

# A Comprehensive Scientific Review of Additive Manufacturing Based on Fiber Laser Technique

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ARTICLE INFO	ABSTRACT
<i>Keywords:</i> Additive manufacturing; fiber laser; metal; mechanical properties	This article presents a thorough scientific review of Additive Manufacturing (AM) grounded in the fiber laser technique, exploring its multifaceted dimensions to unveil both potential and challenges. The introduction sets the stage by emphasizing the transformative impact of AM technologies on modern manufacturing, specifically focusing on the precision and versatility offered by Fiber Laser-based Additive Manufacturing (FLAM). Addressing the critical problem statement, the review identifies existing gaps in understanding FLAM, ranging from material compatibility issues to process optimization challenges. The methodology employs a systematic and interdisciplinary approach, delving into peer-reviewed articles, conference papers, and patents across materials science, mechanical engineering, and laser technology domains. Consequently, the synthesis of this diverse literature aims to provide a comprehensive overview of FLAM's current state, facilitating the identification of research directions and enhancement opportunities. The expected results encompass a detailed analysis of material properties, process parameters, and applications, illuminating both strengths and limitations. Ultimately, the conclusion emphasizes the pivotal role of this review in stimulating further research and development in FLAM, serving as a valuable resource for researchers, engineers, and industry professionals navigating the evolving landscape of advanced manufacturing technologies.

#### 1. Introduction

Metal Additive Manufacturing (AM), commonly referred to as 3D printing, has drawn considerable interest in recent times due to its ability to fabricate intricate metal components with substantial design autonomy [1]. This technology has the potential to revolutionize the way metal components are fabricated, offering benefits such as reduced lead times, material savings, and the ability to create geometries that are impossible with traditional manufacturing methods [2].

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One of the key advantages of metal AM is its ability to produce parts with complex geometries and internal structures without the need for tooling [2,3]. This enables the fabrication of lightweight, high-efficiency elements for aerospace, automotive, and medical uses. Additionally, metal AM enables on-demand production, reducing the need for a large, expensive spare parts inventory. However, challenges such as residual stresses, microstructural defects, and build failures still need to be addressed to improve the quality and reliability of metal AM parts. Researchers and industry experts are actively developing new materials, processes, and post-processing techniques to overcome these challenges and further advance the capabilities of metal AM [4,5].

This comprehensive review will delve into the various aspects of metal AM, including the different technologies, materials, process parameters, and applications [6,7]. By understanding the current state of metal AM and its potential future developments, we can better appreciate its impact on the manufacturing industry and identify opportunities for further research and innovation. Note that Metal AM encompasses a variety of technologies, each with unique strengths and limitations. Some of the most highly used metal AM processes include directed energy deposition, powder bed fusion, and binder jetting [8,9]. These processes differ in their approach to melting and solidifying metal powders, resulting in different part qualities and production speeds.

Metal AM has been applied in a wide range of industries. From producing intricate lattice structures for lightweight aerospace components to creating patient-specific implants for the medical sector, the versatility of metal AM continues to drive innovation and efficiency across various fields [2,10].

# 2. Literature Review

The domain of AM grounded in fiber laser technique has witnessed noteworthy exploration and growth in recent years. Moreover, multiple critical analyses and investigations have offered invaluable perceptions into diverse facets of this technology. One noteworthy sphere of exploration is the AM of carbon fiber-reinforced composites. An exhaustive review paper from Hu et al., [11] presents an all-encompassing overview of this subject, delving into the manufacturing procedure, properties of the composites, and potential applications. Another significant field of study is steel compatibility with AM and restoration through Laser-Directed Energy Deposition (L-DED). Barr et al., [12] reported the role of the intrinsic heat treatment effect on the tensile properties of high-strength steels, providing insights into the predicaments and possible resolutions for utilizing AM processes to mend impaired steels. Furthermore, a review article from Li et al., [13] concentrates on spatter-in-Laser Powder Bed Fusion (L-PBF) AM, discussing its generation, consequences, and potential countermeasures. The article underscores the significance of comprehending and alleviating spatter behaviour, particularly in fabricating large components during the multi-laser L-PBF process. These investigations and reviews furnish valuable insights into the various aspects of AM rooted in fiber laser technique, encompassing themes such as composite materials, steel compatibility, and processrelated challenges. Hence, by incorporating and analyzing the discoveries from these sources, the comprehensive scientific review can yield a thorough comprehension of the field's current state and identify potential areas for further exploration and development.

