



Wire Arc Additive Manufacturing for Lightweight Material Applications: A Systematic Literature Review

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ARTICLE INFO

Article history:

Received 21.03.2026
Revised 28.04.2026
Accepted 17.05.2026

Keywords:

Wire arc additive manufacturing;
Lightweight alloys; Aluminum alloy;
Titanium alloy; Magnesium alloy

ABSTRACT

Wire arc additive manufacturing (WAAM) is increasingly used to fabricate large lightweight metal components because it combines wire feedstock, arc-based heat sources, high deposition rate, and high material utilization. This systematic literature review evaluates recent progress in WAAM for aluminum, titanium, and magnesium alloys, with emphasis on process parameters, microstructure, mechanical properties, defects, and industrial applications. The review followed the PRISMA 2020 framework and searched three academic search platforms using six structured queries covering WAAM, lightweight alloys, process parameters, mechanical behavior, microstructure, defects, and applications. From 1,052 records, 305 duplicates were removed, 747 records were screened, 270 papers were assessed in full text, and 265 studies were included in the evidence synthesis. Aluminum alloys were the most frequently reported material system, particularly Al-Mg, Al-Si, Al-Cu, and Al-Zn-Mg-Cu alloys, followed by Ti-6Al-4V and magnesium alloys such as AZ31, AZ91, and WE43. The synthesis shows that heat input, wire feed speed, travel speed, interpass temperature, shielding gas, and deposition strategy strongly control bead geometry, grain morphology, porosity, residual stress, and anisotropy. Cold metal transfer and pulsed arc variants generally improve process stability for aluminum alloys. At the same time, titanium and magnesium systems require stricter oxidation and thermal-cycle control. Optimized WAAM parts can approach wrought-material properties. However, porosity, hot cracking, surface waviness, distortion, and limited in-situ quality assurance remain barriers to wider certification. Future work should prioritize closed-loop monitoring, WAAM-specific alloy design, hybrid post-processing, fatigue qualification, and life-cycle assessment for large-scale lightweight structures. This review provides a concise evidence map to support parameter selection and research planning for WAAM-based lightweight components.

1. Introduction

Wire arc additive manufacturing (WAAM) is an arc-based directed energy deposition process that fabricates metallic components by continuously feeding a consumable wire into a controlled weld pool. The molten material is deposited layer by layer according to a predefined toolpath until the desired geometry is achieved. Compared with powder-bed fusion and conventional subtractive manufacturing routes, WAAM offers several practical advantages, including higher deposition rates, lower feedstock cost, simpler material handling, and substantially improved material utilization for medium- to large-scale metallic parts [1-3]. These advantages make WAAM particularly attractive for producing structural components, where the buy-to-fly ratio, manufacturing lead time, and raw material consumption are critical considerations.



The relevance of WAAM becomes even more significant when applied to lightweight metallic materials. Aluminum, titanium, and magnesium alloys are widely used in transportation, aerospace, marine, biomedical, and structural engineering sectors because they provide favorable combinations of low density, specific strength, corrosion resistance, damage tolerance, and functional performance [4-8]. In aerospace structures, weight reduction directly contributes to lower fuel consumption and increased payload efficiency. In automotive and electric mobility applications, lightweight components enhance energy efficiency, extend driving range, and improve dynamic performance. In marine and offshore applications, corrosion-resistant aluminum and titanium alloys offer potential benefits for structural durability and maintenance reduction. Therefore, integrating WAAM with lightweight alloy systems is strategically important for advanced manufacturing and sustainable engineering.

Recent developments in robotic motion control, multi-axis deposition systems, cold metal transfer (CMT), pulsed gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), plasma arc welding (PAW), thermal monitoring, and numerical simulation have accelerated the technological maturity of WAAM. Robotic platforms enable complex deposition paths and near-net-shape fabrication. At the same time, advanced arc modes provide improved control over heat input, droplet transfer, bead geometry, and process stability. At the same time, thermal cameras, pyrometers, acoustic sensors, machine vision systems, and computational models are increasingly used to understand melt pool behavior, predict thermal history, and support defect prevention. These developments have expanded WAAM from a laboratory-scale deposition method into a promising manufacturing route for large and customized engineering components.

For aluminum alloys, current WAAM research mainly focuses on controlling heat input, reducing porosity, improving bead stability, refining grain structure, and optimizing post-deposition heat treatment [9-16]. Aluminum alloys are highly attractive for WAAM because of their low density and wide industrial availability. However, they are also sensitive to hydrogen-induced porosity, oxide formation, hot cracking, and solidification-related defects. The selection of welding mode, wire feed speed, travel speed, shielding gas flow rate, interpass temperature, and deposition strategy strongly influences the final microstructure and mechanical performance. In high-strength aluminum alloys, such as the 2xxx and 7xxx series, additional challenges arise from segregation, precipitation behavior, and cracking susceptibility. Consequently, alloy-specific parameter optimization remains essential to obtain reliable WAAM-fabricated aluminum components.

For titanium alloys, especially Ti-6Al-4V, WAAM enables the fabrication of large, high-value components with reduced material waste compared with machining from forged billets. However, titanium alloys require strict control of atmospheric contamination because oxygen and nitrogen pickup can degrade ductility and fatigue resistance [17-20]. WAAM-fabricated titanium parts commonly exhibit columnar prior-beta grain structures, crystallographic texture, residual stresses, and anisotropic mechanical properties. Although tensile strength can be comparable to or exceed that of wrought materials, fatigue performance and fracture behavior are strongly influenced by internal defects, surface roughness, grain morphology, and post-processing conditions. Therefore, research on titanium WAAM increasingly emphasizes grain refinement, interlayer rolling, heat treatment, integration with machining, and fatigue qualification.

Magnesium alloys represent another important class of lightweight materials for WAAM. However, their processing remains more challenging than aluminum and titanium alloys. Their



low density makes them highly attractive for transportation and structural lightweighting; however, magnesium alloys are prone to oxidation, evaporation, hot cracking, and instability during arc-based deposition [21-25]. The limited availability of suitable magnesium welding wires also restricts broader research and industrial implementation. Process control is particularly important because excessive heat input may intensify evaporation and oxidation. In contrast, insufficient heat input may lead to a lack of fusion and poor interlayer bonding. Recent studies have explored pulse control, shielding optimization, alloy design, post-processing, and grain refinement strategies to improve the feasibility of WAAM for magnesium-based components.

Despite its advantages, the industrial adoption of WAAM for lightweight alloys is still limited by several technical and qualification-related issues. Repeatable quality, reliable mechanical properties, dimensional accuracy, surface finish, and standardized qualification procedures remain essential requirements for engineering implementation. The repeated heating and cooling cycles inherent to layer-wise deposition can generate heterogeneous microstructures, anisotropic tensile behavior, residual stresses, distortion, surface waviness, and local variation in mechanical properties [26-30]. These issues become more complex when large components, thin-wall structures, multi-pass deposition, or multi-material systems are involved. As a result, WAAM parts often require post-processing, such as machining, heat treatment, rolling, peening, friction stir processing, or surface finishing, to meet dimensional and performance requirements.

From a process–structure–property perspective, WAAM performance is governed by the interaction between arc energy, material composition, thermal history, solidification behavior, and deposition path. Heat input affects melt pool size, cooling rate, grain growth, porosity formation, and residual stress development. Wire feed speed and travel speed determine bead geometry, layer height, deposition efficiency, and interlayer bonding. Interpass temperature influences heat accumulation and microstructural coarsening, while shielding quality controls oxidation and gas-related defects. Therefore, a systematic understanding of parameter–microstructure–property relationships is necessary to define robust processing windows for each lightweight alloy system.

A focused synthesis is also needed because WAAM research maturity varies across lightweight materials. Aluminum alloys have received the greatest attention and currently show the highest readiness for industrial-scale application. Titanium alloys have demonstrated strong potential for aerospace and biomedical components but still require further work in fatigue reliability, oxidation control, and certification. Magnesium alloys remain at an earlier stage of development, with processing stability, wire availability, and defect control still requiring substantial investigation. Comparing these three material families within one review can help clarify which technological barriers are material-specific and which are common to WAAM as a manufacturing platform.

This review aims to evaluate the current state of WAAM for lightweight material applications by synthesizing recent evidence on process parameters, material behavior, applications, and remaining challenges. The specific research questions are: (1) what process parameters control WAAM of lightweight alloys; (2) how aluminum, titanium, and magnesium alloys perform after WAAM processing in terms of microstructure, defects, and mechanical properties; (3) what structural and transportation applications have been reported for WAAM-fabricated lightweight components; and (4) what challenges should be addressed to enable broader industrial implementation. By addressing these questions, this review provides a



consolidated understanding of the current progress, limitations, and future research directions for WAAM of lightweight metallic materials.

2. Methodology

2.1 Search strategy and study identification

The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 framework. Literature published from January 2021 to June 2026 was searched using three academic search platforms: SciSpace Deep Search, SciSpace Full Text Search, and Google Scholar. Six search strings were used to capture the relationship among WAAM, lightweight alloys, process parameters, microstructure, mechanical properties, defects, and applications (Table 1). The term “three platforms” is used here to correct the inconsistency in the original draft, which described the sources as six databases even though six search queries were distributed across three platforms.

