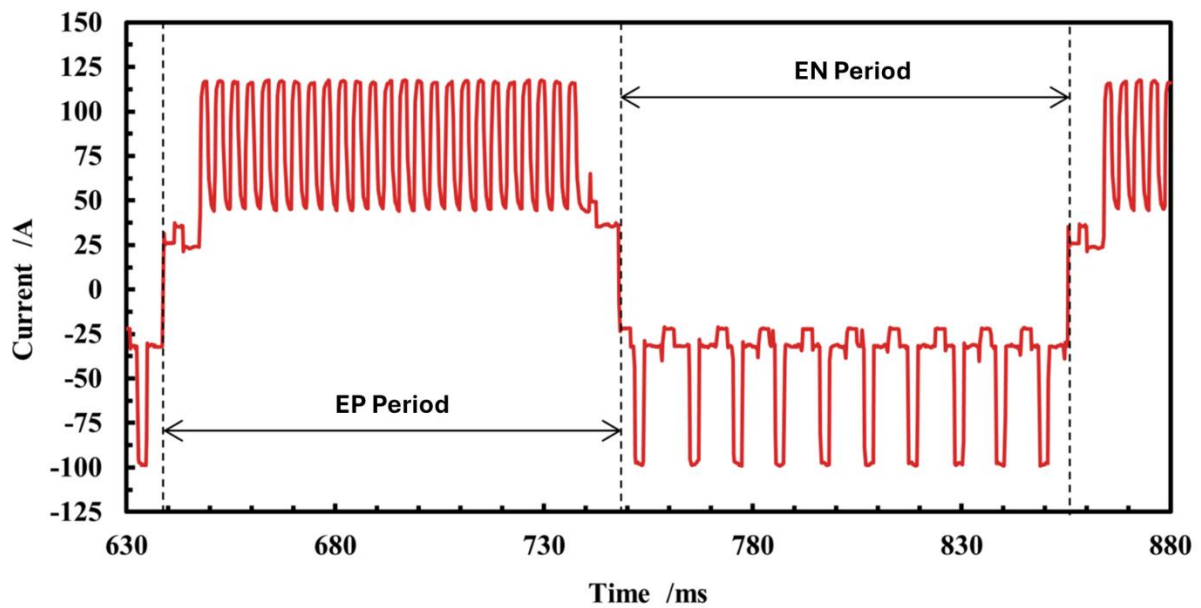


Figure 12 - Arc current waveform in CMT-PADV mode, evidencing the EP and EN periods.

To improve the suitability of Al-Zn-Mg-Cu aluminium alloys for DED, researchers have explored the integration of multi-energy hybrid fields to optimise the deposition process. Wang et al. [123] utilised ultrasonically assisted DED-Arc to fabricate 7075 structures, where the combined effects of acoustic streaming and cavitation reduced porosity by 38.5% [137]. Acoustic streaming is the steady flow generated in a fluid by the absorption of ultrasonic waves, enhancing mixing and heat transfer. Cavitation is the formation and collapse of tiny bubbles caused by ultrasound, which helps break up oxides and remove gas, reducing porosity [137].

Similarly, Chen et al. [138] applied an externally assisted compound magnetic field during DED-Arc of Al-5%Mg alloy, achieving a higher deposition efficiency and lower porosity. These improvements resulted from periodic magnetic oscillations which stabilised the arc and regulated droplet behaviour. Laser-arc hybrid additive manufacturing (LAHAM) leverages the combined influence of a laser beam to regulate the melt pool, effectively minimising imperfections and improving the mechanical properties of Al-Zn-Mg-Cu alloys [94,139]. Liu et al. [94] observed a significant reduction in texture in LAHAM samples compared to conventional DED-Arc samples, attributed to the increased proportion of equiaxed grains and overall grain refinement (Figure 13). Furthermore, integrating beam oscillation technology into laser-arc hybrid welding has demonstrated additional benefits in terms of process stability and joint quality [140]. The oscillating laser induces stirring within the melt pool and helps to regulate the temperature gradient and cooling rate, promoting porosity escape

and microstructural refinement. Among the various hybrid approaches, oscillating lasers have shown superior effectiveness in enhancing process stability and improving component quality [141].

