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Laser-Wire Additive Manufacturing: A Review of Applications and Research Gaps

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Abstract

Multi-material additive manufacturing enables functionally integrated components by combining dissimilar metallic alloys within single structures, addressing performance limitations of homogeneous materials in demanding applications. Among wire-based directed energy deposition processes, laser wire additive manufacturing offers precision, process control, and material efficiency particularly suited for high-performance applications. However, interfacial incompatibilities, intermetallic compound formation, thermal expansion mismatch, and insufficient wettability, pose significant fabrication challenges. This review systematically examines wire-laser-based multi-material additive manufacturing through comprehensive literature analysis. The study first presents established single-material feedstocks organized by alloy family, then analyzes bimetallic material combinations that have received research attention. Findings reveal that stainless steel-Inconel pairings dominate current research due to favorable metallurgical compatibility, demonstrating technical maturity through epitaxial grain growth and defect-free interfaces. However, the majority of material combinations appear in only a few publications, indicating critically limited research density. Analysis identifies key interfacial challenges and mitigation strategies including functionally graded transitions and buffer layers. Significantly, numerous industrially relevant material pairings remain underexplored despite technical feasibility and application potential. Specifically, combinations such as tool steel-copper alloys, aluminum bronze-structural steels, maraging steel-cobalt alloys, and Stellite-Inconel systems could unlock breakthrough capabilities in wear-resistant tooling, thermal management, and high-temperature components. This research gap mapping establishes foundation for advancing wire-laser multi-material manufacturing from narrow laboratory demonstration toward mature industrial technology addressing diverse high-performance applications.

Keywords
Directed energy deposition, Wire-based additive manufacturing, Wire-laser energy deposition, Bimetallic combinations, Characteristics and applications

1. Introduction
The rapid development of modern industries such as aerospace, energy engineering, and automotive manufacturing has led to increasingly extreme and complex operating conditions for key components. As a result, many structural and functional parts must simultaneously exhibit multifunctional properties, combining, for example, high mechanical strength, low weight, thermal stability, and corrosion resistance, while remaining adaptable to diverse and often conflicting environmental conditions (Bandyopadhyay and Heer, 2018; Bose et al., 2018; DebRoy et al., 2019; Kang

et al., 2025). Traditional components fabricated from a single homogeneous material are increasingly reaching their performance limits in this regard, as their inherently isotropic material properties create a fundamental bottleneck that hinders the realization of highly integrated and diversified high-performance requirements.

A promising solution to these challenges is offered by multimaterial structures, which make it possible to deliberately combine the specific advantages of different heterogeneous materials within a single component (Kang et al., 2025; Udupa et al., 2014; Zhang et al., 2018). By tailoring the spatial distribution of materials, functional gradients can be created that enable optimal adaptation to complex loading conditions (Alammar et al., 2022; Calignano et al., 2017; Han and Lee, 2020; Li et al., 2023). In aerospace applications, for instance, lightweight aluminum alloys are combined with high-strength titanium- or nickel-based superalloys in critical load-bearing and heat-conducting components. In the energy sector, functionally graded coatings for nuclear reactors and high-efficiency heat exchangers similarly leverage the combination of corrosion resistance and high thermal conductivity (He et al., 2023; Xiang et al., 2025; Yi et al., 2024).

While existing reviews have addressed multi-material additive manufacturing across process families (Bandyopadhyay et al., 2020; Clare et al., 2025), wire-based DED in general terms (Kang et al., 2025; Rodrigues et al., 2019), or specific material systems such as SS-Ni combinations (Singh Tanwar and Jhavar, 2024), a systematic analysis specifically targeting wire-laser-based multi-material deposition with explicit mapping of investigated bimetallic combinations, associated interfacial challenges, and critically underexplored material pairings remains absent from the literature. This gap is particularly significant given the distinct process characteristics of LWAM, namely its precision, material efficiency, and process stability, which differentiate it from arc- and electron-beam-based alternatives and render it uniquely suited for demanding multi-material applications. The present review addresses this gap by systematically surveying established single-material feedstocks in wire-laser AM, analyzing bimetallic combinations investigated to date across wire-based DED platforms, and identifying industrially relevant material pairings that remain underexplored despite technical feasibility. Section 2 details the literature search methodology and screening process. Section 3 presents the results, encompassing wire-based AM process characteristics, established single-material systems, and the current state of bimetallic research alongside identified research gaps. Section 4 draws conclusions and outlines directions for future investigation.

2. Methods

A systematic literature search was conducted to identify relevant studies on metal additive manufacturing with a particular focus on wire-based processes and multi-material applications. The primary search was performed using Google Scholar, complemented by targeted queries in major scientific databases including Scopus, ScienceDirect (Elsevier), MDPI, IEEE Xplore, Springer, and other publisher platforms. Google Scholar and ScienceDirect emerged as the most productive sources, collectively accounting for approximately 70% of all identified references, with the remainder distributed across the other databases.

The search strategy followed a hierarchical approach, beginning with broad thematic queries and progressively narrowing toward specific material combinations and process variants. Initial searches employed general terms such as "additive manufacturing overview," "additive manufacturing state of the art," "metal 3D printing," and "additive manufacturing of metals." Subsequent queries targeted multi-material contexts using search strings including "additive manufacturing of multi-material structures," "multi-material 3D printing," "additive manufacturing with dual-metal combination," and "additive manufacturing of bimetallic structures." Process-specific searches focused on directed energy deposition variants with terms such as "metal DED," "multi-metal DED," "wire-based DED," "wire-laser DED," and "wire-laser metal deposition." Finally, material-specific queries were conducted by combining individual alloy designations (e.g., stainless steel, titanium alloys, Inconel) with process descriptors such as "wire-laser directed energy deposition" or, where wire-laser-specific literature was sparse, "wire direct energy deposition."

The temporal scope of the search was adjusted according to the nature of the information sought. For contemporary overviews and state-of-the-art assessments, particularly those related to multi-material additive manufacturing, publications from 2022 to 2026 were prioritized to ensure current relevance. Studies addressing process parameters, material behavior, and interfacial phenomena were drawn primarily from the period 2018 to 2026. Foundational content, including process definitions, general AM principles, and well-established metallurgical concepts, was sourced more broadly from publications spanning 2010 to 2026, with older works included only when they remained widely cited or provided essential background information.

