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Recent Trends in Laser Arc Additive Manufacturing Process: A Review

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Abstract
Additional manufacturing technology has been used by using the laser bracket manufacturing method for the purpose of producing various geometric components. This method is characterized by many advantages and also there is a structure that can be described in low and these materials are characterized by highly controlled synthetic synthesis and are characterized by accurate engineering and featuring high deposition rates. It was noted that this method is of a complex nature where this method contains changes in structural and controlled parameters that mechanical, thermal and chemical behavior is affected by those variables. Studies on laser-based additive manufacturing show that improved mechanical properties—such as hardness, fracture resistance, yield strength, and ultimate tensile strength—are closely linked to microstructural advancements. As well because of exact control produces accurate structures, which are affected by microscopic substances. This exact control results in reduced structural contrast and improving granular size as well as improving morphological characteristics. For the purpose of improving the quality of the surface and significantly reducing the article, it has used an advanced technique for predicting the subsequent layer. In addition, interconnection between sedimentary layers may improve and this leads to treatment for conventional metals.

Keywords: Welding; Additive manufacturing; Laser, Arc; Hybrid.

1. Introduction

Laser Arc Additive Manufacturing (LAAM) is an innovative process that uses both a laser and an arc-based heat source in the manufacturing of the product. It is worth noting that common types include additive manufacturing using oscillating laser arc (O-LHAM) and metal deposition by precipitation (LMD). These methods involve the feedstock as layering. The method ensures excellent strength due to high rate of deposition and better surface finish in comparison with products that only use arc-based methods. The manufacturing depends on the consequence of hybrid methods that use laser to melt the material and stabilize the arc. The laser arc method is commonly mentioned as wire arc method (WAAM), which is a byproduct of arc welding. It has the benefit of cost-effective and great deposition. In this process the metal wires can be melted by the arc mechanism. This results a 3D part which satisfies the requirements of the design. A secondary process can be manipulated later such as cutting, machining and heat treating [1–5].

In contrast to laser additive manufacturing, which employs powder forming procedures that cause high laser reflection on metal surfaces, Wire Arc Additive Manufacturing (WAAM) avoids difficulties including oxidation, higher prices, and lower efficiency. In addition, inert gas may safeguard the deposition process, allowing for the creation of an almost unlimited number of pieces. This capability is quite useful for making parts quickly and cheaply in large, medium, or tiny amounts. The following machining procedures may make parts with complicated forms, even though the WAAM process can't make them very precisely. But to maintain the formation stable during the WAAM process, it's important to keep the deposition rate low and the arc current minimal. The high heat input and arc force would lead the deposited material to have more internal stress, which would make the molten pool unstable if there were no other factors. These bad effects work together to make processes unstable and deposition accuracy less than ideal [6–10]. An improvement that addresses these issues is the use of a H.F. galvanometer in oscillating LAHW. Improving laser-arc interaction, decreasing arc center resistivity, and increasing arc current density are all benefits of laser oscillation. The improvements increase the energy density and help keep the arc stable. Moreover, the produced bubble is more easily ensnared, the evacuation of the bubble is encouraged by the rapid rotation of the laser keyhole inside the molten pool, and the molten flow is improved so that the pores are filled more quickly [11–15].

2. Current Areas of Focus

The focus is on the thick sections of the laser arc welding, which are used to improve the additional manufacturing process. Welding in conjunction is one of the prominent techniques that are used to reduce pores. A comparison was made between the laser welding, with fewer defects than the arc welding, and the penetration is greater. To improve this technology, it is quality control and thus the development of hybrid welding processes. Digital simulation is used to find out thermophenomenons.

