

LASER DED TECHNOLOGY: MATERIALS, PARAMETERS AND APPLICATIONS. A REVIEW OF RECENT LITERATURE

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ABSTRACT: Direct Energy Deposition (DED) for metal additive manufacturing has recently become an important solution for industries like aerospace, energy, automotive, and medical. Laser DED melts the material, which can be in powder or wire form, locally and deposits it layer by layer onto a substrate. This makes it possible to fix and upgrade important parts as well as make new, complex, or large parts. Powder-based technologies give you precise control over the microstructure, making them perfect for uses where detail and material properties are very important, like in aerospace or biomedical parts. Wire-based processes are known for their high deposition rate and material efficiency. They are good for quickly making large parts or fixing things in factories. You can use a lot of different materials, such as high-entropy alloys (HEAs), ODS, and functionally graded composites, as well as titanium alloys, nickel superalloys, and stainless steels. To get the desired properties, it's important to choose the right DED configuration and process parameters. Combining DED with traditional machining makes it possible to create custom, high-performance solutions for any modern industry.
KEYWORDS: laser DED, DED-LB/M, process parameters, mechanical properties, optimization, HEA, ODS

1. INTRODUCTION

Metal Additive Manufacturing has rapidly evolved in the last decade, transitioning from niche applications to industrial use in sectors like aerospace, automotive, energy, and medical devices.

According to the ISO/ASTM 52900:2021 terminology, DED-LB/M (Directed Energy Deposition - Laser Beam/Metal) includes processes where the material (powder or wire) is locally melted by a concentrated energy source, and then deposited layer by layer onto a substrate. In industrial practice, the DED family includes variants with laser: LMD/LENS (Laser Metal Deposition / Laser Engineered Net Shaping), WLAM (Wire-Laser Additive Manufacturing), with electron beam: EBF3/EBAM (Electron Beam Freeform Fabrication / Electron Beam Additive Manufacturing), and with arc: WAAM (Wire Arc Additive Manufacturing), each having a distinct profile in terms of productivity, precision, and application scope.

Based on the analysis of the metal additive manufacturing (AM) market [1] for 2025, Powder Bed Fusion (PBF) is set to remain the predominant technology, accounting for approximately 48% of the global market in 2025. Thanks to its precision and versatility, PBF is vital in high-value sectors like the aerospace industry—for complex and lightweight components such as fuel nozzles and brackets—as well as in the medical field, for personalized implants. This technology includes laser-based variants (SLM, DMLS) and electron beam-based variants (EBM), offering manufacturers the flexibility to meet demanding performance requirements.

Directed Energy Deposition (DED) makes up about 22% of the market and is the best way to make and fix big parts in industries like energy, defense, and heavy industry.

Binder Jetting is quickly becoming more popular because it is cheaper and can make a lot of parts quickly. It is becoming more common in the automotive industry for making prototypes and custom parts.

Sheet lamination, metal extrusion, and material jetting are still niche technologies, but their uses are slowly growing. The rise of affordable desktop metal printers for small and medium-sized businesses (SMEs) and the growing need for high-resolution printed production of precious metals are helping this change happen.

Figure 1 shows how metal additive manufacturing (Metal AM) systems will be spread out in 2025 based on the technology used [1].

Powder bed processes (LPBF in particular) have the most installations because they have better resolution and finish. Directed Energy Deposition (Laser DED) technologies, on the other hand, are very useful when you need a high deposition rate, repairs, large parts, and material flexibility, such as when you want to make functionally graded or multi-material structures [1].

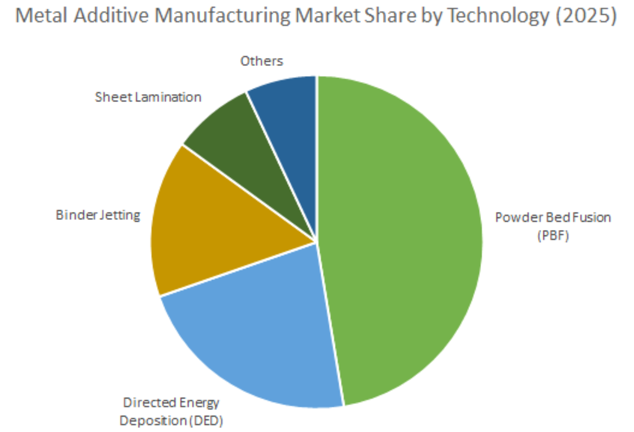


Figure 1. Metal AM systems distribution technology 2025 [1].