2.1 Inclusion and Exclusion Criteria

The review considered internationally available, peer-reviewed journal articles and high-quality conference proceedings published in English. In select cases, technical documentation from reputable manufacturers or research organizations was consulted to clarify process descriptions, practical implementation aspects, or recent advances in single-material and bimetallic deposition. Books and book chapters were included as sources of general background information on additive manufacturing and metal processing.

The scope was restricted to metal additive manufacturing, with particular emphasis on directed energy deposition (DED) processes and a primary focus on wire-laser metal deposition (W-LMD). Related processes such as electron beam additive manufacturing (EBAM) and wire arc additive manufacturing (WAAM) were included where they provided relevant insights into multi-material strategies, interfacial metallurgy, process behavior, or comparative process characterization. Only metallic alloy systems were considered; non-metallic materials, hybrid metal-polymer systems, and composite feedstocks were excluded. Patents and grey literature were not included in the analysis.

2.2 Screening Process and Data Extraction

The literature selection followed a three-stage screening process (Figure 1). In the first stage, titles were reviewed to assess general relevance and assign preliminary thematic categories, yielding approximately 110 potentially relevant publications. In the second stage, abstracts were read to evaluate topical fit and methodological rigor, reducing the pool to approximately 75 sources. In the third stage, the remaining full-text articles were examined in detail, including figures, tables, and key results sections, leading to a final selection of approximately 55 primary sources for in-depth analysis and inclusion in this review.

Publications were assessed primarily based on quality criteria, including citation strength and the reputation of the publishing venue (journal impact factor, conference ranking, or institutional affiliation). In cases where limited literature was available on a specific material combination or process variant, the selection was broadened to prioritize relevance over citation metrics in order to ensure adequate coverage of the topic. All references were managed, annotated, and organized using Zotero reference management software.

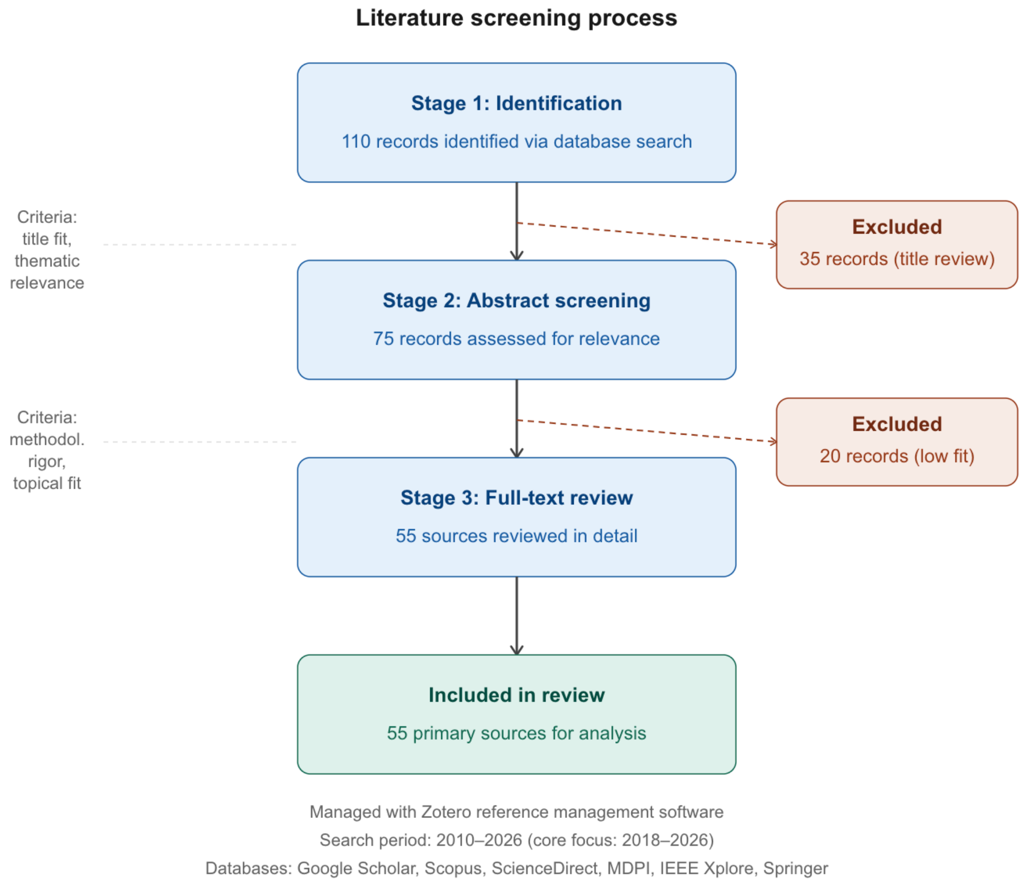

Figure 1. Literature screening process based on a three-stage approach (identification, abstract screening, full-text review), resulting in 55 primary sources included in this review

3. General additive manufacturing (AM) and metal AM

Conventional multimaterial manufacturing technologies, such as diffusion bonding, composite rolling, and casting, rely on fundamental thermomechanical coupling mechanisms to achieve macroscopic material integration by precisely controlling thermodynamic parameters to steer metallurgical interfacial reactions or create mechanical interlocking between dissimilar materials (Huang et al., 2013; Matsuo et al., 2001). Although these processes can provide high-density joints across a broad range of material combinations, they are associated with several important limitations: restricted realization of functional gradients, insufficient formability of complex topological configurations, and low production efficiency due to the need for multiple sequential processing steps (Mahamood and Akinlabi, 2017; Pajonk et al., 2022).