Table 1. Search strategy used for study identification

Search platform	Search focus	Records
SciSpace Deep Search	WAAM process parameters and lightweight metal components including aluminum, titanium, and magnesium alloys	216
SciSpace Deep Search	Mechanical properties, microstructure, defect formation, and performance of lightweight materials processed by WAAM	436
SciSpace Full Text Search	Key process parameters and characteristics of WAAM for lightweight metal components	100
SciSpace Full Text Search	Mechanical properties, microstructure, defects, and performance characteristics of lightweight materials processed by WAAM	100
Google Scholar	WAAM AND aluminum/aluminium OR titanium OR magnesium AND process parameters OR microstructure OR mechanical properties OR defect	100
Google Scholar	WAAM AND aluminum OR titanium OR magnesium AND aerospace OR structural OR application OR optimization OR defect control	100

2.2 Eligibility criteria and screening

Records were screened using four inclusion criteria and three exclusion criteria. Studies were included if they focused on WAAM or arc-based wire-directed energy deposition, investigated aluminum, titanium, or magnesium alloys as the primary material system, reported process parameters and material characterization, and discussed structural relevance or comparisons with conventional manufacturing. Studies were excluded when they focused primarily on non-arc additive manufacturing, heavy metallic systems without a lightweight-alloy focus, or lacked empirical process-property data.

A two-stage screening process was applied. After deduplication, titles and abstracts were assessed using the eligibility criteria and a threshold score of 4.0. Full texts were then evaluated using a stricter threshold score of 4.5. The screening produced 265 studies for synthesis from 1,052 initially identified records.

2.3 Data extraction and synthesis

For each included study, data were extracted for material type, WAAM process parameters, mechanical properties, microstructure, defects, applications, and key findings. The synthesis was narrative and comparative because the experimental conditions, welding equipment, alloy chemistry, wire condition, shielding arrangement, specimen geometry, heat



treatment, and testing standards varied substantially across the included studies. Quantitative ranges are therefore reported as representative windows rather than pooled meta-analytic estimates.

3. Result and Discussion

3.1 Study selection

The literature search identified 1,052 records across the selected academic search platforms. These records were obtained using predefined search strings related to wire arc additive manufacturing, lightweight alloys, process parameters, mechanical properties, microstructure, defects, and engineering applications. Before screening, 305 duplicate records were removed to avoid repeated evaluation of the same publication. This deduplication process yielded 747 unique records eligible for title and abstract screening.

During the title and abstract screening stage, 477 records were excluded for not meeting the predefined eligibility criteria. The main reasons for exclusion were: the study did not specifically focus on WAAM technology, the material system was not related to lightweight alloys, the abstract did not provide sufficient technical detail, or the additive manufacturing route used a non-arc-based heat source such as laser-based directed energy deposition, powder bed fusion, or electron beam processing. This stage was important to ensure that only studies directly relevant to WAAM of aluminum, titanium, magnesium, or other lightweight alloy systems were retained for further assessment.

After abstract screening, 270 papers were selected for full-text assessment. At this stage, each article was evaluated more carefully based on its relevance to the research questions, the completeness of process-parameter information, and the availability of experimental data on material performance. Five papers were excluded during full-text assessment because they did not provide adequate process parameters or sufficient mechanical-property data to support systematic synthesis. In particular, studies that only provided general discussion without reporting deposition variables, microstructural evidence, or quantitative performance data were considered insufficient for inclusion.

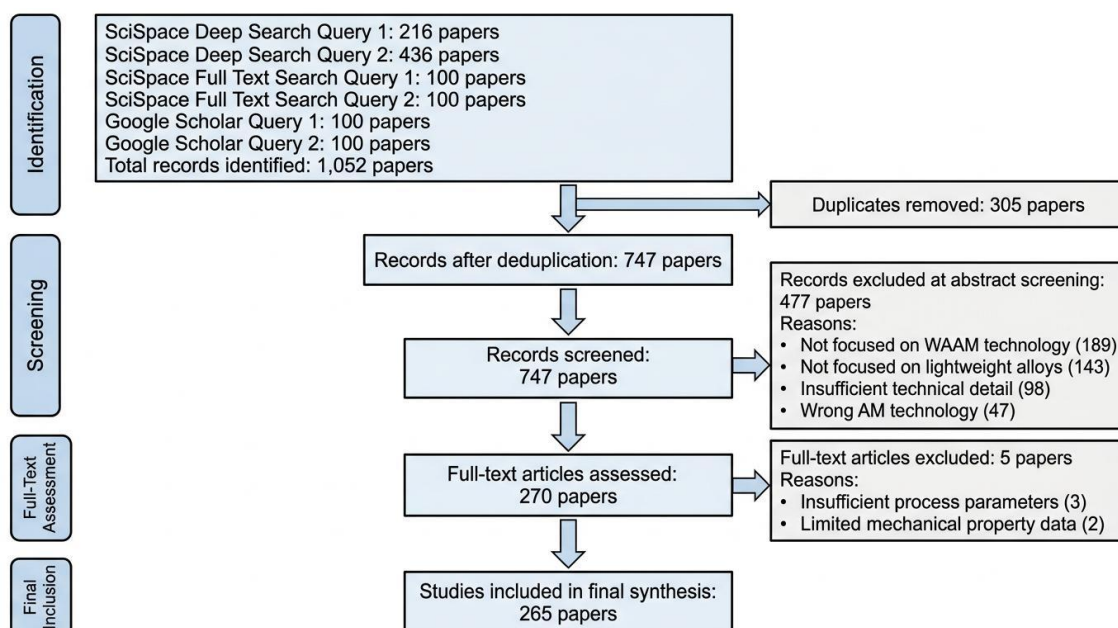


Figure 1. PRISMA 2020 flow diagram of the literature search and screening process

Consequently, the final synthesis included 265 studies, as summarized in the PRISMA flow diagram in **Fig. 1**. This final evidence base provides broad coverage of WAAM research



on lightweight materials, especially aluminum, titanium, and magnesium alloys. The relatively high number of included studies indicates that WAAM has become an increasingly active research field, particularly in process optimization, defect mitigation, microstructural control, mechanical property improvement, and industrial application readiness. The selected studies were then analyzed to identify dominant material systems, commonly used WAAM processes, parameter ranges, microstructural characteristics, mechanical-property trends, reported applications, and remaining research gaps.

3.2 Material distribution and research emphasis

Aluminum alloys dominated the evidence base because they combine low density, wide industrial use, high wire availability, and comparatively good weldability. Their extensive use in aerospace, marine, automotive, railway, and general structural applications also makes them a natural focus for WAAM research. The most frequently investigated aluminum systems were Al-Mg 5xxx alloys, Al-Si 4xxx alloys, Al-Cu 2xxx alloys, and high-strength Al-Zn-Mg-Cu 7xxx alloys [9-16]. Among these, Al-Mg alloys are often selected because they exhibit good weldability, corrosion resistance, and relatively stable deposition behavior. Al-Si alloys are attractive because silicon improves fluidity and can reduce hot-cracking susceptibility. Al-Cu alloys are widely investigated for aerospace-related applications because they can achieve high strength after appropriate heat treatment. Meanwhile, 7xxx aluminum alloys are of particular interest for their high strength-to-weight ratio. However, they are more difficult to process due to their susceptibility to cracking, segregation, and complex precipitation behavior.

The dominance of aluminum studies also reflects the practical compatibility between aluminum welding wire and arc-based deposition systems. Commercially available aluminum wires, such as ER4043, ER5356, ER5183, ER2319, and other alloy variants, allow researchers to explore a wide range of WAAM parameters without requiring extensive custom feedstock development. In addition, aluminum alloys respond strongly to changes in process parameters, including heat input, travel speed, wire feed speed, shielding gas, interpass temperature, and deposition strategy. These variables directly affect bead geometry, porosity formation, grain morphology, residual stress, and mechanical properties. Therefore, aluminum alloys provide a useful platform for studying fundamental WAAM process–structure–property relationships.

Titanium alloys were mainly represented by Ti-6Al-4V due to its strong relevance in aerospace, biomedical, and high-performance engineering [17-20]. Ti-6Al-4V is widely used in aircraft structures, engine-related components, medical implants, and other applications requiring high specific strength, corrosion resistance, and thermal stability. In WAAM research, titanium alloys are important because the technology can reduce material waste compared with conventional machining from expensive forged or rolled billets. However, titanium WAAM requires strict atmospheric protection because oxygen and nitrogen contamination can reduce ductility and fatigue performance. The literature therefore emphasizes shielding strategies, thermal-cycle control, columnar prior-beta grain refinement, residual-stress reduction, and post-deposition treatments such as annealing, interlayer rolling, machining, and surface finishing.