The utilization of the fiber laser technique in AM presents both advantages and disadvantages. An important advantage lies in its ability to deliver high precision and facilitate the production of intricate geometries. Fiber lasers have the capability to achieve incredibly small spot sizes, enabling the incorporation of fine details and complex designs in the manufactured components. Kumaresan *et al.*, [14] stated that Laser Deposition represents the most advanced method for creating or restoring objects ranging from millimeter to meter in size. While this technique can be applied to ceramics and polymers, it is particularly favored for metallic materials and metal-based hybrid compositions, utilizing either wire or powder forms. Mihăilescu et al., [15] reported fiber lasers are distinguished for their commendable energy efficiency, leading to potential cost savings, and reduced environmental impact compared to alternative laser types. Conversely, a notable drawback of the fiber laser technique is the possibility of spatter generation during L-PBF AM. This concern becomes particularly pronounced in the production of large-scale components during the multi-laser L-PBF process [13]. Moreover, applying the fiber laser technique in AM composite materials, such as carbon fiber-reinforced composites, exhibits promise. Nonetheless, challenges persist, particularly in ensuring proper adhesion between the reinforcing materials and the matrix, as well as in minimizing porosity in the manufactured components. Hassan et al., [16] research has demonstrated that including fiber reinforcements can enhance the mechanical properties of printed composites, but optimizing this process remains an ongoing area of study. In conclusion, the fiber laser technique in AM offers exceptional precision and energy efficiency. However, it is accompanied by challenges such as spatter generation and further optimization requirements when producing composite materials. Thus, understanding these advantages and disadvantages is imperative for effectively harnessing this technology in diverse manufacturing applications.

# 3. Material and methods

# 3.1 Identification

Three primary phases of the systematic review process were employed to select a significant number of relevant publications for this investigation. In the initial stage, keywords are selected, and synonymous terms are sought through a thesaurus, dictionaries, encyclopaedias, and prior research. Subsequent to formulating search queries for the Scopus and ScienceDirect databases (refer to Table 1), all suitable keywords were selected. Correspondingly, a total of 871 publications have been obtained from both databases for the current study project during the preliminary stage of the systematic review process.

Table 1	
The search strings	
Scopus	ITLE-ABS-KEY ("additive manufacturing" AND "fiber laser") AND
	PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA,
	"ENGI" ) ) AND ( LIMIT-TO ( DOCTYPE, "ar" ) ) AND ( LIMIT-TO (
	PUBSTAGE, "final" ) ) AND ( LIMIT-TO ( SRCTYPE, "j" ) ) AND ( LIMIT-TO
	( LANGUAGE, "English" ) ) AND ( LIMIT-TO ( OA, "all" ) )
ScienceDirect	"Additive manufacturing" AND "fiber laser"

# 3.2 Screening

The screening phase entails examining the array of potentially pertinent research materials to identify content corresponding to the predetermined research question(s). During this stage, criteria pertaining to content, such as the utilization of AM through the application of fiber lasers, are frequently employed. In this step, duplicate papers are systematically eliminated. Note that the initial screening phase excluded a total of 871 publications, while the subsequent phase evaluated 92 papers, employing distinct exclusion and inclusion criteria as delineated in Table 2. Here, the primary criterion utilized was the literature analysis (research papers), which served as the primary source of practical recommendations. This criterion incorporates evaluations, meta-syntheses, literary works, meta-analyses, chapters, book series, and conference proceedings not encompassed in the most

recent investigation. In addition, the assessment solely focused on publications in the English language, and it is essential to acknowledge that the approach is exclusively aimed at the timeframe spanning from 2021 to 2023. It is noteworthy to highlight that no publications were dismissed on grounds of replication criteria.

Table 2							
The selection criterion is searching							
Criterion	Inclusion	Exclusion					
Language	English	Non-English					
Timeline	2021 – 2023	< 2021					
Literature type	Journal (Article)	Conference, Book, Review					
Publication Stage	Final	In Press					
Subject Area	Engineering	Material Science					

# 3.3 Eligibility

A total of 92 articles were acquired in the third stage, also known as the eligibility stage. At this point, a thorough assessment of the titles and key content of all articles was undertaken to ensure compliance with the criteria for inclusion and alignment with the current research objectives. Subsequently, 63 reports were excluded due to their insufficient relevance to the field, absence of substantial titles, presence of abstracts unrelated to the study's objectives, or absence of full-text access supported by empirical evidence. Ultimately, a total of 29 articles remained for further scrutiny (see Figure 1).