In recent years, the rapid advancement of additive manufacturing (AM) technologies has opened new pathways to address these limitations. Metal AM builds components layer by layer from metallic raw materials such as powder or wire, enabling the fabrication of geometrically complex parts that would be difficult or impossible to produce by conventional subtractive methods (Chowdhury et al., 2023; Srivastava et al., 2022). In contrast to conventional manufacturing routes, AM enables rapid, near-net-shape fabrication with improved material utilization, reduced manufacturing costs, and shorter production times (Feng, 2024; Sanjeeviprakash et al., 2023). Critically for multimaterial applications, AM generates distinct material regions at predefined positions within a part, rather than producing homogeneous composites by bulk mixing, thereby enabling targeted placement of the right materials at the right locations to achieve optimal local properties (Alammar et al., 2022; Calignano et al., 2017; Gu et al., 2021; Li et al., 2023; Wang et al., 2022). Moreover, the relatively low thermal stresses inherent to AM processes allow a continuous compositional gradient at the interface, supporting good interfacial bonding strength in the resulting bimetallic components (Armstrong et al., 2022). As a result, Multi-Material Additive Manufacturing (MMAM) has emerged as a current research frontier (Wang et al., 2022; Xu et al., 2025), enabling the fabrication of functionally graded material structures, composite structures, and bimetallic structures with complex geometric characteristics and superior performance (Guo and Leu, 2013; Liu et al., 2023; Wei et al., 2021).

Within the spectrum of metal AM processes, Directed Energy Deposition (DED) and Powder Bed Fusion (PBF) currently represent the most widely established process categories (Feng, 2024; Srivastava et al., 2022). DED is a particularly active area for MMAM research, as its open deposition architecture facilitates the combination of different metals within a single structure to reduce stress concentrations and optimize mechanical performance (Hajra and Kim, 2024; Zafar et al., 2025). Among DED variants, wire-based processes have attracted increasing attention due to their high material utilization, low cost, and high deposition efficiency (Kang et al., 2025; Suzuki et al., 1992; Venturini et al., 2016; Zhou et al., 2018). Laser Wire Additive Manufacturing (LWAM), a laser-based variant of wire-fed DED, uses a high-power laser to generate a molten pool onto which wire feedstock is continuously deposited, building up solid structures layer by layer via a movable deposition head (Abuabiah et al., 2023). Compared with powder-based AM systems, LWAM offers deposition efficiencies approaching 100% of the wire feedstock material (Abuabiah et al., 2023; Becker et al., 2021; Kisielewicz et al., 2021; Xu et al., 2017), lower material costs (Özel et al., 2023; Piscopo and Iuliano, 2022; Wasmer et al., 2023), reduced risk of contamination during processing (Nowotny et al., 2007), and an overall cleaner manufacturing route (Abuabiah et al., 2023). Furthermore, wire-fed processes enable the fabrication of large-scale and geometrically complex components with a virtually unrestricted build volume, provided the printing system permits it (He et al., 2019; Wu et al., 2018; Xia et al., 2020). A further process advantage is that the laser-based DED method produces a comparatively small heat-affected zone and allows more precise adjustment of laser power relative to other DED approaches (Brückner et al., 2012; He et al., 2019; Sibisi et al., 2020; Svetlizky et al., 2022). These characteristics have established wire-laser-based DED (W-LDED) as a promising manufacturing technology in sectors including aerospace, energy, healthcare, and automotive (Abuabiah et al., 2023; Ghanadi and Pasebani, 2024; Gim et al., 2025; Martin et al., 2017; Ramos et al., 2025).

Despite this potential, Multi-Material Additive Manufacturing via wire-laser-based DED faces significant technical challenges that are primarily associated with two categories: defects at the material interface and instabilities in process control (Kang et al., 2025). The fundamental difficulty in combining dissimilar metals within a single structure lies in the incompatibility of their thermophysical properties, particularly large differences in melting point, coefficient of thermal expansion, thermal conductivity, and density (He et al., 2023). These discrepancies manifest in several critical obstacles. At the interface between dissimilar metals, brittle intermetallic compounds (IMCs) frequently form, substantially reducing joint strength and serving as crack initiation sites (He et al., 2023; Madhavan et al., 2017; Movahedi et al., 2012; Pouranvari, 2017). Differences in thermal expansion coefficients generate shear stresses upon cooling that can lead to microcracking, distortion, or delamination (He et al., 2023; Kang et al., 2025). In material systems with large melting point differentials, insufficient interfacial wettability can result in incomplete fusion defects, restricting the application of high-temperature-resistant and lightweight composites under extreme conditions. Additionally, chemically active metals such as titanium are sensitive to atmospheric contamination, necessitating controlled inert atmospheres or vacuum environments (Kang et al., 2025; Negi et al., 2019; Węglowski et al., 2018). Current research efforts to address these challenges have focused predominantly on wire-based processes, including arc-based (WAAM), laser-based (LWAM), and electron-beam-based (EBAM) additive manufacturing (Kang et al., 2025), and have explored several strategies for controlling material transitions. The introduction of transition layers composed of intermediate materials compatible with both primary metals has been shown to facilitate interdiffusion and suppress the formation of harmful IMCs (Chen et al., 2023; Farias et al., 2024; Rodrigues et al., 2019). Functionally graded materials (FGMs) achieved through precise control of multiple wire feeds enable continuous compositional gradients within a component (Guo and Leu, 2013; Liu et al., 2023; Ma et al., 2024; Wei et al., 2021). More recently, the dual molten pool mechanism (DMPIIM) has been proposed as a means of avoiding direct contact between the liquid phases of highly dissimilar metals, such as aluminum and steel, thereby minimizing IMC layer formation (He et al., 2023; Zhao et al., 2022). Nevertheless, the reliable fabrication of multimaterial structures by wire-laser-based directed energy deposition remains a substantial challenge, as precise control of interfacial reactions, compositional gradients, and process stability during material transitions is not yet sufficiently understood, particularly for dissimilar metal systems with strongly diverging thermophysical properties.

Against this background, the present work aims to systematically assess and contextualize the significance of multi-material and, in particular, bimetallic structures for the future development of additive manufacturing. The study first surveys the most established metallic materials currently employed in wire-laser additive manufacturing. Building on this foundation, a structured overview of bimetallic material combinations that have been investigated to date is provided, with the reported process-related challenges, material interactions, and typical defect mechanisms at material transitions systematically analyzed and categorized. A further focus lies on the identification of material combinations that appear technically feasible based on currently established feedstock materials but have so far received insufficient scientific attention. These combinations are discussed with respect to their potential practical application. The overall objective is to map existing research gaps and to establish a well-founded basis for future investigations in the field of wire-laser-based multi-material additive manufacturing.