Magnesium alloys, including AZ31, AZ91, WE43, and related systems, were less frequently reported because of their high reactivity, tendency to evaporate, and susceptibility to cracking, which complicate arc deposition [21-25]. Magnesium has a very low density, making it highly attractive for lightweight structures, especially in automotive and



transportation applications where mass reduction is directly related to energy efficiency. However, WAAM of magnesium alloys remains technically demanding. Arc heat can promote oxidation, vaporization of alloying elements, unstable bead formation, and hot cracking. Furthermore, the availability of suitable magnesium welding wires is more limited than aluminum and titanium wires. These constraints explain why magnesium alloys are still less represented in the current evidence base.

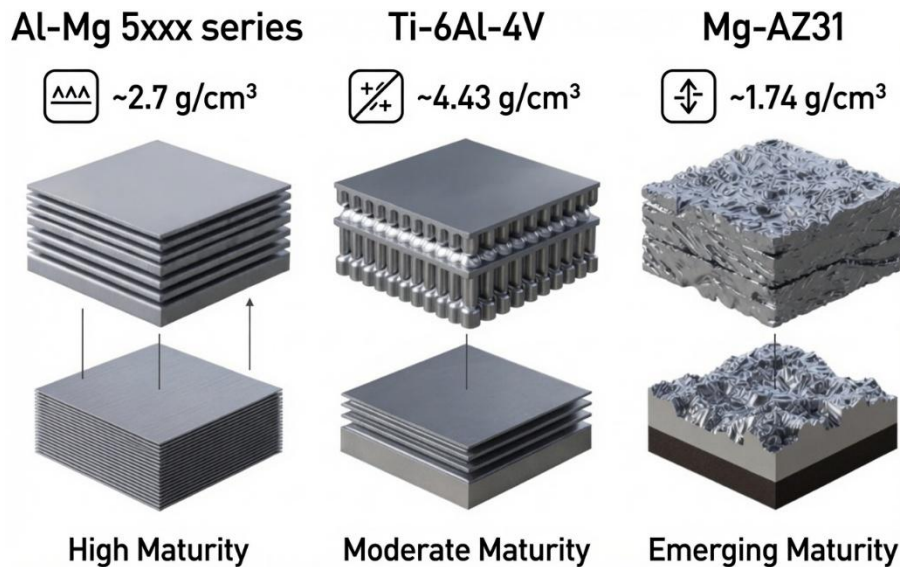


Figure 2. The distribution of WAAM maturity

This distribution indicates that WAAM maturity is highest for aluminum alloys, moderate for titanium alloys, and still emerging for magnesium alloys, as shown in **Fig. 2**. Aluminum WAAM has progressed from basic feasibility studies toward parameter optimization, post-processing, large-scale component fabrication, and application-oriented demonstrations. Titanium WAAM has also reached an advanced research stage, particularly for aerospace-grade Ti-6Al-4V. However, broader industrial adoption still depends on fatigue reliability, defect tolerance, oxidation control, and certification. Magnesium WAAM remains at an earlier stage, with many studies still focusing on deposition feasibility, microstructure formation, and defect mitigation.

Nevertheless, magnesium studies are increasing because its very low density offers an important route for weight-sensitive structures when oxidation and metallurgical stability can be controlled. Future progress in magnesium WAAM will likely depend on improved wire feedstock, advanced shielding systems, low-heat-input arc modes, alloy modification, and hybrid post-processing techniques. Overall, the material distribution shows that lightweight WAAM research is evolving from aluminum-centered process development toward a broader multi-material research field that includes titanium and magnesium alloys for high-value structural applications.

3.3 Process parameters for lightweight alloys

The principal WAAM variables are welding process, current, voltage, wire feed speed, travel speed, heat input, interpass temperature, wire diameter, shielding gas, torch angle, bead overlap, and deposition path. These variables are interdependent; for example, increasing wire feed speed often requires higher current, while increasing travel speed reduces heat input per unit length and changes bead geometry and cooling rate. Heat input is commonly estimated using **Eq. 1**:



$$H = \eta VI / v \tag{1}$$

where H is heat input, η is thermal efficiency, V is arc voltage, I is current, and v is travel speed. Excessive heat input generally coarsens grains, increases distortion, widens the heat-affected zone, and may increase porosity or hot cracking. Very low heat input, however, can cause lack of fusion, discontinuous bead formation, and poor interlayer bonding.

Table 2. Representative WAAM process windows and control issues for lightweight alloys

Material system	Common process variants	Wire feed speed	Travel speed	Interpass temperature	Main control issues
Aluminum alloys	CMT, Pulse, GMAW, PAW, CMT-pulsed, GTAW	2-10 m/min	200-800 mm/min	50-200 °C	Porosity, hot cracking in 2xxx/7xxx alloys, surface waviness, anisotropy
Titanium alloys	GTAW, PAW, GMAW, hot-wire variants	1-5 m/min	150-500 mm/min	100-300 °C	Oxidation, residual stress, columnar grains, fatigue scatter
Magnesium alloys	CMT, GMAW, GTAW, pulsed	1.5-6 m/min	200-600 mm/min	50-150 °C	Oxidation, evaporation, hot cracking, limited wire feedstock

For aluminum alloys, CMT and pulsed arc processes are frequently preferred because lower heat input and controlled droplet transfer improve arc stability, reduce spatter, and promote uniform bead formation [10-12]. Travel speed directly affects bead height, wall width, cooling rate, heat input per unit length, and grain size. Moderate travel speeds can refine the microstructure and improve tensile strength. However, excessive speeds can lead to underfill, discontinuous bead formation, and lack-of-fusion defects [11].

Interpass temperature is equally important because repeated reheating changes precipitate evolution, residual stress, and grain morphology [13-16]. In heat-treatable aluminum alloys, cyclic thermal exposure can dissolve or coarsen strengthening precipitates. In contrast, in non-heat-treatable Al-Mg alloys, it can still influence grain growth and local ductility. For titanium alloys, oxygen and nitrogen pickup must be minimized using high-purity argon, trailing shields, or chamber-based protection. GTAW provides precise heat control for thin walls, while GMAW and PAW improve deposition rate for larger builds [17-20]. For magnesium alloys, shielding effectiveness and thermal management are even more critical, as molten magnesium oxidizes rapidly and is prone to evaporation and cracking [21-25].

3.4 Mechanical properties and microstructure

The microstructure of WAAM components is governed by directional heat flow, cyclic reheating, solidification rate, and post-processing. Many aluminum deposits exhibit mixed columnar and equiaxed grains with layer bands. At the same time, heat-treatable alloys show property changes associated with precipitation and dissolution during repeated thermal cycling. Grain refinement has been achieved through alloying additions such as Sc, Zr, TiB₂, nanoparticles, interlayer friction stir processing, ultrasonic assistance, or mechanical peening [14-16], [26-30].

Table 3. Summary of material performance trends reported for WAAM lightweight alloys

Material system	Microstructural tendency	Representative mechanical behavior	Potential applications
Al-Mg 5xxx	Mixed equiaxed-columnar grains; porosity sensitive to hydrogen and transfer mode	UTS about 280-320 MPa; elongation about 15-25%	Marine, automotive, lightweight structural walls



Material system	Microstructural tendency	Representative mechanical behavior	Potential applications
Al-Cu 2xxx	Precipitation-strengthened; heat treatment improves theta-phase distribution	As-deposited UTS about 250-280 MPa; T6 can exceed 370 MPa	Aerospace panels and stiffened structures
Al-Zn-Mg-Cu 7xxx	High strength but hot-cracking sensitive; Sc/Zr additions refine grains	Heat-treated UTS can exceed 500 MPa in optimized alloys	High-performance aerospace structures
Ti-6Al-4V	Alpha-beta lamellar microstructure; prior-beta columnar grains common	UTS about 900-1050 MPa; yield strength about 850-950 MPa	Aircraft structures, biomedical and repair applications
Mg alloys	Fine equiaxed grains possible with optimized pulsed/CMT processing	UTS about 200-280 MPa in common AZ systems; higher with post-processing	Ultra-lightweight panels, repair, exploratory structural parts

Al-Mg alloys are among the most robust aluminum systems for WAAM because they provide good weldability, corrosion resistance, and relatively stable deposition behavior. Their tensile properties are often close to wrought or conventionally welded counterparts when porosity is controlled [10-13]. Al-Cu and Al-Zn-Mg-Cu systems offer higher strength after heat treatment. However, segregation, hot cracking, residual stress, and complex precipitation response require more careful control of heat input, interpass temperature, and alloy chemistry [9], [14-16].

Ti-6Al-4V deposits can meet or exceed minimum wrought strength requirements. However, ductility and fatigue life are more sensitive to columnar prior-beta grains, anisotropy, surface waviness, and internal defects. Annealing, interpass rolling, interpass milling, and surface finishing can reduce residual stress and improve performance consistency [17-20], [29]. Magnesium alloys can exhibit fine-grained microstructures compared with their cast counterparts. However, oxidation control, feedstock availability, evaporation, and crack prevention remain central barriers [21-25].