The figure shows that Laser DED systems are less common than LPBF systems, but they fill an important niche in the market by meeting specific needs for productivity, scaling, repairs, and material flexibility.

Directed Energy Deposition (DED) technology is a group of additive manufacturing processes that are known for their flexibility and scalability. They work well with other methods, like LPBF. There are different types of this category, and they all depend on the energy source and the type of filler material [3], [4].

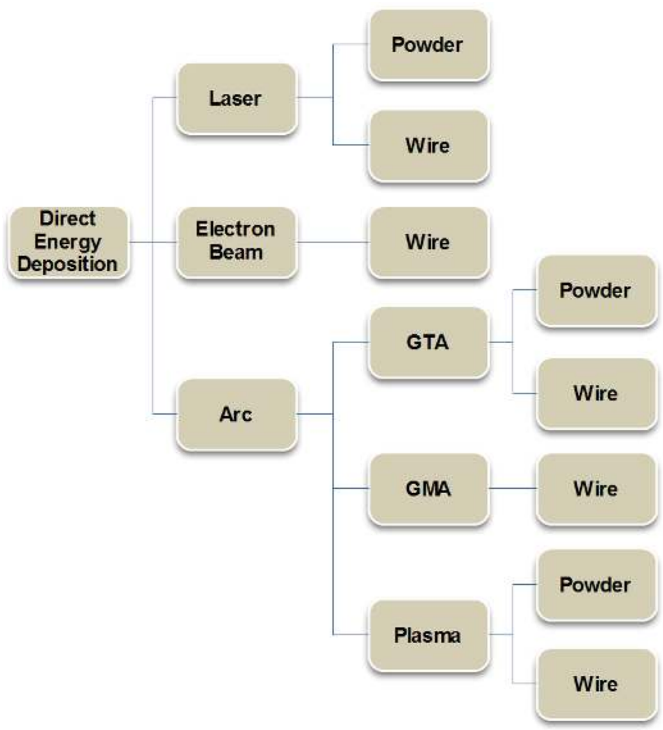


Figure 2. Classification of additive manufacturing processes using the DED method.

Figure 2 shows how to group additive manufacturing processes based on the Directed Energy Deposition principle. The groups are based on the type of energy source and the type of filler material.

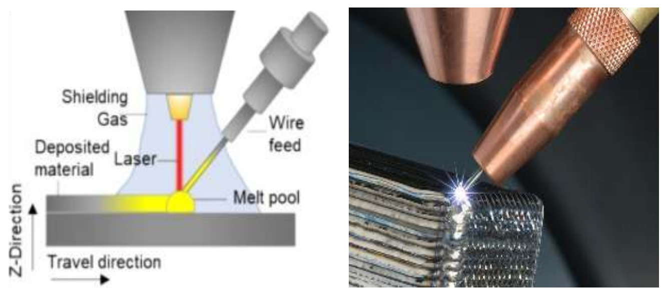
The laser additive manufacturing processes are classified as follows:

– Powder-fed Laser DED is presented in Figure 3. In this process, a fine jet of metal powder is directed into the area where a laser beam intensely heats the surface. The powder melts rapidly and is deposited layer by layer, allowing for the repair or construction of metal parts with high precision.

– Wire-fed Laser DED, in which a metal wire is used as the filler material. The laser constantly feeds and melts the wire, putting it exactly where it needs to go (Figure 4). This method is great for making complicated parts or fixing things [5].

a. b.

Figure 3. Laser DED with powder [2], [5].
a. principle, b..application



a. b

Figure 4. Laser wire [2], [6].
a. principle, b. application

The paper analyzes Laser Directed Energy Deposition (Laser DED) technology, with a focus on materials, process parameters, and key industrial applications. It synthesizes both the operating principles and the main variants of the DED process (powder-fed and wire-fed), along with material selection criteria guided by target properties and application domain.

It examines the behavior of titanium alloys, nickel-based superalloys, stainless steels, shape memory alloys, aluminum, high-entropy alloys (HEAs), oxide-dispersion-strengthened (ODS) alloys, and composite or functionally graded materials, underscoring the advantages and limitations of each in the DED context. The paper also discusses essential process parameters that govern microstructure, mechanical performance, and part quality, as well as current trends in hybridizing additive manufacturing with conventional processes and in optimizing DED through advanced monitoring and numerical control.