2.1. Early-Stage Hybrid Heat Input and Thermal–Microstructural Modeling

Wang et al. (2022) [16] introduced an optimized modeling Method for the examination of thermal dynamics HPAL additive manufacturing. The researchers used a 3-D model of the selected elements in the steady state for a hybrid additive manufacturing process using a PTA laser. There are two heat sources for generating surface heat, so this model is characterized by this and achieves the thermal properties of Ti-6Al-4V. The experimental results show that the expected shape of the melting basin and the heat-affected regions are closely related. The hybrid process is influenced by the heat source, and to analyze this influence, the characteristics of the heat source are affected by the actual arc or laser dimensions. It was observed that the melting was significantly affected by changes in laser energy and transmission speed, and these had a greater impact than changes in the distance between the arc and the laser, as well as the beam size. Furthermore, the cooling rate and its temperature gradient were analyzed. Thermal data were obtained for mineralogical analysis. Liu et al. (2022) [17] presented a concept for the purpose of increasing the evaporation of the Al-Zn-Mg-Cu alloy elements, and thus a sophisticated microstructure is obtained and a more homogeneous alloy, and this leads to an increase in power loads. Two methods have been used to achieve this: the first is the prophet's laser method, and the second is the method of using pregnant tungsten gas. Waam samples were found. The equation for the granules has improved the structure of the microscopic granules and thus the granules are smoother.. The elemental distribution of LAHAM was also observed to be uniform, with Cu, Mg, Al, and Zn exhibiting equal distributions. The WAAM sample doesn't have this. The LAHAM sample had nano-precipitates all over the grains, but the WAAM sample only had them around the edges of the grains. Changes in its microstructure made LAHAM stronger than WAAM. It could hold up to 11.4 percent of its ultimate tensile strength and 29.9 percent of its yield strength. The yield strength went up a lot, but it wasn't because of strengthening at the grain boundaries or in the solid solution; it was mostly because of precipitation strengthening. Gao and his coworkers (2023) [18] looked into the new method of oscillating laser-arc hybrid additive manufacturing (O-LHAM) for AZ31 Mg alloy in order to make the process more stable than traditional methods used with magnesium alloys.. In addition, the effect of beam oscillation on mechanical properties was studied, as well as the effect of both shape and microstructure, and the effect of micro-wall porosity of the components. It was observed that the sedimentation rate of Mg17/Al12 and Al8/Mn5 increased from (1.4-2.6 percent) to (92.5-2.3 percent). The oscillating laser made the melt pool flow in a way that could change the structure of the grains and create more nucleation sites. This method has two benefits: it makes the average size of the particles smaller and makes it easier for them to fall out of the solution. The tensile strength of the porous part reached 205 MPa, which is a little less than the base material's, but it can stretch 20.7% of the way, which is almost twice as much as the base material. The analysis revealed a ductile material due to the behavior of the tearing. The procedure is related to the structure and orientation of the grains. Another way proposed by Wang et al. (2023) [19] to investigate the morphology of the layering depending on PSO-SVR of the LAHAM, the study implemented support vector regression (SVR) and particle swarm optimization (PSO) to perform the procedure. These methods introduced explicit models to determine the size of the layers. The suggested model compared with the SVR, BPNN, and Light GBM models with an error ranged as 2.39%, 7.719%, 9.46%, and 5.356%, respectively. Liu et al. (2023) [20] heated Al-Cu-Zn-Mg alloys with PLAH, laser zone (LZ) showed fine and uniform grains while the arc zone (AZ) showed coarse vertical grains and the crystal structure has changed significantly due to the intense thermal transformations and varying solidification rates, where researchers observed a wide distribution of the two stable phases, magnesium and zinc, between the grains in the laser-affected zone, while they became concentrated in the arc region. All of these phenomena were clearly revealed through thermodynamic modeling analyses. Using two-stage solid solution and aging methods, a lot of η′ nano-precipitates in the shape of disks and a few GP-II zones in the shape of needles were made. There is a lot of information about how heat treatment changes materials, such as their anisotropy, strength, and flexibility. It has a higher ultimate tensile strength than standard 7075 aluminum alloy, which is 602.3 ± 7.6 MPa. So, in short, the material is very strong. Due to the effects of dislocation shearing and Orwan strengthening, the best results appeared in yield strength modeling, noting that dislocation shearing became possible due to the cohesive GP-II region.