Fig. 1. Flow diagram of the proposed searching study [17]

### 3.4 Data Abstraction and Analysis

An integrative analysis was employed as one of the assessment strategies in this study to scrutinize and amalgamate a diverse range of research designs (quantitative methods). The objective of the proficient study was to determine pertinent topics and subtopics. The data collection phase constituted the initial step in formulating the theme. The authors' meticulous examination of 29 publications for assertions or material germane to the topics of the present study has been illustrated in Figure 2. Subsequently, the authors evaluated the current noteworthy studies pertaining to AM based on fiber lasers. The methodology employed in all studies, as well as the research findings, are currently under investigation. Subsequently, the author collaborated with other co-authors to formulate themes based on the evidence within the context of this study.

Other than that, a log was maintained throughout the data analysis process to document any analyses, perspectives, conundrums, or other considerations relevant to the interpretation of the data. Finally, the authors scrutinized the results to identify inconsistencies in the theme development process. It is worth mentioning that the authors engage in discussion if there are discrepancies between the concepts. The produced themes were eventually adjusted to ensure coherence. Consequently, the analysis was selected by two experts, one specializing in mechanical engineering and the other in AM, to ascertain and establish the validity of the issues. The expert review phase assures the significance, clarity, and appropriateness of each subtheme by establishing domain validity.

#### 4. Result and Finding

#### 4.1 Theme 1: Laser-Based Directed Energy Deposition

Laser-Based Directed Energy Deposition of Polymers (DED-LB/P) is an innovative AM technique that demonstrates its potential in fabricating Dielectric Image Lines (DIL) for high-frequency applications. This study introduces an absorber-free DED-LB/P process that utilizes a thulium-doped fiber laser to create DILs composed of Polypropylene (PP). Note that these dielectric lines exhibit minimal signal attenuation, particularly at high frequencies, offering a promising alternative to conventional stripline technology. The research suggests that DED-LB/P has the potential to become a viable manufacturing process for future Radio Frequency (RF) applications, addressing the demand for higher bandwidth in telecommunications and improved radar sensor resolution [17].

An investigation into enhancing the mechanical properties of components produced by Directed Energy Deposition with Laser (DED-L) focuses on mitigating the issue of inadequate fusion. This study introduces laser remelting as an alternative approach to achieve higher densification after DED-L processing. By employing an ytterbium fiber laser, the research explores the deposition of Iron and Inconel 625 powders on a substrate. It reveals that laser remelting significantly reduces voids resulting from DED-L. The findings suggest that this method not only enhances the quality of components by reducing the likelihood of failure but also maintains productivity by utilizing existing equipment. The study emphasizes the necessity for new strategies to improve the robustness of the process and minimize dispersion [18].

The investigation examines the utilization of laser remelting to improve the surface quality in Laser Directed Energy Deposition with powder (pDED-L). Through the use of a 10-kW fiber laser source alongside Iron and Inconel 625 powders, the study assesses the effectiveness of this approach using 2D and 3D surface measurements, scanning electron microscopy, and metallurgical analysis. The results indicate a significant reduction in surface roughness and waviness, making laser remelting a promising technology for improving the quality of 3D metal components. Correspondingly, the

research proposes that this approach could lead to faster production rates compared to traditional post-processing techniques [19].

An exploration of the Direct Laser Metal Deposition (DLMD) of a nickel-based superalloy is conducted. The study investigates the effects of process parameters on geometrical characteristics such as clad width, clad height, penetration depth, and dilution. Experimental tests reveal the substantial influence of standoff and laser-defocusing distances on the deposition process, providing insights for enhanced control and quality in DLMD [20]. Lastly, the thermal effects in the single-point curing process for pulsed infrared laser-assisted 3D printing of optics are discussed. The study presents a precision Additive Freeform Optics Manufacturing (AFOM) method that utilizes a pulsed infrared laser to thermally cure optical silicones. Note that the opto-thermal-chemical-coupled multiphysics model predicts the shape and size of cured polymers, offering a guided design for high-precision AFOM processes [21].