3.5 Defects, dimensional accuracy, and quality assurance

Porosity is the most frequently reported defect in WAAM of lightweight alloys because the process involves repeated melting, solidification, and reheating under arc-based thermal cycles. In aluminum alloys, porosity is commonly associated with hydrogen absorption from moisture, wire contamination, oxide films, inadequate surface cleaning, or shielding-gas instability. During solidification, the solubility of hydrogen decreases sharply, causing gas bubbles to become trapped inside the deposited metal. If these pores are distributed throughout the wall, they can reduce tensile strength, elongation, fatigue life, and fracture resistance. The problem becomes more severe when the wire surface is contaminated, the shielding gas contains moisture, or the melt pool is unstable during droplet transfer.

Lack-of-fusion porosity may also occur when heat input, bead overlap, or interlayer remelting is insufficient. Unlike gas porosity, lack-of-fusion defects are often irregularly shaped. They are usually located at interlayer or inter-track boundaries. These defects act as stress concentrators and can significantly reduce mechanical reliability, particularly under cyclic loading. In thin-wall structures, insufficient fusion may appear as discontinuous bonding between layers. At the same time, in multi-pass components it can occur between adjacent tracks when the overlap ratio is not properly controlled. Therefore, heat input, travel speed, wire feed speed, layer height, and deposition path must be optimized together to minimize both gas-related porosity and lack-of-fusion defects.



For high-strength aluminum and magnesium alloys, hot cracking is another critical defect. Hot cracking is closely related to solidification temperature range, thermal strain, grain-boundary liquid films, and the ability of the remaining liquid phase to feed solidification shrinkage. In Al-Cu and Al-Zn-Mg-Cu alloys, segregation of solute elements during solidification can promote the formation of low-melting-point liquid films along grain boundaries. When tensile thermal stress develops during cooling, these weakened regions may open into cracks. Magnesium alloys are also prone to cracking due to their high thermal sensitivity, tendency to oxidize, and limited tolerance to unstable arc conditions. Grain refinement, reduced heat input, controlled interpass temperature, modified alloy chemistry, and optimized deposition sequence are commonly proposed to reduce hot-cracking susceptibility.

Titanium alloys are generally less prone to hydrogen porosity when high-purity shielding is properly applied. However, their performance can be strongly affected by oxygen and nitrogen pickup, residual stress, surface waviness, and internal discontinuities. Oxygen contamination can increase hardness and strength but reduce ductility and fracture toughness. This effect is particularly important for Ti-6Al-4V because titanium has high affinity for interstitial elements at elevated temperature. In addition, the steep thermal gradients and repeated thermal cycles in titanium WAAM can generate residual tensile stresses and columnar prior-beta grain structures, which may contribute to anisotropic mechanical properties. Even small internal defects or surface notches can become critical under fatigue loading, especially for aerospace components (**Fig. 3**).

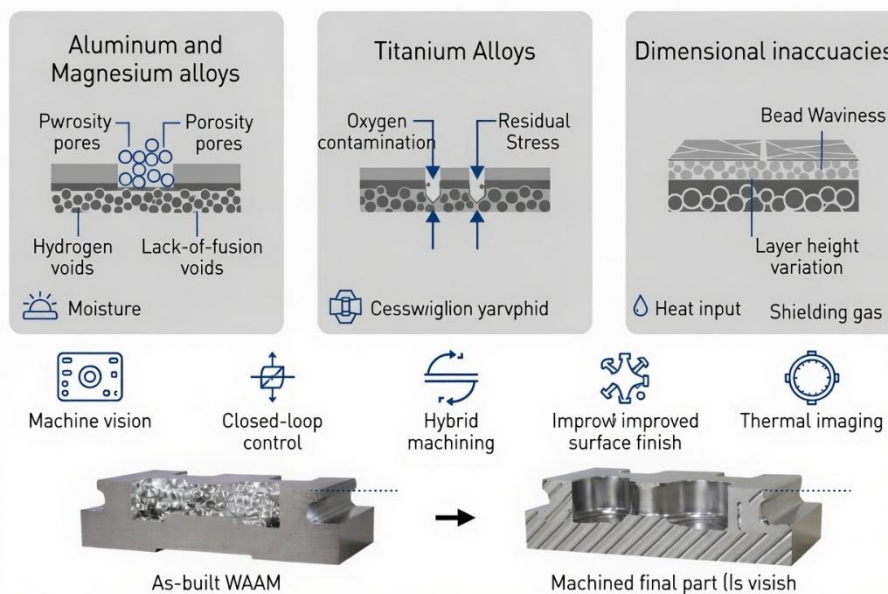


Figure 3. Internal defects or surface notches in WAAM

Dimensional accuracy is limited by bead waviness, layer-height variation, heat accumulation, and path-dependent distortion. The geometry of each deposited layer depends on the interaction between arc power, wire feed speed, travel speed, melt pool fluidity, shielding condition, and substrate temperature. If heat accumulation is not controlled, the upper layers may become wider or less stable than the lower layers. This can generate non-uniform wall thickness, excessive surface waviness, local collapse, or deviation from the intended toolpath. In multi-layer, multi-pass deposition, small errors in bead height and width may accumulate progressively, leading to poor geometric accuracy and increased machining allowances.



Thermal distortion is another important limitation in WAAM, as the localized heat source causes repeated expansion and contraction during deposition. The magnitude of distortion depends on component geometry, clamping condition, substrate thickness, deposition sequence, heat input, and cooling rate. Large components are especially sensitive to distortion because they undergo longer thermal cycles and accumulate greater residual stress. Path planning can therefore influence not only build time and deposition efficiency but also dimensional stability. Alternating deposition direction, balanced layer sequencing, controlled dwell time, and optimized start-stop positions are often used to reduce thermal imbalance and distortion.

Most WAAM parts still require machining to achieve final tolerance and surface finish. This requirement reduces the material-efficiency advantage, especially when near-net-shape control is poor. Although WAAM can achieve higher material utilization than conventional machining from a billet, excessive surface waviness or dimensional deviation increases the amount of material that must be removed during finishing. For high-value, lightweight alloys such as titanium and high-strength aluminum, this additional machining can increase costs, lead times, and tool wear. Surface finish is also critical for fatigue performance because rough surfaces, sharp waviness valleys, and partially fused regions can initiate cracks under cyclic loading.

Current research therefore increasingly combines WAAM with machine vision, thermal imaging, acoustic emission, closed-loop bead control, interlayer mechanical processing, and hybrid machining [26-30]. Machine vision can be used to monitor bead width, layer height, arc position, and surface irregularity during deposition. Thermal imaging and infrared sensing can track heat accumulation, cooling rate, melt pool size, and interpass temperature. Acoustic emission and arc-signal monitoring can provide indirect information on arc stability, droplet transfer, and possible defect formation. When these monitoring systems are integrated with adaptive control algorithms, process parameters can be adjusted in real time to maintain stable bead geometry and reduce defect formation.

3.6 Applications and implementation readiness

The main application driver for WAAM is the fabrication or repair of large metallic components that are expensive to machine from billet. In aerospace, the strongest value propositions are reduced buy-to-fly ratios, shorter lead times for low-volume parts, and the ability to manufacture stiffened or topology-optimized structures. In the marine sector, WAAM is attractive for aluminum repair and replacement of large components. In automotive and electric vehicle development, WAAM can support lightweight prototypes, chassis-related structures, suspension components, and customized components where tooling costs are prohibitive (**Fig. 4**).

Despite these advantages, certification remains challenging. Industrial users need reliable process windows, traceable input materials, calibrated sensors, validated thermal models, standardized post-processing, nondestructive testing, and fatigue data. For safety-critical structures, tensile strength alone is insufficient; crack growth, fatigue behavior, residual stress distribution, corrosion, impact performance, and environmental durability must be documented.

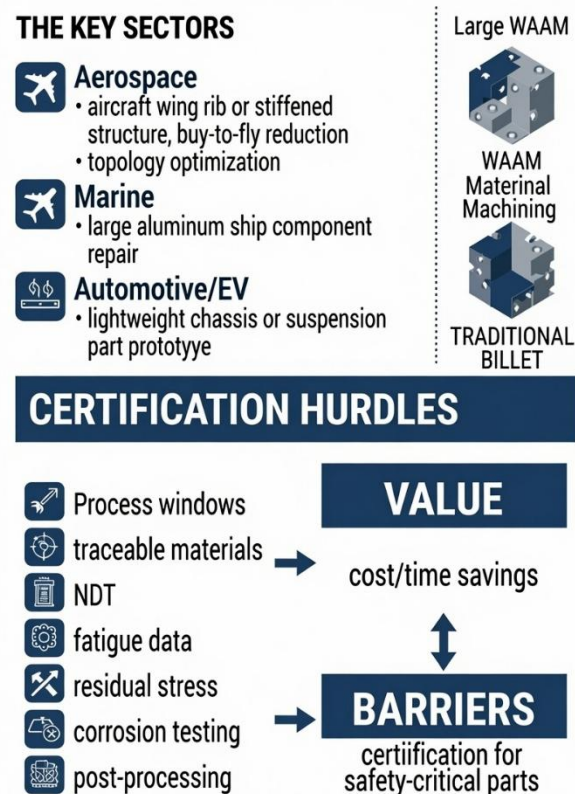


Figure 4. WAAM application sectors

3.7 Research gaps and future directions

Key research gaps in WAAM are shown in Fig. 5. The first is real-time quality assurance. Many studies still rely on post-process characterization methods such as metallography, tensile testing, hardness measurement, surface inspection, and computed tomography. Although these methods are useful for evaluating the final quality of WAAM components, they are not sufficient for industrial production, as defects may already be embedded in the part by the time inspection is performed. Industrial-scale WAAM requires defect detection and process correction during deposition rather than after fabrication is complete. Therefore, closed-loop control based on melt-pool temperature, bead geometry, arc voltage, current signal, acoustic emission, thermal imaging, and machine vision should be prioritized. These monitoring systems can help identify abnormal melt-pool behavior, unstable droplet transfer, excessive heat accumulation, bead-height variation, lack of fusion, and potential porosity. When combined with adaptive control algorithms, the system can automatically adjust wire feed speed, travel speed, arc power, interpass cooling time, or deposition path to maintain stable process conditions.