3.1 Wire-based additive manufacturing methods

Wire-based additive manufacturing represents an important branch of metal AM, encompassing all processes that use metallic wire as feedstock Material. A specific energy source is employed to melt the wire, which is then deposited layer by layer along a predefined path to form three-dimensional components. Depending on the energy source used, wire-AM processes are classified into three main categories: arc-based (WAAM), laser-based (LWAM), and electron-beam-based (EBAM) additive manufacturing. Each of these technologies is characterized by distinct energy transfer mechanisms, process properties, and material compatibility, which in turn define their respective application profiles, cost structures, and achievable part qualities (Kang et al., 2025).

Wire Arc Additive Manufacturing (WAAM) currently accounts for the largest share of wire-AM research activity, estimated at approximately 70-80% of publications in this field. It employs an electric arc as the heat source to melt metallic wire feedstock, enabling the rapid and cost-effective fabrication of large, moderately complex structural components at deposition rates of 2-10 kg/h. The process is particularly attractive due to its low equipment and material costs, near-100% material utilization, and high deposition efficiency. However, the inherently high heat input results in significant thermal distortion and comparatively low dimensional accuracy, typically on the order of several hundred micrometers, which generally necessitates post-process machining (Chakraborty et al., 2022; Indupuri et al., 2024; Meng et al., 2020). Electron Beam Additive Manufacturing (EBAM), by contrast, operates under high vacuum conditions, using a high-energy electron beam to melt wire feedstock. The vacuum environment effectively prevents oxidation and atmospheric contamination, making EBAM particularly well suited for reactive and high-performance metals such as titanium and nickel-based superalloys. While EBAM offers excellent energy efficiency and produces components with a small heat-affected zone, the requirement for vacuum equipment results in very high system costs and limits the achievable build volume (Çam, 2022; Kolubaev et al., 2022; Negi et al., 2019). Laser Wire Additive Manufacturing (LWAM) occupies an intermediate position between these two processes. Using a high-energy-density laser beam to generate a melt pool into which wire is continuously fed, LWAM achieves higher dimensional accuracy than WAAM, on the order of tens of micrometers, while avoiding the vacuum requirements of EBAM. Protective gas shielding is typically employed to prevent contamination of the deposited material; for reactive metals, a fully inert processing chamber is required. Although LWAM is associated with slower deposition rates (0.5-2 kg/h) and higher costs than WAAM, and exhibits limited compatibility with highly reflective materials, its combination of precision, process stability, and low residual stress makes it particularly valuable for complex components, medical implants, and precision tooling (Abuabiah et al., 2023; Kang et al., 2025).

Table 1 provides a structured comparison of these three wire-based AM processes with respect to key process characteristics including deposition rate, achievable build size, forming accuracy, heat input, cost, as well as their principal advantages, disadvantages, and typical application domains.

Table 1. Overview of wire-based additive manufacturing processes with regard to various characteristics

characteristic	EBAM (Electron Beam Additive Manufacturing)	LWAM (Laser Wire Additive Manufacturing)	WAAM (Wire Arc Additive Manufacturing)	source
Deposition rate	Moderat-high (1-5kg/h)	Moderate (0,5-2kg/h)	High (2-10kg/h)	(Abuabiah et al., 2023; Meng et al., 2020; Miao et al., 2022; Treutler and Wesling, 2025)
Deposition size	Large (limited by chamber)	Medium-large	Very large	(Chakraborty et al., 2022; Treutler and Wesling, 2025)

Forming accuracy	Medium-high	Higher (tens of micrometers)	Lower (several hundred micrometers)	(Marefat et al., 2023; Meng et al., 2020; Syed et al., 2006)
Heat input	High	Low-medium	High	(Chakraborty et al., 2022; Sadhya et al., 2024)
Cost	Very high	High	Low	(Chakraborty et al., 2022; Treutler and Wesling, 2025)
Advantages	High energy, vacuum anti-oxidation, small heat-affected zone	Low stress, high precision, stable quality	Low cost, high material utilization rate, fast deposition	(Abuabiah et al., 2023; Dhinakaran et al., 2020; Näsström et al., 2019; Osipovich et al., 2023; Pant et al., 2023; Rodrigues et al., 2019)
Disadvantages	High cost, limited size, and high energy consumption	Slow deposition and poor compatibility with highly reflective materials	Large thermal deformation, low precision, and numerous defects	(Abuabiah et al., 2023; Dhinakaran et al., 2020; Näsström et al., 2019; Osipovich et al., 2023; Pant et al., 2023; Rodrigues et al., 2019)
Applications	Precision components for aerospace and nuclear industries	Complex components, medical implants, precision moulds	Large and low-precision structural components	(Abuabiah et al., 2023; Dhinakaran et al., 2020; Näsström et al., 2019; Osipovich et al., 2023; Pant et al., 2023; Rodrigues et al., 2019)

3.2 Materials in wire-based additive manufacturing (focus on W-LMD)

Although laser wire additive manufacturing (LWAM) is a relatively recent development within the broader landscape of metal AM, significant progress has been made in recent years in establishing a range of processable metallic alloys. A growing number of material systems have been successfully deposited, characterized, and increasingly employed in industrial applications. Table 2 provides an overview of currently established materials and alloys in wire-based additive manufacturing with a focus on laser-based energy sources. The materials are organized into seven principal alloy families: iron-based, nickel-based, cobalt-based, titanium-based, copper-based, aluminum-based, and specialty alloys. For each group, representative alloys are listed alongside their characteristic properties, main advantages, and primary application fields. Where applicable, specific attention is given to frequently used alloys within each family, such as SS316L, which represents the most widely studied stainless steel grade in LWAM research. This structured overview is intended to provide a comprehensive picture of the current state of the art with regard to single-material deposition in laser wire-based additive manufacturing.