**Fig. 2.** Simplified illustration of the DED-LB process using powder feedstock material [18]

Authors	Title	Year	Journal	Methodology	Findings
Wittmann A.; Bader T.; Chamandani S.A.; Hentschel O.; Schmidt M.; Gold G.[18]	Feasibility of Manufacturing Dielectric Image Lines by Using Laser-Based Directed Energy Deposition of Polymers	2023	IEEE Access	Free DED-LB/P process with a thulium- doped fiber laser	DED-LB/P could represent such an alternative manufacturing process for future RF- applications
dos Santos Paes L.E.; Pereira M.; Xavier F.A.; Weingaertner W.L.; Vilarinho L.O.[19]	Lack of fusion mitigation in directed energy deposition with laser (DED-L) additive manufacturing through laser remelting	2022	Journal of Manufacturing Processes	The paper discusses the application of laser remelting in mitigating voids in AM of Iron and Inconel 625 DED-L deposits. This technique entails scanning a laser over the previously deposited AM beads, resulting in coalescence and redistribution of material	The use of laser remelting has led to a notable decrease in the void percentage of Iron from 7.1% to 1.7% and Inconel 625 from 7.1% to 3.7%. This implies that laser remelting has the potential to enhance productivity and decrease the occurrence of surface-connected voids
dos Santos Paes L.E.; Pereira M.; Xavier F.A.; Weingaertner W.L.; D'Oliveira A.S.C.M.; Costa E.C.; Vilarinho L.O.; Scotti A.[20]	Understanding the behavior of laser surface remelting after directed energy deposition additive manufacturing through comparing the use of iron and Inconel powders	2021	Journal of Manufacturing Processes	The study compared surface finishes of multi-pass overlayers made with laser heating and powder before and after a remelting treatment. Iron and Inconel powders were used for comparison. The study examined the effect of the remelting technique on top surface finish	The DED-L with Iron and Inconel powders. Iron powder achieved a 30% reduction in average roughness, while Inconel powder achieved a 70% reduction. The technique's effectiveness was attributed to remelting adhered particles, resulting in improved surface quality
Ma CT.; Zhang FY.[21]	Design and Implementation of a Power Semiconductor- Based Switching Mode Laser Diode Driver	2024	Micromachines	Power semiconductor device (PSD)- based full-bridge phase-shifted (FB-PS) DC-DC converter	The suggested LD driver demonstrates acceptable driving characteristics
Jadhav S.D.; Goossens L.R.; Kinds Y.; Hooreweder B.V.; Vanmeensel K.[22]	Laser-based powder bed fusion additive manufacturing of pure copper	2021	Additive Manufacturing	Copper parts were made using L-PBF machine. A small focal spot diameter infrared fiber laser with wavelength of 1080 nm was used. The properties of the parts were measured and analyzed	The L-PBF fabricated copper parts show a 94 $\pm$ 1% electrical conductivity compared to the International Annealed Copper Standard (IACS). They also display a tensile strength of 211 $\pm$ 4 MPa, a yield strength of 122 $\pm$ 1 MPa, and an elongation at break of 43 $\pm$ 3% in the as-built condition
Alsaddah M.; Khan A.; Groom K.; Mumtaz K.[23]	Use of 450-808 nm diode lasers for efficient energy absorption during powder bed fusion of Ti-6Al-4V	2021	International Journal of Advanced Manufacturing Technology	Investigated diode lasers (450-808 nm) for melting Ti-6Al-4V in powder bed fusion. Used DAM approach to study laser wavelength effects on material absorption and processing efficiency	Diode lasers with short wavelengths can be used in powder bed fusion AM systems in the future

Okamoto Y.; Shinonaga T.; Takemoto Y.; Okada A.; Ochi A.; Kishimoto R.; Pityana S.; Arthur N.; Omoniyi P.; Mahamood R.; Maina M.; Akinlabi E.[24]	Study on joint characteristics in laser butt welding of AMed and wrought Ti-6Al-4V plates	2023	Welding in the World	Butt welding of the Ti-6Al-4V plate was performed using a fiber laser in argon shielding. The study examined the joint characteristics of laser weld wrought/wrought, AMed/AMed, and AMed/wrought Ti-6Al-4V plates through experimentation	Ti-6Al-4V plates made using AM have greater tensile strength than plates made through traditional methods. Laser-welded joints of AMed/AMed plates are stronger but less malleable compared to those of wrought/wrought plates
Robinson J.; Stanford M.;	Stable formation of powder	2020	Materials Today	400W fiber laser system, pure silver	SLM processing of pure silver is feasible with
Arjunan A.[25] Asadi R.; Queguineur A.; Wiikinkoski O.; Mokhtarian H.; Aihkisalo T.; Revuelta A.; Ituarte I.F.[26]	Process monitoring by deep neural networks in directed energy deposition: CNN- based detection, segmentation, and statistical analysis of melt pools	2024	Communications Robotics and Computer- Integrated Manufacturing	powder Inconel alloy 625 wire, 3 kW fiber laser, and off-axis welding camera	YOLOv8l showed higher precision in identifying the boundaries of the melted metal pool
Mazzarisi M.; Errico V.; Angelastro A.; Campanelli S.L.[27]	Influence of standoff distance and laser defocusing distance on direct laser metal deposition of a nickel-based superalloy	2022	International Journal of Advanced Manufacturing Technology	DLMD for 3D manufacturing of nickel- based superalloy on stainless steel plates. Use a ytterbium fiber laser source and deposition head with motorized optics. Study the effect of standoff distance and laser defocusing distance. Developed a multiphysics model to simulate the curing process of optical silicones	Standoff distance and laser defocusing distance influence the clad's geometry, including its width and height. An experimental setup allowed for observing powder distribution during deposition. An analytical model was proposed and validated to predict powder distribution and clad width. Numerical simulation showed agreement with experiments. Demonstrated a path for theoretically guided design of high-precision AFOM process
Li Z.; Hong Z.; Xiao Y.; Hao Q.; Liang R.[28]	Thermal Effects in Single- Point Curing Process for Pulsed Infrared Laser- Assisted 3D Printing of Optics	2020	3D Printing and Additive Manufacturing	Q-switched fiber laser, optical silicones	Numerical simulation shows good agreement with experiments