Through relevant literature examples and comparative tables, the paper offers a concise overview of recent advances and emerging directions in Laser DED.

2. MATERIALS USED

In current practice, material selection for DED-LB/M starts from a few key considerations: weldability (porosity, solidification cracking, oxidation), the intended objective (repair, functional coating, new part, FGM/multi-material), the feed form (powder vs. wire), and the protective atmosphere.

Recent literature [11], [12], [13], [14] highlights that LP-DED (Laser Powder Directed Energy Deposition) with powder maximizes compositional flexibility and dilution control, while wire-fed DED improves efficiency and deposition rate.

Additive manufacturing via Directed Energy Deposition (DED) has advanced rapidly, substantially broadening the palette of processable alloys—from established systems like Ti-6Al-4V to emerging alloys with advanced functionalities, including NiTi shape memory alloys and biomedical β-Ti alloys characterized by a reduced elastic modulus. The following sections present several categories of materials used in Laser DED production processes.

2.1 , Titanium alloys

Titanium alloys such as Ti-6Al-4V are widely used in Laser DED—both powder- and wire-fed—thanks to their combination of high specific strength, low density, and excellent corrosion resistance. In powder-fed configurations, these alloys enable the manufacture of complex parts with fine microstructures, tight compositional control, and the possibility of graded or multi-material architectures, making them ideal for applications where precision and localized properties matter, such as aerospace and medical. Conversely, wire-fed titanium in DED offers near-100% material utilization and very high deposition rates, supporting rapid fabrication or repair of large components at lower operating costs, albeit with somewhat reduced geometric versatility [15], [16] [17], [18]..

2.2 Nickel alloys

Nickel-based superalloys such as Inconel 718 and Inconel 625 are mainstay materials for Laser DED—both powder- and wire-fed—especially where parts must withstand very high temperatures and extreme service conditions, as in aerospace, energy, and automotive applications. In powder-fed setups, these alloys enable complex geometries, functional layers, and high-precision repairs, delivering fine microstructures and adequate control over local properties.

By contrast, wire-fed nickel superalloys are favored for large parts or rapid repairs due to near-complete material utilization and high deposition rates, albeit with less capability for fine geometric detail than powder-fed builds. In either case, the resulting components offer an excellent combination of mechanical strength, high-temperature stability, and corrosion resistance, which is why these superalloys are chosen for performance-critical applications.

2.3 Shape Memory Alloys

Titanium–nickel shape memory alloys (TiNi), commonly known as Nitinol, are increasingly used in Laser DED—both powder- and wire-fed—thanks to their unique ability to return to their original shape after deformation and their superelastic behavior. In powder-fed configurations, Nitinol enables the fabrication of complex or patient-specific geometries, ideal for biomedical applications (stents, implants, surgical instruments) as well as smart components in robotics and aerospace. Wire-fed TiNi DED offers rapid deposition with minimal material waste, making it attractive for larger parts or projects where efficiency is paramount. Regardless of the approach, the resulting parts retain Nitinol's essential properties—shape memory, superelasticity, and biocompatibility—opening new possibilities for functional, customized components in advanced applications [22], [23].

2.4 Stainless Steels

Stainless steels are among the most extensively studied materials in additive manufacturing, particularly with Laser DED (L-DED). The flexibility of L-DED for building or repairing large components warrants a deep look at the interplay between process parameters, microstructure, and resulting properties. Austenitic grades—especially AISI 316L—are widely used in powder-fed Laser DED for their corrosion resistance, ductility, and well-balanced mechanical behavior [24]. Powder processing enables complex geometries and graded layers with fine microstructures and solid mechanical performance, but quality is highly sensitive to parameters such as scan speed, laser power, and powder feed rate, which drive porosity and geometric fidelity [25].

For wire-fed DED, comparative studies show that 316L builds tend to exhibit fewer oxide inclusions and smoother surfaces, although the microstructure may contain more δ-ferrite; microhardness is generally comparable between powder- and wire-built parts, indicating similar mechanical performance [26]. In practice, choosing between powder and wire is a trade-off: geometric flexibility and surface detail versus material efficiency and operational simplicity—while preserving the inherently strong performance of stainless steel.