Table 2. Overview of materials usable in wire laser-based additive manufacturing

material	properties/main advantages	applications	source
→iron-based alloys -SS316L (Stainless Stell) -austenitic steel	Excellent durability and corrosion-resistance, low reactivity and adequate	Corrosion prone applications, mechanical engineering, chemical	(Brubaker et al., 2022; Meltio, 2025a; Rodrigues et al., 2022; Santaolaya et

	temperature properties, good weldability	industry, food industry and shipbuilding	al., 2023; Shakibi et al., 2025; Wang et al., 2019)
-SS308L (Stainless Steel) -austenitic chromium-nickel steel	Operating temperature from -196°C to 350°C, distinctive combination of corrosion resistance, mechanical strength, and low-temperature properties (excellent impact strength at low temperatures)	Nuclear, aerospace, automotive, marine and chemical industrie, steamship manufacturing	(Anand et al., 2023; Gürol et al., 2023; Meltio, 2025a; Osama et al., 2025; Ye et al., 2020)
-17-4PH (Stainless Steel) -precipitation-hardening martensitic stainless steel	Excellent mechanical properties and corrosion resistance, high strength and hardness, good toughness and resistance to stress corrosion cracking	Wide range of applications in the aerospace and chemical industries	(Caballero et al., 2019; Li et al., 2024; Meltio, 2025a; Sun et al., 2020; Yeli et al., 2017)
-Mild Steel (ER70-S) -low alloy carbon steel or mild steel	Good strength, ductility and toughness, excellent weldability and machinability, low cost weldability and machinability, low cost	Versatile applications inareas such as construction, transport, automotive, manufacturing and structural applications	(Ermakova et al., 2020; Klobčar et al., 2018; Le et al., 2020; Meltio, 2025a; Rafieazad et al., 2019)
-Tool Steel (H11, H13)	Good resistance to thermal fatigue cracking and high-temperature abrasion, good strength and hardness at high temperatures	Mechanical components in aerospace industr, hot working tools such as forging, die-casting tools or extruding	(Hackenhaar et al., 2022; Meltio, 2025a; Nie et al., 2016; Widomski et al., 2025; Yang et al., 2024)
→nickel-based alloys -Inconel 625	Excellent strength and ductility, high-temperature, corrosion and oxidation resistance, good mechanical properties and weldability	Wide range of applications in aerospace, chemical, petrochemical and naval industry, coating and repair of components	(Chaurasia et al., 2024; Meltio, 2025a; Özel et al., 2023; Rodrigues et al., 2022; Su et al., 2024; Zhang et al., 2023)
-Inconel 718	Highly corrosion and oxidation resistance, excellent mechanical properties, high temperature resistant up to 700°C	Popular in aerospace (propulsion systems, turbine engines), energy (Industrial gas turbines), marine, chemical and petrochemical industries, repair of components	(Alvarez-Leal et al., 2024; Meltio, 2025a; Murray, 2025, 2024a; Özel et al., 2023; Santaolaya et al., 2023; Zhong et al., 2022)
→cobalt-based alloys -CoCr, Stellite 6, Stellite 21)	High strength and surface hardness, excellent wear resistance and biocompatibility, very durable, retention of properties at elevated temperatures	Preferred for aerospace (turbine blades, engine components and other critical parts), automotive (Engine components, transmission parts) and medical applications (dental implants and orthopedic devices), coating material (hardcoating, high-temperature wear protection)	(Bakhshayesh et al., 2024; Clare et al., 2013; Lin et al., 2020; Moradi et al., 2020; Murray, 2024b; Rajeev et al., 2020; Smoqi et al., 2021; Yao et al., 2005)
→titanium-based alloys -Ti6Al4V	Excellent combination of strength, low density,	Widley used in aerospace and chemical processing,	(Baufeld et al., 2011; Meltio, 2025a; Özel et al.,

	corrosion resistance and mechanical properties	preferred choice for lightweight applications	2023; Valentin et al., 2019; Wang et al., 2023; Williams et al., 2016; Yokota et al., 2025)
→copper-based alloys -CuCrZr, CuSn1, CuCrNb	High-strength and high-conductivity, non-magnetic, corrosion-resistant, withstands temperature up to 400°C, excellent flex life and redrawability	Use in demanding electrical and mechanical applications, aerospace, automotive, railway cables	(Bharadwaj et al., 2024; Kini et al., 2020; Meltio, 2025a; Zardoshtian et al., 2023)
-ERCuNiAl, NAB-alloy	High strength and durability, excellent resistance to corrosion, particularly in seawater and other aggressive environment, good mechanical properties, non-magnetic	Applications in demanding environments with high requirements for saltwater resistance as well as wear and corrosion resistance, offshore structures, maritime, shipbuilding (ship propellers and fittings), power plants (valves, piping systems)	("Copper Alloy CuNiAl (NAB) | AML3D (ASX," 2023; "ERCuNiAl Wire Nickel Aluminum Bronze Welding MIG / TIG," 2020; Hatala et al., 2021; Kavinjr et al., 2019; Meltio, 2025a)
→aluminum-based alloys -Al-5356, Al-5087, Al-6082, Al-4046	Low density, high specific strength, good corrosion resistance, artly excellent fluidity, high weldability and thermal conductivity	Aerospace, automotive, large- structural components, lightweight construction, welding applications that requiring high-quality in strong welds	(Froend et al., 2018; Köhler et al., 2019; Langelandsvik et al., 2021; Meltio, 2025a; Omiyale et al., 2022; Valentin et al., 2019)
→special alloy irnon-nickel alloy -Invar 36	Low coefficient of thermal expansion and high dimensional stability over a wide temperature range, low thermal conductivity, high toughness and high susceptibility to work hardening	Applications that require precision and stability: precision instruments, scientific measuring devices, cryogenics, composite molds, aerospace components	(Grimvall, 1999; Huang et al., 2024; Meltio, 2025a; Schimmel et al., 2022; Veiga et al., 2022)

The ability to process such a diverse portfolio of alloys is closely linked to recent advances in LWAM system capabilities. Modern commercial systems, exemplified by platforms such as the Meltio M450, have been specifically designed to accommodate the requirements of multi-material processing. Key enabling features include dual-wire feeding systems that allow sequential deposition of dissimilar metals within a single build, open material platforms that permit the use of custom or experimental wire feedstocks without vendor lock-in, and integrated hot-wire technology that electrically preheats the wire prior to melting, thereby reducing the laser power demand and facilitating the processing of high-melting-point alloys. Furthermore, advanced environmental control, including closed build chambers with active oxygen monitoring and adjustable inert gas atmospheres (argon, nitrogen, helium), ensures that reactive metals such as titanium and aluminum can be processed with minimal oxidation. Substrate preheating capabilities of up to 500 °C further reduce thermal gradients and residual stresses, which is particularly beneficial when transitioning between materials with differing thermophysical properties. Closed-loop process control based on real-time monitoring of melt pool temperature and geometry enables automatic adjustment of laser power and wire feed rate, supporting stable deposition across a wide range of material systems. Collectively, these technological capabilities provide a robust platform for research into multi-material additive manufacturing, enabling systematic investigation of novel material combinations and functionally graded structures (Li et al., 2020; Meltio, 2025b; Meltio3d, 2026).