The second research gap is alloy design. Conventional filler wires were originally developed for welding, not for repeated layer-by-layer arc deposition. In WAAM, the material undergoes cyclic remelting, reheating, directional solidification, and heat accumulation, all of which differ from conventional welding conditions. As a result, standard commercial wires may not always provide the best combination of crack resistance, grain refinement, precipitation behavior, and mechanical stability. WAAM-specific aluminum and magnesium wires with improved crack resistance, oxide management, and precipitation response are therefore needed. For aluminum alloys, alloy design should focus on reducing hot cracking, controlling hydrogen porosity, improving grain refinement, and maintaining strengthening precipitates



after repeated thermal cycling. Additions such as Sc, Zr, TiB₂, rare-earth elements, or nanoparticle refiners may offer potential benefits. However, their costs, availability, and process compatibility must be carefully evaluated.

The third research gap is the integration of hybrid processing. WAAM alone can achieve high deposition rates and material efficiency, but the as-deposited parts often exhibit surface waviness, residual stress, anisotropic microstructure, and dimensional deviations. Hybrid processing techniques such as interlayer friction stir processing, rolling, peening, ultrasonic assistance, laser shock peening, heat treatment, interlayer milling, and finish machining can reduce anisotropy and improve dimensional quality. Interlayer rolling and friction stir processing can refine grain structure, reduce porosity, and improve isotropy. Peening and ultrasonic assistance can modify residual stress and improve surface integrity. Heat treatment can improve precipitation behavior and reduce residual stress, especially in heat-treatable aluminum and titanium alloys. Finish machining is still required for many engineering components to achieve final tolerance and surface finish.

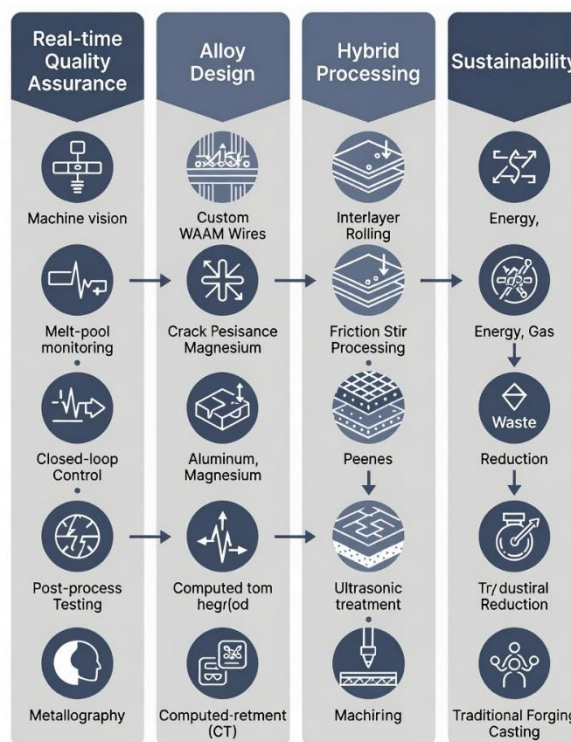


Figure 5. Key research gaps in WAAM

The fourth research gap is sustainability assessment. WAAM is often described as a material-efficient and sustainable manufacturing process because it uses wire feedstock and can produce near-net-shape parts with lower material waste than subtractive machining. However, many studies make this claim qualitatively without detailed comparative analysis. Future research should quantify energy consumption, shielding gas use, wire waste, machining allowance, post-processing requirements, and life-cycle environmental impact relative to forging, casting, and conventional machining. Sustainability assessment should also consider the environmental burden of wire production, electricity use, inert gas consumption, failed builds, support structures, heat treatment, and final machining.

3.8 Expanded Scopus-indexed evidence base

The reference list was expanded from 30 to 60 items to reflect the international evidence base better. Priority was given to peer-reviewed articles from internationally indexed journals



and proceedings that are commonly covered by Scopus, including Additive Manufacturing, Journal of Manufacturing Processes, Journal of Materials Research and Technology, Materials Science and Engineering A, Journal of Materials Processing Technology, Materials & Design, Thin-Walled Structures, Journal of Magnesium and Alloys, Advanced Engineering Materials, and Materials Science and Technology. **Table 4** summarizes the additional references integrated into the discussion.

Table 4. Additional published articles integrated into the expanded WAAM evidence base

Theme	Main contribution	References
Aluminum alloy WAAM	Al-Mg, Al-Cu, Al-Zn-Mg-Cu, Al-Li, Al-Si systems, heat treatment, porosity, grain refinement	[31-50]
Titanium alloy WAAM	Ti-6Al-4V shielding, residual stress, interpass rolling, fatigue and microstructure	[51-54]
Review, defects, and quality improvement	General WAAM process review, process parameters, defects, and quality enhancement routes	[55-57]
Magnesium alloy WAAM	AZ31, AZ31B, WE43 processing, process mode effects, grain refinement and properties	[58-60]

3.9 Bibliometric mapping

To complement the systematic review, bibliometric maps were prepared from the titles of the 60 international articles integrated into the expanded evidence base. The bibliometric analysis was conducted to identify the intellectual structure of recent WAAM research and to support the qualitative synthesis presented in the previous sections. Terms with at least two occurrences were grouped into a VOSviewer-style co-occurrence analysis to show dominant themes, temporal emphasis, and topic density in the recent literature on WAAM for lightweight alloys. Although the mapping was not intended to replace full-text systematic analysis, it provides a useful visual overview of how research topics are connected across aluminum, titanium, and magnesium alloy studies.

The keyword mapping also helps clarify the relative maturity of different research directions. In a systematic review, narrative synthesis can describe material systems, process parameters, and defect mechanisms. However, bibliometric visualization provides an additional layer of evidence by showing which topics appear most frequently and how they cluster. Therefore, the VOSviewer-style figures were used to support the interpretation of research emphasis, emerging trends, and knowledge gaps. Three types of maps were generated: a keyword co-occurrence network (**Fig. 6**), an overlay visualization based on average publication year (**Fig. 7**), and a density visualization of dominant research themes (**Fig. 8**).