# 4.2 Theme 2: Laser Additive Manufacturing of Metals

The examination of the DLMD technique for Inconel 718 superalloy (a nickel-based material) utilizing a 1 kW fiber laser, in combination with a coaxial nozzle head, demonstrates a systematic approach to the process of AM. The research examines scanning speed, powder feed rate, and scanning strategies using a complete factorial design. Consequently, the outcomes disclose the impact of these variables on the geometrical dimensions and stability of additively manufactured walls. By means of statistical modelling and optimization, the research ascertains the optimal conditions for DLMD, providing valuable insights into attaining desired characteristics in the AM process [28]. The examination of technological assurance in titanium AM is addressed through a study exploring the fabrication of Ti-6AI-4V components utilizing selective metal laser sintering. The research scrutinizes different variables, including layer thickness, hatch spacing, laser travel speed, and laser power, in conjunction with the influence of thermal treatment. This comprehensive inquiry aims to facilitate the identification of optimal technological parameters for producing components with satisfactory mechanical properties. The study is a fundamental exploration for further progress in advancing titanium composites through AM techniques [29].

The investigation of DLMD of Inconel 718 superalloy examines elemental, microstructural, and physical properties. Using a 1 kW fiber laser, the study investigates the effects of scanning speed and powder feed rate on the AM process. Microstructural analysis, microhardness evaluations, and stability assessments of 3D printed walls provide insights into the complexities of DLMD. The results emphasize the impact of process parameters on the width, height, and stability of the deposited layers, underscoring the importance of understanding these factors for successful metal AM [30]. Figure 3 below illustrates the impact of the rate at which powder is fed and the speed at which scanning is performed on the height of the wall.



Fig. 3. The effect of powder feed rate and scanning speed on wall height [29]

Authors	Title	Year	Source title	Methodology	Findings
Moradi M.; Hasani A.; Pourmand Z.; Lawrence J.[30]	Direct laser metal deposition additive manufacturing of Inconel 718 superalloy: Statistical modelling and optimization by design of experiments	2021	Optics and Laser Technology	Design of Experiments used to study the impact of process parameters on output results. DLMD technique employed for AM. Analysis of Variance used to assess the effect of input parameters	Inconel 718 superalloy was deposited on AISI 4130 steel using the DLMD process. Lower Dh indicates more stability of the AM wall. The elemental composition of Inconel 718 powder was analyzed using ICP analysis
Kromanis A.; Vevers A.[31]	Technological Assurance of Ti-6Al-4V Parts Produced by Additive Manufacturing Using Selective Metal Laser Sintering	2022	Latvian Journal of Physics and Technical Sciences	The study used SMLS with a fiber laser 3D printer to make Ti-6Al-4V parts. Experiments were done to examine the effects of layer thickness, hatch spacing, laser travel speed, and laser power on the parts. Thermal treatment was investigated as a post-processing technique to enhance mechanical properties	The density of the parts was least affected by layer thickness. The parts had the best mechanical properties when the layer thickness was 0.07 mm, hatch spacing was 0.1 mm, laser travel speed was 80 mm/s, and laser power was 70 W. The physical properties of the 3D printed parts were significantly improved by thermal treatment in an inert environment
Moradi M.; Pourmand Z.; Hasani A.; Karami Moghadam M.; Sakhaei A.H.; Shafiee M.; Lawrence J.[29]	Direct Laser Metal Deposition (DLMD) additive manufacturing (AM) of Inconel 718 superalloy: Elemental, microstructural and physical properties evaluation	2022	Optik	DLMD technique used for AM of Inconel 718 Superalloy. Experiments conducted with a 1 kW fiber laser and coaxial nozzle head. Effects of scanning speed and powder feed rate investigated. Geometrical dimensions, microstructure observations, and microhardness measured for 3D- printed wall specimens	The height of the 3D printed samples depends on scanning speed and powder feed rate. Slower scanning speeds lead to taller walls and wider layers. The stability of layer height improves at slower scanning speeds.
Ullsperger T.; Liu D.; Yürekli B.; Matthäus G.; Schade L.; Seyfarth B.; Kohl H.; Ramm R.; Rettenmayr M.; Nolte S.[32]	Ultra-short pulsed laser powder bed fusion of Al-Si alloys: Impact of pulse duration and energy in comparison to continuous wave excitation	2021	Additive Manufacturing	Experiments were conducted using a mode-locked fiber laser system that produced pulses of varying durations at a specific wavelength. Comparative studies were also conducted using a continuous wave Yb-fiber laser at a different wavelength	The width of the melt pool decreases with shorter pulse durations and higher repetition rates while keeping the average power constant