With the foundational single-material processes now well established and the necessary system infrastructure available, attention is increasingly shifting toward the controlled integration of multiple materials within individual components. The following sections build upon the material overview presented in Table 2 by examining bimetallic material combinations that have already been investigated in the scientific literature, identifying the associated interfacial challenges and process strategies, and subsequently highlighting potential material pairings that remain unexplored despite their technical feasibility and promising application potential.

3.3 Currently researched material combinations

As wire-based additive manufacturing capabilities have matured, research attention has increasingly focused on the fabrication of bimetallic and multi-material structures. Table 3 provides an overview of material combinations that have received substantial research attention within the wire-laser-based DED community, along with representative publications and brief descriptions of their scope. The selection of combinations reflects both metallurgical feasibility and industrial relevance, with particular emphasis on pairings that enable functionally graded transitions between dissimilar alloy systems.

Table 3. Material combinations in wire laser-based additive manufacturing and their sources, as well as unexplored but interesting combinations

Material-combination	source
Stainless steel/Inconel (especially the combinations SS316L/SS308L with Inconel 625 /Inconel 718)	-Investigation of the fabrication of SS316L-IN625 bimetals using laser wire DED with a focus on microstructure, interfacial bonding and improved mechanical properties compared to WAAM (Tyagi et al., 2024) -Fabrication and characterization of an SS316L–IN625-FGM using GMAW-based WAAM with a focus on defect-free interface and comparable mechanical properties to conventional materials (Sasikumar et al., 2022) -Investigation of 316L-IN625-FGMs produced by Twin-Wire Arc AM, where the direct interface variant showed better mechanical properties and lower residual stresses than the smooth-graded one (Rodrigues et al., 2022) -Fabrication of 308L-IN625-FGMs with a continuous composition gradient via dual-wire arc AM and analysis of their microstructure and properties (T. Li et al., 2022) -Gradient joining of carbon steel, 316L and IN625 via WAAM to produce an FGM and analysis of microstructure, defects and mechanical properties of the transition regions (Amiri and Naffakh-Moosavy, 2024) -Geometrical Study and Characterization of Multi-Material Deposition of Stainless Steel 316L and Inconel 625 Using Coaxial Laser Wire Additive Manufacturing (Kapil et al., 2025) -Laser additive manufacturing of thin-walled SS316L–IN718-FGMs with analysis of solidification behavior, microstructure evolution, secondary phase formation and hardness profile to improve lifetime (Ghanavati et al., 2021) -Optimization of the W-DED/LB (Wire-Directed Energy Deposition/Laser Beam) process parameters for the production of dense SS316L and IN718 components, including characterization, CT defect analysis and influence of heat treatment on tensile behavior (Santaolaya et al., 2023) -Examination of IN718-SS316 multi-material sandwich samples (different number of layers) using W-LMD with a focus on defects, microstructure and hardness gradient at the IN718/SS316 interface (Ureña and Alvarez-Leal, 2024) -Numerical and experimental investigation of the relationships between process, solidification and hardness profile in DED-fabricated SS316L–IN718 multi-material structures (Ghanavati et al., 2022) -(not all listed)
SS/SS	-Multi-material stainless steel fabrication using plasma wire arc additive manufacturing (Segovia-Guerrero et al., 2024)

	-Multi-Material Additive Manufacturing of Duplex and Austenitic Stainless Steel by Laser Wire DED (Patra et al., 2025)16.07.2026 15:29:00
Mild Steel/SS	-Production of damage-free bimetallic structures made of structural steel and stainless steel using WAAM, whereby overlapping and superimposed walls were produced and examined with regard to microstructure and mechanical properties (Suárez et al., 2022)
Ti/Inconel	-Microstructure and mechanical properties of laser welding of Ti6Al4V to Inconel 718 using Nb/Cu interlayer (Liu et al., 2020) -Review article on high-deposition-rate laser DED, showing how significantly increased deposition rates affect process control, microstructure and component properties in nickel superalloys and titanium alloys, and what optimization strategies can be derived from this (Z. Li et al., 2022) -Inconel 718 und Ti6Al4V wurden per LENS™ mit einer Vanadiumcarbid-haltigen Zwischenschicht zu rissfreien bimetallischen Strukturen aufgebaut, um Mikrostruktur, Phasenbildung und mechanische Eigenschaften zu verbessern (Onuike and Bandyopadhyay, 2018) -Coaxial wire-based LMD made of Inconel 718 and Ti-6Al-4V with a specially designed ring beam head (Kelbassa et al., 2019)
Ti/SS	-Bimetallic structures made of Ti6Al4V and SS410 were fabricated, whereby direct and stepped structures without an intermediate layer failed due to brittle intermetallic phases and delamination, whereas a NiCr intermediate layer enabled the formation of crack-free, microstructurally characterized compounds (Sahasrabudhe et al., 2015)
CuCrZr/Inconel	-Inconel 718 was deposited onto a CuCrZr substrate with a cold-sprayed intermediate layer using wire-based laser DED, resulting in a fine-grained, defect-free metallurgical bond whose microstructure and mechanical properties were further improved by heat treatment (Li et al., 2025) -
CuCrZr/SS	-Cu-Cr-Zr/316L composites were produced using double-wire laser-arc hybrid AM, with the 316L addition refining the grains and significantly improving the mechanical properties of the Cu-Cr-Zr alloy (Di et al., 2025) -Characterization of a bimetallic multilayer composite material made of stainless steel and copper, produced by wire-guided electron beam additive manufacturing (Osipovich et al., 2021) -Laser metal deposition of copper on SS304L, directly and with Ni-based Deloro-22 interlayer, for the fabrication of Cu/stainless steel multi-material structures and investigation of microstructure, bond strength and thermal properties (Zhang et al., 2021)
Al/SS	-WAAM fabrication of an SS304L-CuNi-AA2319 multimetallic structure with a CuNi interlayer to join steel and aluminium and to investigate the influence of the interlayer on microstructure, intermetallic phase formation and mechanical properties (Manohar et al., 2025) -Overview of laser fusion brazing processes for Al/steel joints, demonstrating how targeted heat input control in single, double and laser arc hybrid beams can limit the intermetallic layer and reduce welding defects such as pores, cracks and high residual stresses (Wang et al., 2016)
Al/Al	-Multi-material WAAM of aluminum alloys 6060 and 5087 with smooth, defect-free transition areas where mechanical properties are dominated by the individual alloys (Hauser et al., 2021)
Al/Ti	-Force-assisted wire-laser DED for aluminum and titanium alloys, in which an additional wire pressure stabilizes the droplet transfer, reduces defects and improves the mechanical properties of the structures (Zhao et al., 2023)
CoCrMo/Inconel 718	-DED enabled the fabrication of Inconel-718/CoCrMo bimetallic structures exhibiting a crack- and pore-free, intermetal-free transition zone with a uniform element gradient. This improves mechanical strength as well as oxidation and wear behavior at high temperatures without interface-related weakening (Groden et al., 2022)
Tool Steel (H13)/Copper alloy	unexplored