2.5 Aluminum Alloys

Aluminum alloys, like AlSi10Mg, are quite appealing for powder-fed Laser DED due to their low density, excellent strength-to-weight ratio, and corrosion resistance—all critical for weight-sensitive applications. However, their high reflectivity and thermal conductivity make laser absorption tricky and can destabilize the melt pool. Without optimized parameters (high power, precisely calibrated speed, and energy density), you're looking at potential porosity and cracking. For instance, relative density can hit over 99% at energy densities around 125 J/mm^3, but push that energy too high, and you'll get turbulence and increased porosity [27].

When it comes to wire-fed DED for aluminum, the literature is still a bit sparse, but techniques like EHLA (Extreme High-Layer Additive) are being explored as promising options for fast, efficient repairs, delivering corrosion- and wear-resistant layers with high productivity [28]. Ultimately, both methods can produce functional aluminum parts, and the choice boils down to balancing geometric accuracy, build speed, and material efficiency.

2.6 High-Entropy Alloys (HEAs)

High-entropy alloys (HEAs)—which blend at least five principal elements in equiatomic or near-equiatomic ratios—are increasingly compelling for Laser DED, whether powder- or wire-fed. In powder mode, HEAs can be built layer by layer with fine, uniform microstructures that curb elemental segregation and deliver strong mechanical performance—high strength with usable ductility—thanks to rapid solidification and the characteristic “cocktail effect” of HEAs [29], [30]. DED also makes it straightforward to create compositionally graded layers directly from elemental powders, avoiding pre-alloying and giving designers wide latitude to tune properties on demand [31].

For wire-based DED, the literature is thinner, but the approach is promising: higher deposition rates and excellent material utilization make it attractive for quickly building larger HEA components. Taken together, Laser DED HEAs bring optimized microstructures, improved mechanical properties, and rich options for functional customization—marking a forward edge in advanced materials.

2.7 Oxide Dispersion Strengthened (ODS) Alloys

Oxide dispersion–strengthened (ODS) alloys—metal matrices reinforced with nanoscale oxide particles, typically Y_2O_3—are prized for applications demanding high strength and thermal stability, such as turbine and nuclear reactor components. In powder-fed

Laser DED, these nanoparticles can be distributed relatively uniformly, but the slower solidification rates raise the risk of agglomeration, which can produce slag-like inclusions and erode the intended strengthening effect [32], [33]. Advanced approaches like High-Speed Laser Cladding (HSLC) improve oxide dispersion, refine dispersoid sizes to roughly 50–150 nm, and increase hardness (around 320 HV 0.1) compared with conventional DED.

Powder-based Laser DED can thus yield homogeneous microstructures and elevated hardness, but achieving truly uniform oxide distribution requires tight control of process parameters [33].

On the wire side, promising efforts—such as developing ODS wire feedstock for WAAM—aim to pair high material efficiency and build rate with the preservation of ODS properties. Research into wire-fed ODS DED is rapidly progressing, targeting gains in both efficiency and structural quality [34].

2.8 Composite and Functionally Graded Materials (FGM)

Composite and functionally graded materials (FGMs) sit at the cutting edge of Laser DED—whether powder- or wire-fed. They let you blend the properties of two or more materials within a single part, dialing in hardness, wear resistance, or high-temperature capability exactly where it’s needed. By precisely controlling composition, you can engineer smooth transitions between materials and avoid common issues in conventional builds, such as stress concentrations or interfacial defects.

Powder-based DED offers the greatest flexibility for fine compositional gradients and true multi-material architectures, making it ideal for aerospace, medical, or chemical-industry components where performance requirements vary across different regions of the same part [35], [36]. In parallel, wire-fed variants—while less agile for abrupt compositional changes—deliver rapid, efficient deposition well-suited to large components or functional repairs, where local property tailoring still matters but production rate is a priority.

Both approaches enable “customized-performance” parts, significantly reducing the need for complex assemblies, extra materials, or costly downstream processes, and allowing each zone of the component to be optimized for its specific service environment [37]. For process selection,

Table 1 summarizes the key compatibilities between LASER DED methods and various material categories.