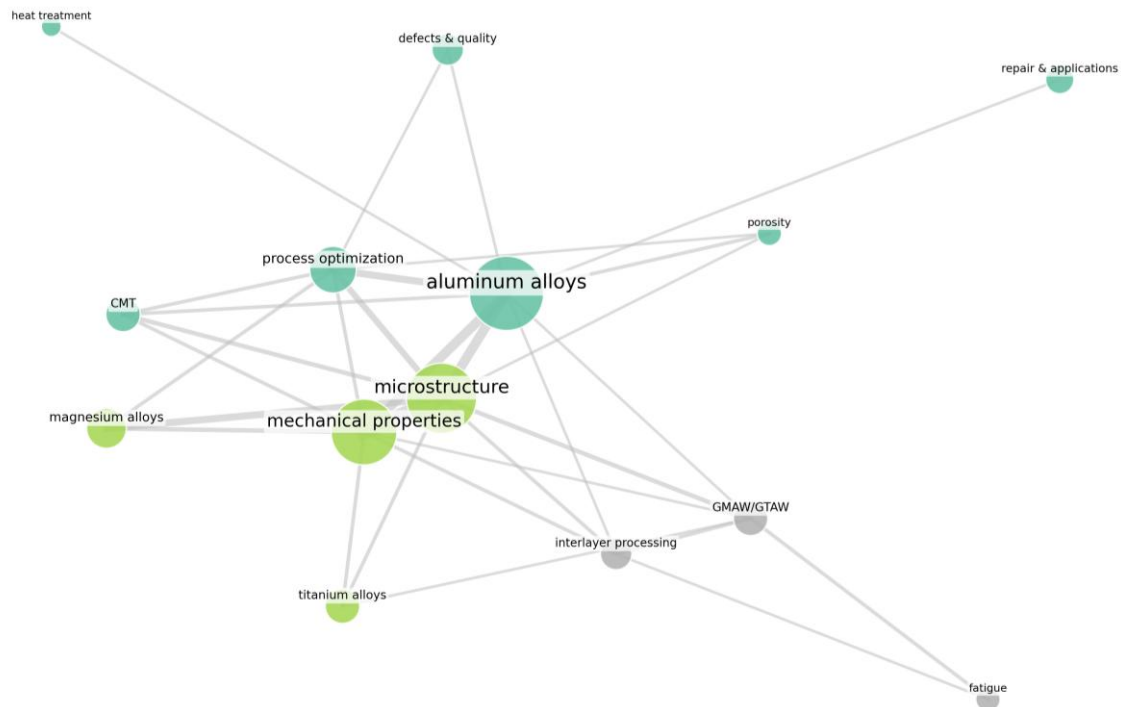


Figure 6. Co-occurrence network derived from the Scopus-indexed WAAM literature

The network visualization shows three dominant thematic clusters. The first cluster is centered on aluminum alloys, CMT/GMAW-based processing, and process optimization. This cluster confirms that aluminum alloys remain the most intensively studied lightweight material group in WAAM research. The strong connection between aluminum alloys, CMT, GMAW, heat input, travel speed, porosity, and mechanical properties indicates that current studies still focus heavily on process stability and parameter optimization. This is reasonable because aluminum alloys are sensitive to hydrogen porosity, oxide formation, heat accumulation, and solidification behavior. Therefore, most aluminum-related studies aim to establish stable process windows that yield acceptable bead geometry, low porosity, and reliable tensile properties.

The second cluster groups titanium and magnesium alloy studies with strong links to microstructure, mechanical properties, and post-processing. This cluster reflects the fact that titanium and magnesium alloys are often discussed in terms of metallurgical control rather than solely deposition efficiency. In titanium alloys, especially Ti-6Al-4V, research typically focuses on prior-beta grain morphology, texture, residual stress, fatigue behavior, and post-deposition treatments. In magnesium alloys, the dominant concerns are oxidation, evaporation, hot cracking, and grain refinement. The connection between these materials and post-processing terms indicates that achieving acceptable performance often requires additional treatments such as heat treatment, interlayer rolling, milling, laser shock peening, or other hybrid processing strategies.

The third cluster is associated with defects, quality control, fatigue, corrosion, and application-oriented terms. This cluster is important because it shows that WAAM research is no longer limited to demonstrating deposit formation. Instead, many studies are moving toward engineering qualification, component reliability, and service performance. The presence of fatigue, corrosion, residual stress, surface quality, and repair-related terms indicates that the field is progressing toward application readiness. These topics are particularly relevant for aerospace, automotive, marine, and structural components, where static strength alone is insufficient to justify industrial adoption.

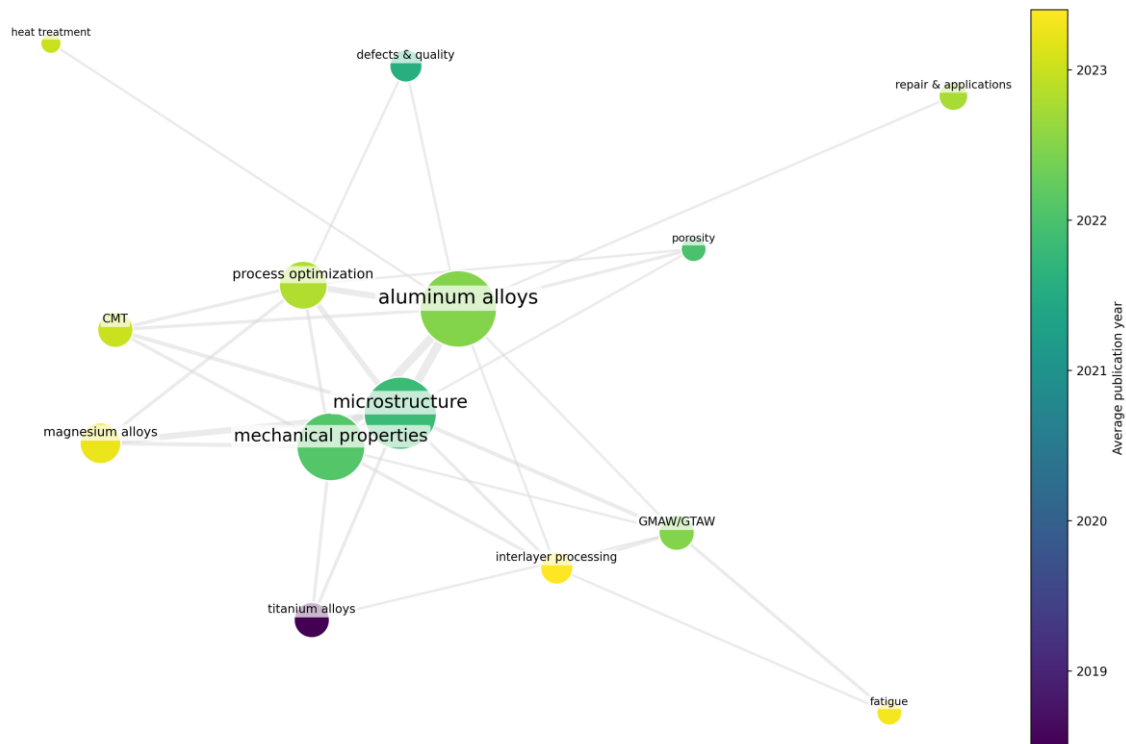


Figure 7. Overlay visualization of the main WAAM topics

The overlay map suggests that earlier studies were dominated by general process development, alloy feasibility, and basic mechanical-property evaluation. In the initial stage of WAAM research, many publications focused on whether specific lightweight alloys could be deposited successfully using arc-based additive manufacturing. These studies generally reported bead formation, wall geometry, simple tensile properties, hardness distribution, and basic microstructural features. Such topics form the foundation of WAAM development because they establish the feasibility of depositing aluminum, titanium, and magnesium alloys using wire-based feedstock.

More recent publications show a shift toward interlayer processing, fatigue performance, residual stress, multi-material development, and application-driven research. This trend indicates that WAAM research is transitioning from process feasibility toward quality assurance and industrial implementation. For example, studies on interlayer rolling, friction stir processing, ultrasonic-assisted processing, laser shock peening, and hybrid machining are increasingly reported because they can improve microstructural uniformity, reduce porosity, refine grains, and enhance fatigue performance. Similarly, residual stress and distortion have become more prominent topics because they directly influence dimensional accuracy and qualification of large-scale components.

The temporal trend also shows that research attention is expanding from aluminum-dominated studies to broader lightweight alloy systems. Aluminum alloys still occupy the central position, but titanium and magnesium topics are increasingly linked to advanced post-processing and performance reliability. This suggests that WAAM development is becoming more material-specific. Rather than applying a general deposition strategy to all alloys, current research increasingly recognizes that each lightweight material requires a different combination of heat input control, shielding strategy, deposition path, interpass management, and post-processing.

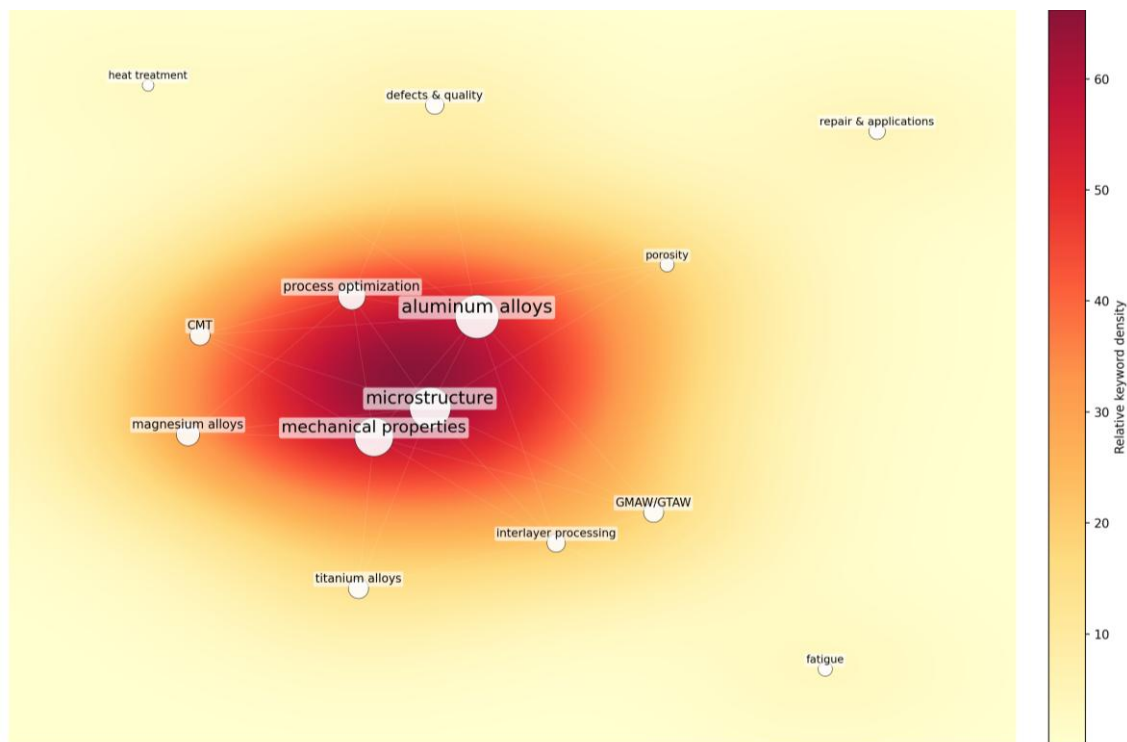


Figure 8. Density visualization highlighting the most intensively studied themes in WAAM for lightweight alloys

The density visualization confirms that the highest concentration of studies is still focused on aluminum alloys, microstructure, mechanical properties, and process optimization. These dense regions represent the core knowledge base of WAAM research for lightweight materials. The concentration of terms around aluminum alloys indicates that this material family has the most mature research foundation, especially for Al-Mg, Al-Si, Al-Cu, and Al-Zn-Mg-Cu systems. The strong density around microstructure and mechanical properties also confirms that WAAM performance is commonly evaluated through process–structure–property relationships.