Aluminum Bronze (NAB)/Steel Grades (Mild Steel or H13)	unexplored
Maraging Steel/Cobalt-based alloys (Stellite 6/21)	unexplored
Cobalt-based alloys (Stellite 6/21)/Nickel-based alloys (Inconel 626/718)	unexplored

As wire-based additive manufacturing capabilities have matured, research attention has increasingly focused on the fabrication of bimetallic and multi-material structures. Table 3 provides an overview of material combinations investigated within the W-DED community, reflecting both metallurgical feasibility and industrial relevance. A clear trend emerges: combinations pairing iron-based alloys with nickel-based superalloys exhibit the highest research density, studied across all three major wire-based DED platforms employing direct interfacial bonding, FGM transitions, and intermediate buffer layers.

The SS316L/SS308L-Inconel 625/718 system represents the most comprehensively investigated combination in LW-DED. A shared austenitic FCC matrix and comparable thermal expansion coefficients enable epitaxial grain growth and crack-free interfaces with transition zones as narrow as approximately 55 µm (Jadhav et al., 2025; Tyagi et al., 2024; Ureña and Alvarez-Leal, 2024). Process parameters can be adjusted to minimize brittle phase formation while achieving high strength and density (Chen et al., 2024; Ghanavati et al., 2022; Sagong et al., 2022). Singh Tanwar and Jhavar (2024) confirm that SS-Ni multi-materials are successfully fabricated across LPBF, LDED, and WAAM, identifying carbide and Laves phase formation, hardness gradients, and interfacial fracture behavior as key research areas. SS-SS combinations yield defect-free gradient-like duplex structures with tailorable hardness distributions (Patra et al., 2025; Segovia-Guerrero et al., 2024).

Titanium-based combinations present significant interfacial challenges due to brittle Fe-Ti and Ti-Ni intermetallic phase formation. Direct deposition of Ti-6Al-4V on dissimilar substrates consistently leads to delamination, mitigated through NiCr or Nb/Cu interlayers that suppress intermetallic formation and enable crack-free bonding (Liu et al., 2020; Onuike and Bandyopadhyay, 2018; Sahasrabudhe et al., 2015). Coaxial wire-laser deposition of IN718 and Ti-6Al-4V achieves near-complete material utilization but remains constrained in wire flexibility and dimensional accuracy (Kelbassa et al., 2019). Ti-6Al-4V-NbZr1 structures produced via WAAM demonstrate defect-free, intermetallic-free interfaces with heat-input-dependent mechanical properties (Jadhav et al., 2023).

Copper-based combinations have been investigated for thermal and electrical management applications. IN718/CuCrZr bimetals fabricated via wire-laser DED with a cold-sprayed interlayer yield fine-grained, defect-free interfaces with properties further improved by post-deposition heat treatment (Li et al., 2025). Cu-Cr-Zr/316L composites produced by double-wire laser-arc AM demonstrate that increasing steel content refines grain structure and enhances mechanical performance through solid-solution and dispersion hardening (Di et al., 2025). Multilayer steel-copper bimetallic structures produced by wire-based electron beam AM exhibit mechanical properties in the range of the individual constituent materials, with interface formation and Fe/Cu mixing governing the resulting microstructure (Osipovich et al., 2021). Ni-based interlayers improve bonding, reduce defects, and enhance thermal conductivity in Cu/SS304L multi-material builds (Zhang et al., 2021).

Aluminium-based systems remain constrained by high reactivity and large thermophysical property mismatches relative to ferrous and nickel-based alloys. CuNi interlayers enable joining of SS304L and AA2319 via WAAM, substantially reducing harmful intermetallic phases, though brittle Al-Cu regions persist locally at the aluminium interface (Manohar et al., 2025). Al-Al multi-material structures exhibit smooth, defect-free transitions with mechanical properties governed by the individual alloys rather than the transition zone (Hauser et al., 2021). Force-assisted wire-laser DED stabilizes droplet transfer in Al-Ti builds, reducing porosity and improving bond quality through controlled melt pool dynamics (Zhao et al., 2023). Mild steel-stainless steel bimetals produced by WAAM achieve defect-free overlapping and stacked walls suitable for targeted property improvement (Suárez et al., 2022), while IN718-CoCrMo structures fabricated via laser DED exhibit crack- and intermetallic-free interfaces combining wear and oxidation resistance without interface-related weakening (Groden et al., 2022).

The current research landscape is characterized by concentrated investigation of stainless steel-Inconel systems alongside limited exploration of other combinations, many of which appear in only one or two publications. While successful implementations have been demonstrated for titanium-, copper-, and aluminium-based systems, often requiring interlayers or FGM transitions, significant research potential remains in establishing robust processing windows, characterizing long-term performance, and expanding viable material pairings toward industrial application.