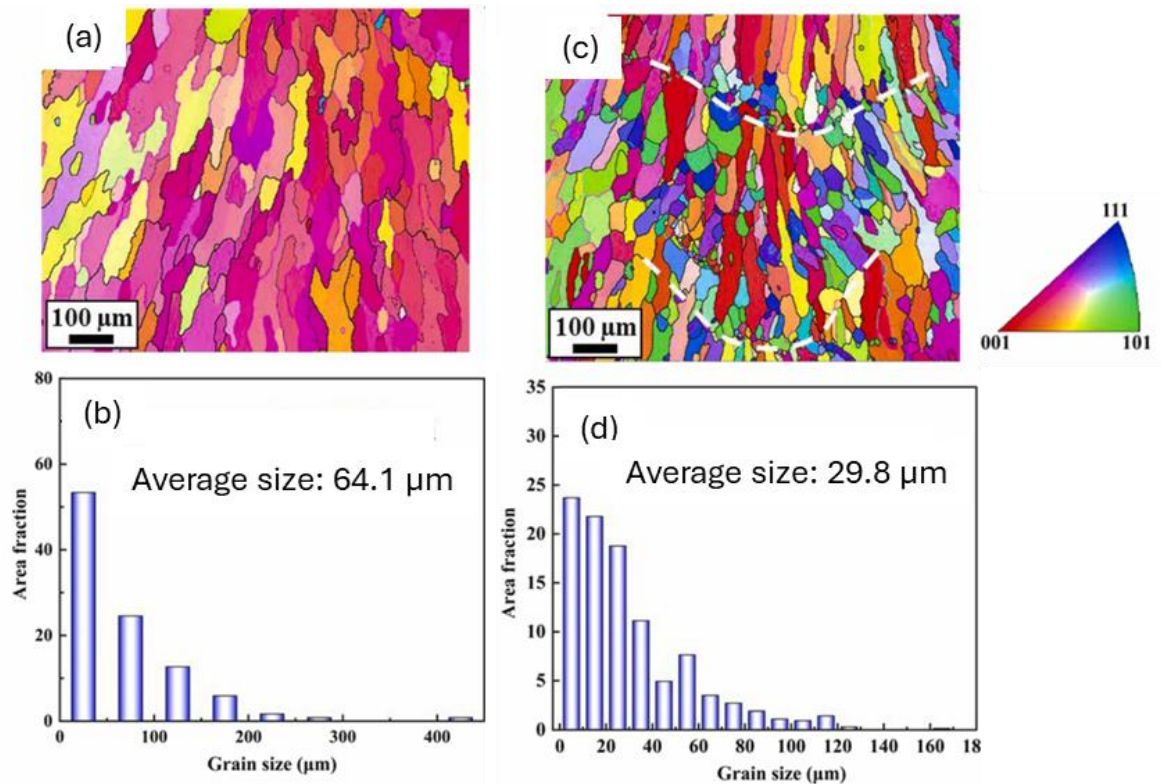


Figure 13 – EBSD micrographs of (a) DED-Arc and (c) LAHAM specimen. Grain size distribution of (b) DED-Arc and (d) LAHAM specimen. Adapted from [94].

Without such optimisation, even high-quality filler materials or reinforcement strategies may fail to deliver consistent performance. Therefore, a systematic and data-driven approach to process parameter control could unlock the full mechanical potential and structural integrity of DED-Arc fabricated 7xxx aluminium alloy components.

3.4 Mechanical properties

As previously mentioned, inherent challenges, such as porosity, oxide layer formation, cracking, distortion and process control, significantly impact the mechanical properties of DED-Arc fabricated 7xxx series Al alloy components. Wang et al. [142] demonstrated that Al-Zn-Mg-Cu alloy structures exhibit a pronounced anisotropy in tensile strength, elongation and stress corrosion cracking (SCC) susceptibility, with distinct differences observed between the vertical and horizontal build orientations. In their study, samples were tested in different directions (vertical and horizontal) and for the horizontal ones, the bottom (Horizontal-B),

middle (Horizontal-M) and top (Horizontal-T) regions of the Al wall were analysed (Figure 14).