Bai S.; Liu J.[33]	Additive manufacturing of bimetallic structures	2020	SN Applied Sciences	Reviewing AM technologies for bimetallic structures. Summarizing the pros and cons of different AM technologies. Discussing processing strategies and challenges in AM. Exploring characterization methods for bimetallic structures	Bimetallic structures with distinct properties were created through AM technologies. The microstructure of these structures can influence their mechanical properties. Fractography can reveal bond strength and internal defects in bimetallic joints. EDS mappings and EBSD results showed compositional differences and grain growth
Caballero A.; Suder W.; Chen X.; Pardal G.; Williams S.[34]	Effect of shielding conditions on bead profile and melting behaviour in laser powder bed fusion additive manufacturing	2020	Additive Manufacturing	Experiments were conducted using a 500W laser on a single layer of metal powder. The impact of different shielding gases (argon and helium) on melting was investigated. The melting process was recorded by high-speed cameras	directions in materials like Inconel 625 Argon shielding resulted in plasma plumes and instability during melting, making metal shape control difficult. Helium shielding produced smaller plasma, enabling stable melting and improved metal shape control. The width and depth of the melted metal with helium were determined by the laser's energy. Increasing the laser duration resulted in wider melted metal, up to ten times the size of the laser
Lee S.; Ahmadi Z.; Pegues J.W.; Mahjouri- Samani M.; Shamsaei N.[35]	Laser polishing for improving fatigue performance of additive manufactured Ti-6Al-4V parts	2021	Optics and Laser Technology	Parts were produced using a unique 3D printer known as laser beam powder bed fusion (LB-PBF). Parts were subjected to heat in a specialized oven with argon gas to alleviate stress. The surface of the parts was refined using a laser. The roughness of the surface was assessed pre- and post-polishing by employing a microscope. The interior structure of the parts was examined using a high-powered microscope called SEM	LP enhanced the surface roughness of Ti-6Al- 4V parts by 60-70%. The fatigue strength of polished specimens was superior to that of as- built specimens. Fatigue strengths were further improved after secondary stress relief. Residual stresses induced by LP were effectively relieved by secondary stress relief
Goffin N.; Jones L.C.R.; Tyrer J.R.; Woolley E.[36]	Just how (in)efficient is my laser system? Identifying opportunities for theoretical and auxiliary energy optimization	2021	Journal of Laser Applications	a framework is needed for categorizing process states and subsystems in a laser machine tool	The data analysis revealed that the laser accounts for just 18% of the overall power consumption, with the water-cooling subsystem being the most significant contributor at 37%. This paper presents a comprehensive analysis of energy efficiency in laser welding at a system level

## 4.3 Theme 3: Laser-Enhanced Material Processing

In the domain of laser-assisted material processing, recent investigations have brought to light significant advancements in AM methodologies. The successful implementation of direct Selective Laser Sintering (SLS) using a Yb fiber laser has been demonstrated in producing High-Entropy Carbide Ceramics (HECC). Notable findings include the creation of single-phase non-equiatomic HECC specimens with a uniform distribution, achieved by introducing a solid solution during the SLS process [36]. The exploration of femtosecond fiber lasers in Laser Additive Manufacturing (LAM) has showcased the fabrication of multi-material layered structures.

This innovative approach was applied to manufacturing solid oxide fuel cell components, eliminating the need for binders and post-treatment, marking a crucial step in the realization of a complete and functional fuel cell through a single-step process [37]. Further broadening the range of applicable materials, the investigation into LAM with mixed powders of boron carbide and aluminum alloy has demonstrated meticulous optimization of parameters. Consequently, the resulting parts exhibit a well-mixed composition of 20 wt% boron carbide and 80 wt% aluminum alloy, displaying mechanical properties closely aligned with aluminum. Moreover, the fabrication of thin-wall structures for neutron scattering measurement serves as an example of the versatility of this approach [38].