Table 1. Compatibility of LASER DED processes with different material categories

No.	Category of Material	Laser Powder	Laser Wire	Source
1	Titanium Alloys (e.g., Ti-6Al-4V	Excellent	Good	[38] [39]
2	Nickel Alloys (Superalloys)	Excellent	Good	[38] [40]
3	Shape Memory Alloys (TiNi)	Excellent	Feasible	[41] [42]
4	Stainless Steels	Excellent	Excellent	[38] [47]
5	Aluminum Alloys	Bun	Good	[38] [48]
6	High-Entropy Alloys (HEAs)	Excellent	Limitations	[43] [44]
7	ODS Alloys	Excellent	Limitations	[45] [46]
8	Composite and Graded Materials	Excellent	Limitations	[49] [50]

3. APPLICATIONS

Additive manufacturing via DED has established itself as a high-performance, highly adaptable technology, covering a wide range of industrial needs—from repairing critical components to producing large, complex structures.

Laser Powder DED delivers excellent microstructural control and high precision and is widely used for mold and die repair, hard facing, and the fabrication of aerospace components from superalloys, where quality and customization are paramount [51].

Wire-fed L-DED enables fast, efficient deposition, making it ideal for building bulky or large-format parts. It is often preferred for processing titanium and steel alloys in the marine and aerospace sectors, where high deposition rates translate into economic and operational advantages—even if geometric precision is somewhat lower than with powder-based methods [52].

Table 2. Applications Depending on the Working Process

Process	Applications	Example
LENS (Laser DED with powder in an Argon chamber; dense parts [56]	Repair, rework, manufacturing of parts from Ti/Inconel/SS Repair of turbine blades, hardfacing, material addition to critical components Deposition + in-situ CNC machining for near-net Ti/Inconel/SS parts:	 Additive manufacturing  Repair
Laser Cladding/LMD Laser with powder; Coaxial powder deposition into a laser weld pool; coating, repair [57]	Anti-wear/corrosion coating, repair of turbine blades; HS-LMD for brake discs (very high speeds). Anti-wear/corrosion coating and repair of turbine blades High-Speed LMD for functional layers (e.g., brake discs, very high speeds):	 Additive manufacturing  Coating  Repair  Joining
WLAM (Wire + Laser [58])	Massive structures with subsequent 5-axis post-processing. Large/near-net parts, tooling, and repair with low dilution; Robotic/CNC integration for large geometries and 5-axis post-processing:	 Additive manufacturing

Today, new approaches are boosting energy efficiency and enabling richer material grading, opening fresh avenues for advanced industrial applications [53].

Whichever route you choose, L-DED is geared toward repairing and restoring components or building large, fully 3D structures. When integrated with conventional machining (milling, turning) in hybrid workflows, these technologies deliver end-to-end solutions—from prototype through to full-scale production [54], [55].

The applicability of Directed Energy Deposition (DED) depends on the specific modality—powder or wire. Table 2 outlines the most relevant applications by DED type.

4. WORKING PARAMETERS

Process parameters are the primary control levers in Directed Energy Deposition (DED) additive manufacturing. Their values govern the properties of the deposited material—from microstructure and mechanical performance to productivity and geometric quality [59]. Whether the DED process is powder-fed (Laser DED) or wire-fed (Wire DED), several core parameters define it:

4.1 Laser power

For laser-based DED, source power typically ranges from about 500 W to 10 kW. Power dictates melt-pool depth and width, as well as melting rate. Excessive power can cause evaporation; too little leads to lack of fusion. While higher power can boost deposition rate, it generally compromises feature resolution, making fine details harder to achieve at elevated power levels.

4.2 Scan speed

Scan speed (mm/s) is the velocity at which the heat source travels over the substrate or the previously deposited layer. It sets the thermal interaction time and, by extension, the melt-pool size. It also directly controls cooling rate: higher speeds drive faster cooling (finer microstructure but increased cracking risk); lower speeds lead to slower cooling.

4.3 Mass feed rate

The mass feed rate (g/min) is the amount of feedstock delivered per unit time. It directly affects bead height (layer thickness) and has a much smaller impact on bead width. Keeping a stable powder feed is challenging because powder characteristics can drift over time (e.g., moisture uptake), necessitating periodic recalibration. It must be tuned with laser power to avoid lack of material (fusion porosity) or excess (agglomeration).

4.4 Hatch Spacing

Hatch spacing h (mm) is the distance between adjacent deposition tracks. Proper spacing ensures optimal overlap and adequate remelting of the prior track. Incorrect spacing can cause lack-of-fusion defects at track interfaces. The interplay of power, mass feed rate, and scan speed determines single-track bead characteristics such as height and width.