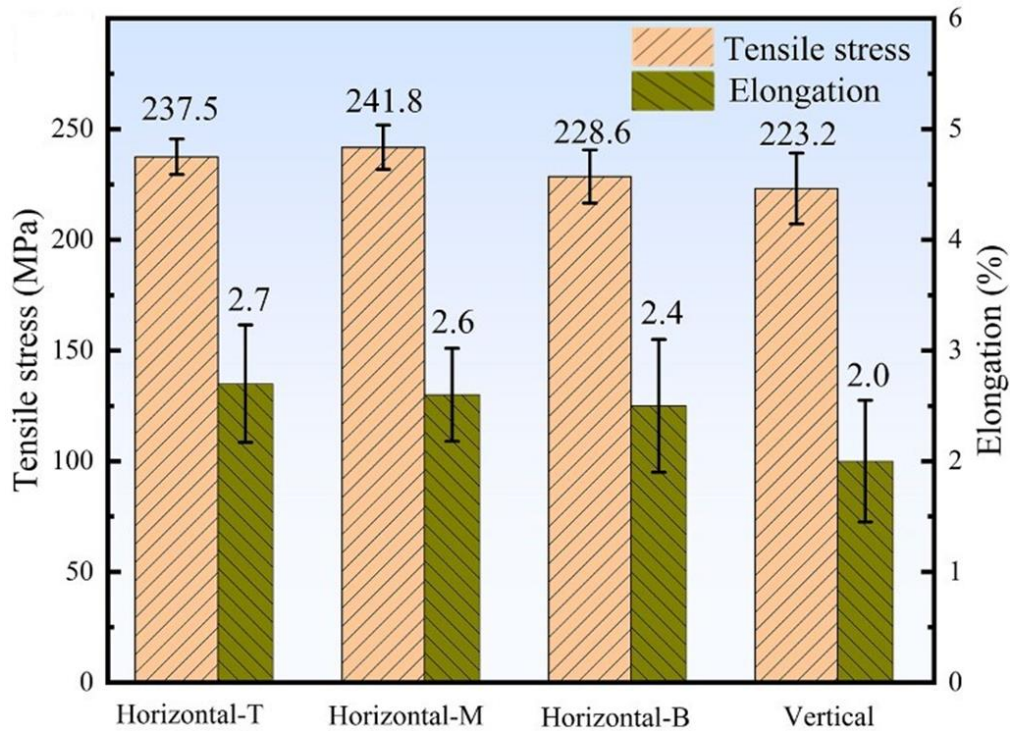


Figure 14 – Tensile stress and elongation of DED-Arc-fabricated Al- Zn-Mg-Cu alloy in different build directions [142].

Similarly, Hu et al. [143] found that the anisotropic microstructure of Al-Zn-Mg-Cu alloys fabricated via DED-Arc significantly influences their mechanical response, with horizontally oriented samples exhibiting a higher tensile strength than those built in the vertical direction. The superior tensile strength of horizontally oriented DED-Arc samples is primarily attributed to a stronger intra-layer cohesion, more favourable grain orientation and the absence of weak interlayer interfaces, which are more susceptible to imperfections and failure under tensile loading [144,145]. This directional dependence highlights the need for further optimisation to enhance the mechanical reliability and mitigate the anisotropy of AM-processed aluminium alloys.

As previously mentioned, researchers have focused on incorporating inoculant particles (fine ceramic particles – TiC and TiN) into the material to improve the microstructure, promote heterogeneous nucleation, refine the grain morphology, and consequently, enhance the mechanical performance by addressing the anisotropy [124,126,146,147]. Fu et al. [147] observed that the introduction of TiC into 7075 improved its dynamic properties compared to unreinforced AM-fabricated samples, which was evaluated by split Hopkinson pressure bars

(SHPB). For the unreinforced ones, the maximum tensile stress observed reached approximately 600 MPa, whereas TiC reinforced samples exhibited stresses about 50 MPa higher. Furthermore, Chi et al. [146] reported that TiC-reinforced deposits exhibited a uniform mechanical behaviour across all orientations, effectively mitigating anisotropy. Following a T6 heat treatment, these reinforced structures achieved a microhardness of 223 HV and an ultimate tensile strength of 606 MPa, exceeding the performance of wrought 7075 (530 to 565 MPa) [148].