Titanium and magnesium alloy themes are present, but they are less dense. This supports the earlier finding that research maturity remains highest for aluminum, followed by titanium, while magnesium is still developing. Titanium WAAM has progressed significantly, particularly for Ti-6Al-4V. However, the number of studies remains lower than for aluminum alloys due to higher material costs, stricter shielding requirements, and more demanding qualification procedures. Magnesium WAAM remains less dense because of limited wire availability, high oxidation sensitivity, evaporation issues, and cracking susceptibility. Nevertheless, the presence of magnesium-related terms in the density map indicates that this topic is gaining research attention, especially for applications requiring extreme weight reduction.

4. Conclusion

This systematic review shows that WAAM is a promising manufacturing route for large lightweight metal components, particularly when conventional machining generates high material waste. The most mature material system is aluminum alloy, especially Al-Mg alloys and increasingly high-strength Al-Cu and Al-Zn-Mg-Cu alloys. Titanium alloys such as Ti-6Al-4V show strong potential for aerospace and repair applications. In contrast, magnesium alloys remain technically challenging but attractive for ultra-lightweight structures. Process stability and material performance are controlled primarily by heat input, wire feed speed, travel speed,



interpass temperature, shielding quality, and deposition strategy. Optimized WAAM can produce tensile properties comparable to conventional materials, but porosity, hot cracking, residual stress, surface waviness, anisotropy, and insufficient in-situ monitoring still limit broader adoption. Future research should focus on closed-loop process control, WAAM-specific alloy development, hybrid post-processing, fatigue and durability qualification, and life-cycle assessment. These directions are essential for moving WAAM of lightweight alloys from laboratory-scale demonstration to certified industrial production.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgment

This research was funded by the Directorate of Research and Community Service, Ministry of Higher Education, Science, and Technology under the Regular Fundamental Research scheme with contract number B/17.71/UN34.9/PT/2025.

References

- [1] S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal, and P. Colegrove, "Wire + arc additive manufacturing," *Materials Science and Technology*, vol. 32, no. 7, pp. 641-647, 2016, doi: 10.1179/1743284715Y.0000000073.
- [2] Z. Pan, D. Ding, B. Wu, D. Cuiuri, H. Li, and J. Norrish, "Arc welding processes for additive manufacturing: A review," in *Transactions on Intelligent Welding Manufacturing*, 2018, doi: 10.1007/978-981-10-5355-9_1.
- [3] K. Derekar, "A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium," *Materials Science and Technology*, vol. 34, no. 8, pp. 895-916, 2018, doi: 10.1080/02670836.2018.1455012.
- [4] M. C. Chaturvedi et al., "Wire arc additive manufacturing: Review on recent findings and challenges in industrial applications and materials characterization," *Metals*, vol. 11, no. 6, 2021, doi: 10.3390/met11060939.
- [5] G. Langelandsvik, O. M. Akselsen, T. Furu, and H. J. Roven, "Review of aluminum alloy development for wire arc additive manufacturing," *Materials*, vol. 14, no. 18, 2021, doi: 10.3390/ma14185370.
- [6] B. O. Omiyale, T. O. Olumide, A. T. Akinlabi, and F. P. Kavishe, "Wire arc additive manufacturing of aluminium alloys for aerospace and automotive applications: A review," *Materials Science and Technology*, vol. 38, 2022, doi: 10.1080/02670836.2022.2045549.
- [7] D. Pan et al., "Research status and development trend of wire arc additive manufacturing technology for aluminum alloys," *Coatings*, vol. 14, no. 9, 2024, doi: 10.3390/coatings14091094.
- [8] A. Shah et al., "A review of the recent developments and challenges in wire arc additive manufacturing (WAAM) process," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 3, 2023, doi: 10.3390/jmmp7030097.
- [9] T. Klein et al., "Wire-arc additive manufacturing of a novel high-performance Al-Zn-Mg-Cu alloy: Processing, characterization and feasibility demonstration," *Additive Manufacturing*, vol. 37, 2021, doi: 10.1016/j.addma.2020.101663.
- [10] G. B. Ferreira et al., "Wire-arc additive manufacturing of Al-Mg alloy using CMT and PMC technologies," 2024, doi: 10.60692/m4bf3-0qs74.
- [11] T. M. M. et al., "Effect of travel speed on the properties of Al-Mg aluminum alloy fabricated by wire arc additive manufacturing," *Journal of Materials Engineering and Performance*, vol. 30, no. 10, 2021, doi: 10.1007/s11665-021-05959-y.
- [12] E. Aldalur, A. Suarez, and F. Veiga, "Metal transfer modes for wire arc additive manufacturing Al-Mg alloys: Influence of heat input in microstructure and porosity," *Journal of Materials Processing Technology*, 2021, doi: 10.1016/j.jmatprotec.2021.117271.
- [13] Y. Gu et al., "Investigation of microstructure and fracture mechanism of Al-5.0Mg alloys fabricated by wire arc additive manufacturing," *Journal of Materials Engineering and Performance*, vol. 30,



- no. 10, 2021, doi: 10.1007/s11665-021-05973-0.
- [14] T. Pickin et al., "Wire arc additive manufacturing of Al-Mg alloy with the addition of scandium and zirconium," *Materials*, vol. 14, no. 13, 2021, doi: 10.3390/ma14133665.
- [15] F. Guo et al., "Achieving high strength-ductility of Al-Zn-Mg-Cu alloys via hot-wire arc additive manufacturing enabled by strengthening precipitates," *Additive Manufacturing*, 2022, doi: 10.1016/j.addma.2022.103042.
- [16] J. Wang et al., "Enhancing mechanical properties and defect elimination in 2024 aluminum alloy through interlayer friction stir processing in wire arc additive manufacturing," *Materials Science and Engineering A*, 2024, doi: 10.1016/j.msea.2024.146582.
- [17] D. Erbe et al., "Development of microstructure and mechanical properties of Ti-6Al-4V processed by wire and arc additive manufacturing," *Advanced Engineering Materials*, vol. 25, no. 1, 2022, doi: 10.1002/adem.202201025.
- [18] R. S. Tanwar and S. Jain, "Ti based alloys for aerospace and biomedical applications fabricated through wire + arc additive manufacturing (WAAM)," *Materials Today: Proceedings*, vol. 98, 2024, doi: 10.1016/j.matpr.2023.11.121.
- [19] S. Seifi et al., "Low-cycle fatigue behavior of wire and arc additively manufactured Ti-6Al-4V material," *Materials*, 2023, doi: 10.3390/ma16186083.
- [20] C. Chen et al., "Improvement of microstructure and mechanical properties of TC4 titanium alloy GTAW-based wire arc additive manufacturing by using interpass milling," *Journal of Materials Research and Technology*, 2023, doi: 10.1016/j.jmrt.2023.10.006.
- [21] Y. Hao, W. Qiao, and H. Chen, "Wire-arc directed energy deposition of magnesium alloys: Microstructure, properties and quality optimization strategies," *Journal of Materials Research and Technology*, vol. 20, 2022, doi: 10.1016/j.jmrt.2022.07.083.
- [22] M. Nalla, V. J., and M. S., "Recent developments and challenges accompanying wire arc additive manufacturing of Mg alloys: A review," *Materials Today: Proceedings*, vol. 46, 2021, doi: 10.1016/j.matpr.2021.03.548.
- [23] T. Klein, A. Arnoldt, M. Schnall, and S. Gneiger, "Microstructure formation and mechanical properties of a wire-arc additive manufactured magnesium alloy," *JOM*, vol. 73, no. 4, 2021, doi: 10.1007/s11837-021-04567-4.
- [24] F. Chen, X. Chen, B. Du, and S. Li, "Microstructure and mechanical properties of WE43 magnesium alloy fabricated by wire-arc additive manufacturing," *Thin-Walled Structures*, 2024, doi: 10.1016/j.tws.2024.112699.
- [25] J. Zihao et al., "Synergistic optimization of efficiency-microstructure-performance in wire-arc additive manufacturing of AZ31 magnesium alloy," *Journal of Magnesium and Alloys*, 2025, doi: 10.1016/j.jma.2025.04.026.
- [26] X. Guo et al., "Achieving isotropic ultra-high strength and fatigue properties in a wire arc directed energy deposited Al-Zn-Mg-Cu-Sc alloy via interlayer friction stir processing," *Materials Science and Engineering A*, 2025, doi: 10.1016/j.msea.2025.148026.
- [27] X. Li et al., "Gradient microstructure and prominent performance of wire-arc directed energy deposited magnesium alloy via laser shock peening," *International Journal of Machine Tools and Manufacture*, vol. 188, 2023, doi: 10.1016/j.ijmactools.2023.104029.
- [28] A. Farzadi and N. V. Haden, "Characterizing surface waviness of aluminum alloy: An approach to minimize post-processing in wire arc additive manufacturing production," *Journal of Manufacturing and Materials Processing*, 2025, doi: 10.3390/jmmp9110347.
- [29] Q. Bojin and C. Linwei, "Review of regulation means in wire arc additive manufacturing of aluminum alloy," 2025, doi: 10.12073/j.hjxb.20240515002.
- [30] W. Zekai et al., "Effect of deposition path strategies on residual stress distribution in CMT+P WAAM of 205C aluminum alloy," 2026, doi: 10.1117/12.3098123.
- [31] B. Duan et al., "Wire arc additive manufacturing of Al-Zn-Mg-Cu alloy: Microstructures and mechanical properties," *Additive Manufacturing*, vol. 36, 2020, doi: 10.1016/j.addma.2020.101447.
- [32] T. Klein, A. Aurel, L. Robert, and M. Schnall, "Microstructure and mechanical properties of a structurally refined Al-Mg-Si alloy for wire-arc additive manufacturing," *Materials Science and Engineering A*, vol. 830, 2022, doi: 10.1016/j.msea.2021.142318.
- [33] H. Chen et al., "Improvement of microstructure and fatigue performance of wire-arc additive manufactured 4043 aluminum alloy assisted by interlayer friction stir processing," *Journal of Materials Science & Technology*, 2022, doi: 10.1016/j.jmst.2022.07.001.
- [34] R. Fu et al., "Hot-wire arc additive manufacturing of aluminum alloy with reduced porosity and high deposition rate," *Materials & Design*, 2021, doi: 10.1016/j.matdes.2020.109370.
- [35] F. Siyue et al., "Microstructure and mechanical properties of Al-Cu-Mg alloy fabricated by double-