In the pursuit of resource-efficient practices, laser beam remelting of stainless-steel plates for cladding, as compared to conventional methods, has exhibited enhanced productivity, reduced heat input, and lower distortions. With the potential for reducing CO<sub>2</sub> emissions, this method uses scrap metal plates, presenting a sustainable alternative to cladding processes [39]. By exploring the synergy between laser and material processing, the laser polishing of selective laser melting alloy samples has showcased the capability of a fiber laser to polish rough surfaces in-situ. Moreover, this process effectively reduces surface roughness, providing valuable insights for optimizing the polishing strategy through simulation [40]. The feasibility of laser surface finishing for Ti-6Al-4V parts obtained through electron beam melting has been investigated, revealing a significant reduction in surface roughness under optimized conditions. This study sheds light on the potential for enhancing the post-processing of additive-manufactured components [41]. Figure 4 outlines the SLM parameters for four representative alloys.

	Ti6Al4V	AlSi10Mg	316L	IN718
Power (W)	276	350	320	175
Feed rate (m/s)	0.76	1.15	0.65	0.60
Layer thickness (µm)	50	50	50	50
Hatch spacing (µm)	120	170	140	140

Fig. 4. SLM parameters of four typical alloys [37]

Authors	Title	Year	Source title	Methodology	Findings
Zhang X.; Li N.; Chen X.; Stroup M.; Lu Y.; Cui	Direct selective laser sintering of high-entropy carbide ceramics	2023	Journal of Materials Research	Combine various carbide powders and ball-mill them equally to achieve a consistent blend. Utilized a specialized laser to unite and fuse the	The findings have significant implications on the mechanisms of laser interaction with
B.[38]				powder particles. Formed the powder mixture into a compact shape using an automated machine.	monocarbide powders in SLS.
Bai S.; Liu J.[39]	Femtosecond laser additive manufacturing of multi-material layered structures	2020	Applied Sciences (Switzerland)	A powerful laser was used to create layers of materials for fuel cells. The laser was controlled using mirrors and a computer to achieve precise patterns. The focus and power of the laser were adjusted to melt the materials accurately.	Parameters were evaluated to find the best density and porosity. This is the first report to build a fuel cell using the LAM approach.
Bai S.; Lee H.J.; Liu J.[40]	3D printing with mixed powders of boron carbide and al alloy	2020	Applied Sciences (Switzerland)	Mixed powders of boron carbide and aluminum alloy were used for 3D printing radial collimators. The laser power, scan speed, scan pattern, and hatching space were optimized for AM. A powder bed fusion system was modified for low-mass ceramic 3D printing.	The AM part has a combination of 20 wt% boron carbide and 80 wt% aluminum alloy that is well synthesized during melting. Its mechanical properties are similar to aluminum.
Bunaziv I.; Ren X.; Hagen A.B.; Hovig E.W.; Jevremovic I.; Gulbrandsen- Dahl S.[41]	Laser beam remelting of stainless-steel plate for cladding and comparison with conventional CMT process	2023	International Journal of Advanced Manufacturing Technology	Laser beam remelting is used to clad stainless steel plates on carbon steel substrates. Comparison made between laser remelting and cold metal transfer welding-based arc cladding. High-power fiber laser beam is used to melt the plates. Different defocusing distances were studied to optimize the laser remelting process. Microhardness testing is used to evaluate hardness in the cladded layers.	Laser remelting increased productivity and decreased heat input by 50% compared to CMT. Lower distortions were seen in the laser remelting process. Microhardness testing revealed higher hardness in the intermediate layer towards the fusion line.
Zhang D.; Yu J.; Li H.; Zhou X.; Song C.; Zhang C.; Shen S.; Liu L.; Dai C.[37]	Investigation of laser polishing of four selective laser melting alloy samples	2020	Applied Sciences (Switzerland)	Laser polishing of SLM alloy samples using a fiber laser. Surface roughness measurement with a 3D optical profiler. Data processing using Gwyddion, a software for scanning probe microscopy data analysis.	The surface roughness of SLM alloy samples was greatly decreased by laser polishing. Initial roughness values of 8.80-16.64 $\mu$ m were reduced to about 3 $\mu$ . Increased laser power resulted in a more evident enhancement in surface smoothness. The correlation

between laser power, scanning speed, and roughness was

determined.