Despite limited research on the fatigue behaviour of Al-Zn-Mg-Cu alloys processed by DED-Arc, Morais et al. [117] identified substantial variability in axial fatigue test results, particularly at higher stress levels (Figure 15). This variability was likely attributed to material heterogeneity and residual porosity.

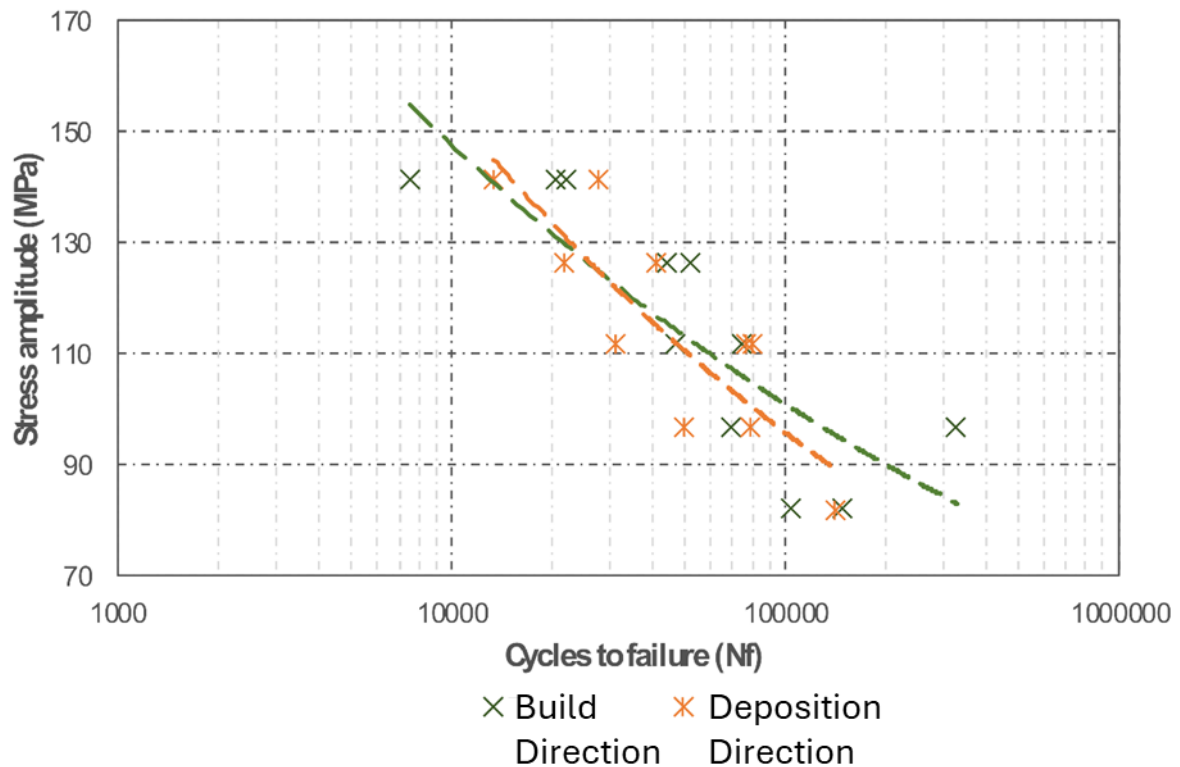


Figure 15 - S-N curves of longitudinal and transverse specimens of DED-Arc manufactured Al-Zn-Mg-Cu alloy in the T73 condition. Adapted from [117].