- wire CMT arc additive manufacturing,” *Metals*, 2022, doi: 10.3390/met12030416.
- [36] H. Tobias et al., “Multi-material wire arc additive manufacturing of low and high alloyed aluminium alloys with in-situ material analysis,” *Journal of Manufacturing Processes*, 2021, doi: 10.1016/j.jmapro.2021.08.005.
- [37] L. Feiyue et al., “Microstructure and mechanical properties of Al-Zn-Mg aluminium alloy samples produced by wire + arc additive manufacturing,” *Journal of Materials Research and Technology*, vol. 9, no. 6, 2020, doi: 10.1016/j.jmrt.2020.09.114.
- [38] Y. Qing Feng et al., “Microstructure and mechanical properties of TiB₂/AlSi₇Mg_{0.6} composites fabricated by wire and arc additive manufacturing based on cold metal transfer,” *Materials*, 2022, doi: 10.3390/ma15072440.
- [39] Y. Jiannan et al., “Heat treatment optimization of 2219 aluminum alloy fabricated by wire-arc additive manufacturing,” *Coatings*, 2023, doi: 10.3390/coatings13030610.
- [40] C. Chen et al., “Wire-arc additive manufacturing of nano-treated aluminum alloy 2024,” *3D Printing and Additive Manufacturing*, 2022, doi: 10.1089/3dp.2022.0150.
- [41] H. P. et al., “Microstructure and properties of 6061 aluminum alloy by MIG wire and arc additive manufacturing,” *Transactions of the China Welding Institution*, 2021, doi: 10.12073/j.hjxb.20210608001.
- [42] G. Xinpeng et al., “Microstructures and properties of wire-arc additively manufactured ultra-high strength aluminum alloy under different heat treatments,” *Journal of Materials Research and Technology*, 2023, doi: 10.1016/j.jmrt.2023.03.100.
- [43] Z. Liang et al., “Mechanical properties and microstructure evolution of vibration assisted wire arc additive manufacturing 2319 aluminum alloy,” *Materials Science and Engineering A*, 2023, doi: 10.1016/j.msea.2023.145634.
- [44] W. Yajun et al., “Study on the process window in wire arc additive manufacturing of a high relative density aluminum alloy,” *Metals*, 2024, doi: 10.3390/met14030330.
- [45] H. Xuru et al., “A comparative study on Al-Mg-Sc-Zr alloy fabricated by wire arc additive manufacturing with controlling interlayer temperature and continuous printing: Porosity, microstructure, and mechanical properties,” *Journal of Materials Science & Technology*, 2024, doi: 10.1016/j.jmst.2023.12.062.
- [46] F. Chen, Y. Yihang, and F. Hualong, “Regional control and optimization of heat input during CMT by wire arc additive manufacturing: Modeling and microstructure effects,” *Materials*, vol. 14, no. 5, 2021, doi: 10.3390/ma14051061.
- [47] Y. Zhanliang et al., “Microstructure and mechanical properties of Al-Zn-Mg-Cu alloy fabricated by wire + arc additive manufacturing,” *Journal of Manufacturing Processes*, vol. 62, 2021, doi: 10.1016/j.jmapro.2020.12.045.
- [48] X. Chengpeng et al., “Improving mechanical properties of wire arc additively manufactured AA2196 Al-Li alloy by controlling solidification defects,” *Additive Manufacturing*, vol. 43, 2021, doi: 10.1016/j.addma.2021.102019.
- [49] L. Andreas, “Comparative study of the relationship between microstructure and mechanical properties of aluminum alloy 5056 fabricated by additive manufacturing and rolling techniques,” *Materials*, 2023, doi: 10.3390/ma16124327.
- [50] A. M. et al., “Metallurgical and mechanical properties of marine grade AA5356 using wire arc additive manufacturing,” *Materials Research Express*, 2024, doi: 10.1088/2053-1591/ad5817.
- [51] J. Ding, P. Colegrove, F. Martina, S. Williams, R. Wiktorowicz, and M. R. Palt, “Development of a laminar flow local shielding device for wire + arc additive manufacturing,” *Journal of Materials Processing Technology*, vol. 226, pp. 99-105, 2015, doi: 10.1016/j.jmatprotec.2015.07.005.
- [52] F. Martina, M. J. Roy, B. A. Szost, S. Terzi, P. Colegrove, and S. Williams, “Residual stress of as-deposited and rolled wire + arc additive manufacturing Ti-6Al-4V components,” *Materials Science and Technology*, 2016, doi: 10.1080/02670836.2016.1142704.
- [53] F. W. Wang, S. W. Williams, P. A. Colegrove, and A. A. Antonysamy, “Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V,” *Metallurgical and Materials Transactions A*, vol. 44, no. 2, 2013, doi: 10.1007/s11661-012-1444-6.
- [54] P. A. Colegrove et al., “High pressure interpass rolling of wire + arc additively manufactured titanium components,” *Advanced Materials Research*, vol. 996, 2014, doi: 10.4028/www.scientific.net/amr.996.694.
- [55] B. Wu et al., “A review of the wire arc additive manufacturing of metals: Properties, defects and quality improvement,” *Journal of Manufacturing Processes*, 2018, doi: 10.1016/j.jmapro.2018.08.001.
- [56] S. Sarathchandra et al., “Recent developments and challenges associated with wire arc additive manufacturing of Al alloy: A review,” *Materials Today: Proceedings*, 2021, doi:



- 10.1016/j.matpr.2021.03.542.
- [57] T. Buntly, S. S., and N. Tameshwer, "A review on wire arc additive manufacturing: Processing parameters, defects, quality improvement and recent advances," *Materials Today Communications*, vol. 31, 2022, doi: 10.1016/j.mtcomm.2022.103739.
 - [58] Y. Wenzhe et al., "Microstructure evolution and mechanical properties of large-size AZ31 magnesium alloy block fabricated by wire arc additive manufacturing," *Journal of Magnesium and Alloys*, 2024, doi: 10.1016/j.jma.2024.04.024.
 - [59] C. Fukang et al., "Effect of process modes on microstructure and mechanical properties of CMT wire arc additive manufactured WE43 magnesium alloy," *Journal of Materials Research and Technology*, 2023, doi: 10.1016/j.jmrt.2023.10.063.
 - [60] K. Jae-Deuk et al., "On the fabrication of finer grain structure through using finer wire diameter for wire arc additive manufacturing of AZ31B magnesium alloy," *Journal of Materials Research and Technology*, 2024, doi: 10.1016/j.jmrt.2024.04.113.