3.4 Industrial Scalability and Sustainability Considerations

Despite the technical progress demonstrated in laboratory settings, the transition of LWAM to robust industrial deployment remains constrained by several unresolved challenges. Process control constitutes a primary barrier: laser power, wire feed speed, travel speed, and beam profile interact in ways that are material-system specific, and no universal parameter optimization guidelines currently exist for multi-material deposition across diverging thermophysical properties (Ghanadi and Pasebani, 2024). Although AI-driven approaches including neural network-based melt pool monitoring, CNN-assisted defect detection, and reinforcement learning for parameter adaptation have demonstrated promising results in isolated laboratory conditions, these systems are predominantly trained on limited, static datasets and rarely integrated into fully closed-loop, standardized industrial WAAM or LWAM cells (He et al., 2023). Robust, real-time multivariate process control that simultaneously addresses heat accumulation, geometric deviation, and material transition instabilities remains an open research challenge (Ghanadi and Pasebani, 2024; He et al., 2023). Furthermore, the absence of qualification standards, certified process windows, and digital twin frameworks capable of virtual process validation represents a critical gap that impedes regulatory acceptance and industrial scalability of LWAM for multi-material applications (Clare et al., 2025; Treutler and Wesling, 2025).

Wire-laser directed energy deposition offers inherent sustainability advantages over subtractive manufacturing routes, primarily through reduced material waste and favorable buy-to-fly ratios that translate into measurable reductions in cumulative energy demand and CO_2 emissions across cradle-to-gate system boundaries (Catalano, 2022; Pagone et al., 2022). Repair and remanufacturing applications via wire-based DED can reduce environmental impact by approximately an order of magnitude compared to new part fabrication, as energy- and emission-intensive primary material production is largely avoided (Pagone et al., 2022). However, several sustainability challenges remain insufficiently addressed. Energy consumption during LWAM operation is strongly parameter-dependent, and the relationship between deposition efficiency and energy efficiency involves trade-offs that have not been systematically characterized across material systems (Catalano, 2022). Life cycle assessment data specific to wire-laser processes remain scarce, methodologically inconsistent across studies in terms of system boundaries, impact assessment methods, and input data sources, limiting comparability and standardization (Kokare et al., 2025; Pagone et al., 2022). The social dimension of sustainability in wire-based DED, encompassing supply chain ethics, occupational health, and community impact, has only recently begun to receive systematic attention and remains underrepresented relative to environmental and economic assessments (Kokare et al., 2025). Establishing standardized LCA frameworks specific to wire-laser multi-material deposition constitutes a prerequisite for credible sustainability claims and life cycle-based design decisions in industrial applications.

4. Conclusion

This review has systematically examined wire-based multi-material additive manufacturing with particular emphasis on laser wire directed energy deposition as an enabling technology for bimetallic and functionally graded structures. Through coordinated multi-wire feeding and precise heat source control, this technology achieves near-net-shape fabrication of dissimilar metal combinations and functionally graded materials, providing transformative solutions for multi-functional components in aerospace, energy, and biomedical applications.

The three principal process variants serve distinct application domains. WAAM dominates large-scale components through low cost and high deposition efficiency. LWAM achieves superior dimensional accuracy and process stability, making it particularly suited for precision multi-material applications. EBAM enables metallurgical bonding of high-melting-point and reactive metals under vacuum conditions, expanding refractory composite possibilities. No universal solution exists; process selection demands careful consideration of component requirements and thermophysical material properties.

Analysis of established material combinations reveals concentrated progress in stainless steel-Inconel pairings, which demonstrate technical maturity through consistent epitaxial grain growth, narrow compositional gradient zones of approximately 55 µm, and defect-free interfaces across multiple DED platforms. Beyond this system, the majority of investigated combinations appear in only one or two publications, exposing limited research density and substantial opportunity for systematic investigation. Five key challenges impede broader industrialization: insufficient interfacial wettability in high melting-point differential systems causing incomplete fusion defects; thermal expansion coefficient mismatches generating interfacial shear stresses and microcracking during thermal cycling; brittle intermetallic compound formation at dissimilar metal interfaces; the absence of systematic process optimization guidelines for laser parameter selection across material systems with diverging thermophysical properties; and limited multi-material deposition strategies specific to wire-laser DED. Addressing these challenges requires integrated material design, process innovation, and cross-scale characterization.

Future research must prioritize process-structure-property relationships for underexplored combinations, development of robust process windows through multi-scale modeling and in-situ monitoring, and advanced characterization of melt pool dynamics, solidification behavior, and intermetallic phase formation kinetics. Interlayer strategies and functionally graded transitions offer validated pathways for managing property mismatches. Systematic long-term performance studies addressing fatigue, creep, corrosion resistance, and thermal cycling behavior are critical for qualification in safety-relevant applications.

Substantial progress in single-material feedstocks contrasts sharply with the limited state of bimetallic exploration. As aerospace, energy, and chemical processing industries face escalating demands for higher operating temperatures, enhanced thermal management, and superior wear and corrosion resistance, single-material structures encounter fundamental performance limitations that multi-material approaches uniquely address. Industrially relevant yet critically underexplored combinations, specifically tool steel-copper alloys for hot-work tooling with integrated cooling, aluminum bronze-structural steel for marine applications, maraging steel-cobalt alloys for high-performance cutting tools and aerospace components, and Stellite-Inconel systems for extreme-environment turbines and chemical reactors, each offer distinct application advantages but lack the research density required to establish reliable processing windows, interface characteristics, and long-term performance data. Systematic investigation of these combinations through wire-laser DED, supported by advanced characterization and multi-scale modeling, represents not incremental progress but a critical pathway toward transforming wire-based multi-material additive manufacturing from laboratory demonstration to mature industrial technology.

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Biographies

Simon Robel is a Mechanical Engineering student at Technische Universität Chemnitz, Germany, currently completing his Diplom degree (expected March 2027) with a focus on lightweight engineering and advanced manufacturing technologies. His academic interests center on additive manufacturing, process development, and the exploration of innovative material combinations for functionally integrated structures. He has worked for three years as a research assistant at TU Chemnitz, contributing to manufacturing-related research projects and gaining early experience in applied scientific work. During an international research stay at Stellenbosch University, South Africa, he investigated material compatibility and interfacial challenges in wire-laser-based multi-material additive manufacturing. In addition, he completed an industrial internship at TRUMPF, a global leader in high-power laser systems, where he gained practical insight into industrial laser technology and machine development. He aims to pursue an international career in research and development, focusing on application-driven innovation in advanced manufacturing and lightweight structural systems.

Stephen Matope is a Full Professor in the Department of Industrial Engineering, Stellenbosch University with over 16 years of lecturing industrial engineering related subjects at university level. His research interests are in advanced manufacturing covering additive manufacturing, manufacturing processes and manufacturing systems.