In their study, the primary site of fracture initiation across most specimens was found to be dispersed pores, presenting volumetric pore fraction changes along the height of the sample. Post-test examination of the fracture surfaces revealed that cracks commonly initiated at or near surface pores. In some cases, these pores were initially internal or subsurface

imperfections that emerged near the surface due to machining and polishing processes. Additionally, some intergranular brittleness was observed, potentially resulting from minor oscillations in deposition conditions (such as current, voltage, anchoring), which could have led to a reduction in fatigue performance. The intergranular decohesion in the region between the pore and surface, that possibly generated the initiation site is observed in Figure 16. Despite the observed differences in fracture behaviour, the material exhibited nearly identical performance in both longitudinal and transverse orientations, indicating its potential for mechanical applications due to reduced anisotropy.

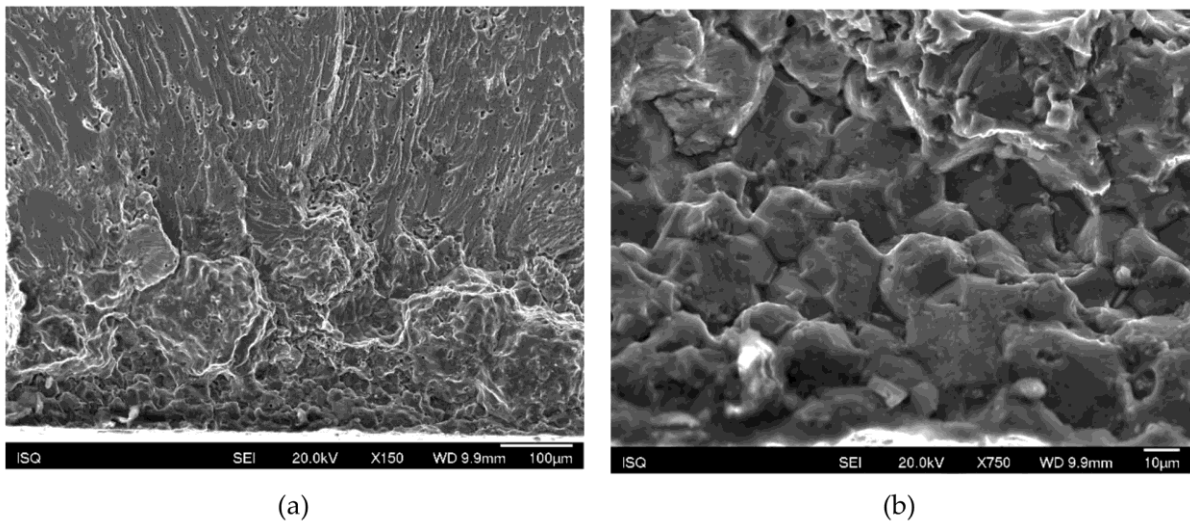


Figure 16 – DED-Arc Al–Zn–Mg–Cu alloy in the T73 condition sample subjected to fatigue testing, highlighting: (a) initiation site of a fatigue crack; (b) detail of the region between the pore and the surface, showing intergranular decohesion [117].

Also, the tensile strength reached more than 600 MPa, superior to wrought 7075 (530 to 565 MPa) [148]. Similarly, Guo et al. [149] reported that fatigue fractures in Al-Zn-Mg-Cu-Sc alloys initiated at regions of porosity. By employing interlayer friction stir processing (FSP), they were able to enhance the fatigue performance up to 170 MPa due to porosity elimination. After T6 heat treatment, the fatigue strength significantly increased to 250 MPa in both horizontal and vertical directions for 10^7 cycles when comparing S-N curves for different test conditions, achieving isotropic properties. The observed fatigue strength was higher than that documented for the same material in other studies [117] (Figure 15). Fatigue fractures in their study were primarily linked to coarse second-phase particles (η and η' phases) that had not dissolved into the aluminium matrix.