Genna S.; Rubino G.[42]	Laser finishing of Ti-6Al- 4V additive manufactured parts by electron beam melting	2020	Applied Sciences (Switzerland)	Studied laser surface finishing on Ti-6Al-4V samples made by EBM using a 450 W fiber laser. Employed various laser energy densities and scanning speeds for surface treatment. Examined the samples with a 3D profilometer, digital microscopy, and scanning electron microscopy. Conducted ANOVA to assess the impact of process parameters on finishing quality.	Laser treatment decreased roughness by 80%. Laser finishing quality was affected by laser energy density and scanning speed. Laser tracks were visible due to the Gaussian shape of a laser beam. Ablation was higher at a 5 mm focal distance. 3D maps and surface profiles compared as- built and laser-polished samples.
De Lima Xavier Ribeiro G.; De Castro R.S.; Dos Santos R.G.; De Fátima Santos Bugarin A.; Terada M.; Batalha G.F.; Couto A.[43]	Characterization of Ti- 6Al-4V Alloy Produced by Laser-Powder Bed Fusion and Surface Modification Using Nanosecond Laser	2023	Materials Research	L-PBF is used for AM of Ti-6Al-4V specimens with different laser power. Specimens were analyzed with Scanning Electron Microscopy (SEM). Microhardness of the specimen measured.	The microstructure of L-PBF specimens exhibited varied martensite phases and pores caused by insufficient fusion. Increased laser power in L-PBF resulted in more noticeable pores due to the balling effect. Microhardness values slightly reduced as laser power increased.
Alsaddah M.; Khan A.; Groom K.; Mumtaz K.[44]	Diode area melting of Ti- 6Al-4V using 808 nm laser sources and variable multi-beam profiles	2022	Materials and Design	Used Ti-6AI-4V alloy powder with specific particle size and composition for Diode Area Melting (DAM) processing - Employed a custom- built chamber with argon gas to prevent oxidation - Utilized an argon air knife to reduce spatter during laser processing - Varied the speed of the laser head to create solid tracks and melt pool characteristics - Integrated an IR- Pyrometer to measure surface temperature during the process.	Multi-beam profiles have an impact on the microstructure and mechanical properties of melted components. The use of a low laser wavelength (808 nm) resulted in effective energy absorption and temperatures exceeding 2000°C in the powder bed. The cooling rate of the melt pool was reduced to $600^{\circ}$ C/s, which is lower compared to traditional laser powder bed fusion (10^5 - 10^7 C/s)
Jafari D.; van Alphen K.J.H.; Geurts B.J.; Wits W.W.; Gonzalez L.C.; Vaneker T.H.J.; Rahman N.U.; Römer	Porous materials additively manufactured at low energy: Single- layer manufacturing and characterization	2020	Materials and Design	Utilized LPBF with PW to create porous stainless-steel structures. Developed experimental approaches with a pulsed fiber laser system to study laser scan settings. Characterized sintered porous material by measuring pore size, layer thickness, porosity, and thermal conductivity. Used SEM to characterize powder feedstock.	A significant decrease in pore size was achieved in porous stainless- steel structures made with a unique 3D printing method. The structures had a porosity ranging from 51% to 61%. The average pore radius was measured to be between 22 and 29 micrometres.

G.W.; Gibson I.[45]						The thermal conductivity of a single powder particle was 31.5% of the thermal conductivity of the sintered layer.
Hadi R.M.; Taha Z.A.[46]	Selective laser melting of Inconel 601 alloy using nanosecond fibre laser	2022	Periodicals Engineering Natural Sciences	of and	The impact of selective laser melting factors, including using a nanosecond fiber laser, laser powers, scanning speed, and thickness of layer, on the relative density and microhardness Vickers of IN 601 samples was studied.	Using a microsecond laser in SLM leads to the achievement of full density (almost 99.5%), whereas using a nanosecond laser allows the achievement of less density (75-95%), which will be very useful for functions that require a porous structure and less weight, such as those in the aerospace applications, automotive industry and so on.

#### 5. Discussion and Conclusion

The main focus of this paper is to highlight the potential of DED-L techniques, such as laser remelting and laser remelting with powder, in enhancing the quality and performance of components manufactured through AM. These techniques can improve surface finish, minimize voids, and increase productivity, thus making them suitable for various applications in high-frequency, telecommunications, and optics manufacturing. Research conducted on LAM of metals, specifically Inconel 718 superalloy and Ti-6AI-4V parts, aims to investigate the impact of different parameters on the geometrical dimensions, stability, and mechanical properties of additively manufactured walls. By utilizing statistical modeling and optimization, these studies provide valuable insights into achieving desired characteristics and facilitating the identification of optimal technological parameters for successful metal AM.

Consequently, this study also explores various applications and advancements in laser-enhanced material processing, including LAM with mixed powders, laser beam remelting for cladding stainless steel plates, diode area melting as an alternative to laser powder bed fusion, reduction of pore size in porous stainless-steel structures, laser surface finishing for additive manufactured parts, and selective laser melting of Inconel 601 alloy. These studies effectively demonstrate the potential of laser-based processes in achieving efficient and high-performance AM, enhancing the quality of parts, and optimizing process parameters for specific applications.

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