4.5 Dwell Time

Dwell time (s) is the idle interval between deposited layers. It sets the substrate temperature before the next pass and strongly influences the repeated thermal cycles that drive microstructure evolution and residual stress. Temperature at the layer base directly affects the cooling rate, which in turn dictates phase formation (critical for Ti and NiTi). If dwell is too short, heat accumulates, promoting grain coarsening

4.6 Spot diameter

Spot diameter (mm) refers to the projected size of the energy source on the substrate. Although lasers can be tightly focused, DED often uses a slightly defocused or diffuse beam. Spot size matters: a smaller spot, paired with lower power, increases feature resolution. In DED systems, the spot diameter is tuned via focusing optics and the working distance between the deposition head and the substrate. Spot size impacts both deposition rate (productivity) and geometric/microstructural outcomes (see table 3).

Table 3 Impact of spot diameter

Aspect	Large Spot	Small Spot
Track Width	Increases	Decreases
Deposition Rate	Increases (due to wider tracks)	Decreases
Resolution/Precision	Decreases (Less fine details)	Increases (Fine detail, thin walls)
Energy Density (VED))	Decreases (Energy is distributed over a larger area)	Increases (Energy is concentrated)
Melt Pool	Larger melt pool, slower cooling rate	Smaller melt pool, faster cooling rate

4.7 Specific Energy Density

The Energy Density Index (ESI) describes how much energy is delivered per unit area or volume during melting or sintering. The Volumetric Energy Density (VED) is especially useful because it normalizes the three primary operating parameters, enabling apples-to-apples comparisons across different DED systems. Energy density drives part quality via its effects on microstructure, mechanical properties, and defect formation (porosity, cracking, etc.). Tuning the ESI lets you optimize process parameters for different materials and application requirements. An optimal energy density delivers stable processing, low consumables usage, and high productivity.

$$VED=\frac{P}{v \cdot h \cdot t} \quad (1)$$

Unde:

P = laser power (W)
v = scan speed (mm/s)
h = hatch spacing/track spacing (mm)
t = ayer height/thickness (mm)

In wire-based DED systems, the feed angle and direction of the wire are also critical. Wire orientation relative to the melt pool governs filler transfer and bead quality. Because these parameters interact in complex, coupled ways, finding the sweet spot typically still relies on practical trials and process experience

5. CONCLUSIONS

Laser Directed Energy Deposition (Laser DED) has matured in recent years into a versatile, high-performance solution for metal additive manufacturing, meeting a widening range of industrial needs in repair, refurbishment, and the production of complex components. A review of recent literature underscores that smart material selection—spanning titanium and nickel alloys, stainless steels, and advanced systems like HEAs, ODS alloys, and functionally graded composites—is pivotal to achieving the targeted mechanical and functional properties.Process efficiency and final part quality are strongly governed by operating parameters (laser power, scan speed, feed rate, spot geometry), which demand careful, material- and application-specific calibration. Moreover, integrating DED with conventional machining and adopting advanced monitoring and control methods is opening new pathways to highly customized, high-performance parts.At the same time, although laser-based DED offers clear strengths—especially in material flexibility and microstructural control—it still faces hurdles. Ensuring uniform microstructures, preventing defects, and improving energy efficiency remain active areas of research. Looking ahead, continued tuning of process parameters, a wider range of processable materials, and the adoption of advanced monitoring tools are likely to strengthen Laser DED's standing as a next-generation additive manufacturing technology with broad applications in high-end industries. This study also has inherent limitations. It is based solely on a literature review, so the findings depend on the quality of the reported data and methods in the cited sources. That variability—particularly in terminology and process parameters—makes direct comparisons challenging. In addition, as a non-experimental synthesis, the work does not present original experimental results and does not claim to comprehensively cover all emerging materials or technologies. Instead, it focuses on validated solutions and the main trends shaping the industry. As for future directions, there is a clear need for dedicated experimental studies that probe optimal parameters in depth—especially for new alloys and innovative combinations of materials and process strategies. Given the rapid pace of the field and the steady emergence of niche materials and technologies, systematic investigations are essential both to validate current conclusions and to broaden our knowledge of laser-based DED in additive manufacturing. In this sense, the present study provides a solid informational baseline, while also underscoring the importance of continued research to keep pace with the swift developments in this dynamic technological domain.

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