Achieving the high mechanical strength required for Al-Zn-Mg-Cu alloys in AM applications necessitates a comprehensive understanding of the processing mechanisms that

govern material behaviour. Research efforts have primarily focused on optimising heat treatment strategies [150,151], refining process parameters [143,152] and developing hybrid manufacturing approaches [153,154] to improve the structural integrity and mechanical properties. The application of a T6 heat treatment (470 °C solution treatment for 2 hours followed by artificial aging at 120 °C for 24 hours) to the 7075 aluminium alloy reinforced with TiB₂ resulted in a marked enhancement of the mechanical performance. Specifically, the tensile strength increased from 361.8 ± 4.8 MPa to 510.2 ± 5.4 MPa, the microhardness increased from 145 ± 5 HV to 190 ± 4 HV and the elongation rose slightly from $9.5 \pm 0.5\%$ to $10.2 \pm 0.4\%$ [150]. Wang et al. [151] found that heat treatment significantly improved the performance of 7075 aluminium alloys. The T6 and retrogression and re-aging (RRA) [155] treated samples exhibited the highest yield strength, approximately 470 MPa and elongation of about 4–5%, besides achieving a 24% increase in tensile strength compared to the as-deposited condition. RRA is a two-step heat treatment designed to combine the high strength of T6 with the enhanced stress corrosion resistance of T7, achieved by briefly heating the alloy to an intermediate temperature (retrogression) and then re-aging at a lower temperature. Qin et al. [152] observed that the tensile strength remained stable across different heat inputs, increased heat input led to higher porosity and a significant reduction in elongation from 3.7% to 2.4%, underlining the importance of process control for optimising both strength and ductility in additively manufactured Al-Zn-Mg-Cu-Sc alloys. Hybrid DED-Arc techniques, such as oscillating laser-arc [153] and ultrasonic-assisted [154] processes, can significantly enhance the mechanical performance of fabricated Al alloy parts. The use of ultrasonic vibrations contributes to pronounced grain refinement, reduction of grain boundary segregation and more uniform microstructures. These improvements lead to an increased tensile strength, improved hardness and enhanced ductility, while also mitigating common DED-Arc imperfections such as porosity and anisotropy [154]. As a result, hybrid DED-Arc approaches enable the production of aluminium alloy components with superior and more consistent mechanical properties. Continued advancements in these areas will be critical for expanding the applicability of DED-Arc in high-performance aerospace and structural applications.

4. Future developments

The application of 7xxx series Al alloys in arc-based additive manufacturing presents significant potential for industries such as aerospace, automotive and defence. However, due to its high strength and susceptibility to hot cracking, achieving optimal mechanical properties

and process stability remains a challenge. Future research and advancements in processing Al-Zn-Mg-Cu alloys are expected to focus on the following key areas:

1. **Process optimisation** – Advanced DED-Arc techniques, such as hybrid manufacturing and real-time process control, can be explored for a more accurate control of heat input, interlayer cooling and deposition strategies to minimise imperfections and improve the mechanical performance.
2. **Microstructural refinement** – Grain refinement techniques, including the addition of inoculants, interlayer deformation, or tailored thermal cycling, can enhance the microstructure, reduce porosity and anisotropy while improve ductility and strength.
3. **Post-processing treatments** – Improved heat treatment strategies, such as novel aging processes, may further enhance the mechanical properties of DED-Arc built 7xxx series Al alloys, reducing residual stresses and improving fatigue resistance. This may also enable improved control of precipitation when multiple families of precipitates are present, for example through the addition of grain refining elements.
4. **Alloy customisation** – The development of custom made 7xxx Al alloys specific for DED-Arc application, with adjusted compositions to reduce hot cracking susceptibility, porosity and enhance weldability.
5. **Computational modelling and AI integration** – The use of machine learning and computational simulations will help to predict and optimise deposition parameters, mechanical properties and imperfection formation, leading to more efficient DED-Arc processes.
6. **Industrial applications and certification** – As research advances, efforts are focused on qualifying DED-Arc produced 7xxx Al alloy components for critical applications, particularly in the aerospace and military sectors, to ensure compliance with industry standards and enable widespread adoption. These challenges become even more evident when producing complex and large parts, where efficient heat accumulation control and effective management of interpass temperature across the entire component are required.

Future developments in DED-Arc of 7xxx series Al-Zn-Mg-Cu alloys will likely lead to improved material performance, process reliability and broader applications across industries that demand lightweight yet high-strength components.

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Authors Contributions

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Conflicts of Interest

The authors declare no competing interests.

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