2.2. Microstructural Evolution and Mechanical Property Enhancement in Hybrid Additive Deposition

The stability of the arc during deposition enhanced the surface finish in the hybrid laser additive manufacturing method. This was demonstrated through comprehensive evaluations of the microstructure, mechanical properties, and surface attributes of products fabricated using two distinct hybrid welding additive manufacturing techniques, WAAM-SH and WAAM-SA, on an aluminum magnesium silicon alloy, employing a novel approach in hybrid laser additive manufacturing introduced by Ma et al. in 2023 [21]. The microstructure of the LAHAM deposits was finer and more even than that of the WAAM_SH samples, even though they both experienced the same amount of heat. The size of the grains in LAHAM deposits was the same as in WAAM_SA, even though LAHAM normally demands more heat. When tested with machines, the LAHAM samples exhibited a better and more stable micro-hardness profile. This is better because less magnesium is lost during processing and the microstructure is denser and more polished. It was observed that the tensile strength reached 345 MPa for walls produced using WAAM-SA and LAHAM in all three directions. It was also noted that using WAAM-SH resulted in slightly lower UTS (Unforced Tolerances) for the walls. Comparing LHAM and WAAM deposits, the LAHAM deposit exhibited a 26% greater extension when measured from top to bottom. The construction method did not affect the building's mechanical integrity, as the building's variability remained unchanged. Zhang's team (2024) [22] developed two manufacturing methods: LAM-W and the classic WAAM, both of which are laser-based. This development aimed to determine whether steel could be printed to strength more reliably. Microscopic analysis of LAM-W samples revealed finer grains and a more polished finish compared to WAAM samples. This was reflected in performance, as LAM-W steel exhibited greater strength and stiffness while exhibiting slightly less ductility. In summary, both methods yielded steel with high hardness even at -40°C, with energy absorption exceeding 100 J. Both techniques can be used to create strong HSLA steel. LAM-W exhibited greater strength and precision than WAAM. Study [23] investigated the structure and properties of multilayer components of St 316 fabricated using LAHAM, employing both a tungsten gas laser arc and a tungsten inert gas arc as heat sources. The results revealed distinct microstructures, particularly at the center of the samples, where roughness was observed in the dendritic structure with a uniform growth direction. Variable growth was noted in the cross-linked dendritic structure, along with interlayer transitions. Despite the stacking of fillers, the dendritic structures did not fully develop, although they possessed good microstructure. A decrease in sample hardness was observed, with hardness increasing upwards. The arc size was reduced due to the laser technique, resulting in greater stability and efficiency in fabrication, as well as a decrease in heat consumption. A distribution of both chromium and nickel was observed along the grain boundaries at the bottom of the sample. The nickel was in the γ austenite phase in both the upper and middle regions, while the chromium was found within a δ ferrite. The microstructure here was observed to be of a higher quality than that achieved using inert tungsten. The grain boundaries were also noted to have small angular edges. Adding laser improved the micro-hardness and tensile properties of the samples. Hydrogen porosity appeared as a type of defect resulting from the thermal treatment of samples produced by HLAM. Liu et al. 2024 [24] demonstrated the possibility of producing aluminum, copper, and zinc alloys in this way and improving their mechanical properties. They also showed that they can withstand high temperatures by controlling their crystal structure. The heat treatment stopped the hard-brittle eutectics from spreading evenly along the grain boundaries. The heat-treated Al-Zn-Mg-Cu alloy exhibited uniformly dispersed high-density η' precipitates, but at 473 K, they became coarser and broke apart because Zn and Mg moved about quickly. The ultimate tensile strength (362 ± 20 MPa) and average yield strength (318 ± 16 MPa) at 473 K following heat treatment were better than the values of the as-deposited specimen by around 58% and 51%, respectively. At high temperatures, the η' precipitates also created lattice distortions and strain fields, which made it difficult for dislocations to migrate and made the material less likely to slide. Intergranular fracture was seen in the as-deposited material at 473 K, with fractures favoring propagation along the aggregated eutectics. Using oscillating laser-arc hybrid additive manufacturing, deposits of 2219 aluminum alloy enhanced with TiC nanoparticles were made. This improved the surface quality and reduced porosity (Jiang et al., 2024, [25]). We utilized an optical microscope to look at the surface quality and 3D X-ray computed tomography (XCT) to find out how porous it was. Compared to the wire-arc additively manufactured (WAAMed) deposits, the OLHAMed deposits had a 46.0% lower surface roughness and an 88.3% lower volume porosity. To monitor the behavior of the arc and the piscine's fuse, high-speed photography was used at the testing site, so that we could learn more about how the surface was polished and the porosity was decreased. The enhanced surface quality is due to the hybrid heat source, which makes the layer width less variable and the arc more stable. The OLHAMed deposit's porosity was much reduced because massive droplets no longer transfer and the molten pool's fluidity improved. This led pores to form in the WAAMed deposit.

2.3. Process Stability, Molten Pool Dynamics, and Geometric Control Enhancements

Wu et al. (2024) [26] in the segment of the study, they evaluate the effect of changing of the oscillation diameter, while maintaining the frequency at its optimal value, on the printed thin walls. They examined all aspects: their accuracy, internal structure, and strength. The findings were rather remarkable. As the diameter was raised from 0 to 1.2 mm, they observed a significant reduction in porosity from 0.1% to a negligible 0.01%. Simultaneously, the effective width of the formation reached a maximum of 88.9%. The processing variation was reduced from 15.1 mm to 1.25 mm, which improved the formation accuracy. The microstructure was clearly improved due to the increased oscillating diameter, and the average particle size decreased by 19.9%, from 55.9 µm to 44.8 kJ. As a result of this arrangement, the mechanical properties were altered. Even the microhardness variation along the wall appeared more uniform, and the maximum tensile strength increased from 219.1 MPa to 227.3 MPa. Elongation also increased from 12.9% to 14.6%. These results were recorded using a high-speed camera. The melting basin flow and droplet transport were affected by the oscillation of the laser beam, which in turn led to improvements in deposition. In a study conducted by Gong et al. in 2024 [27], they observed that the use of HP-LHAM in St components resulted in greater strength and consistency. By controlling the material structure and the degree of bonding of certain elements, such as tension and directionality, a generally better environment was created. It was concluded that the addition of other materials leads to improved mechanical properties of stainless steel. A difference in grain size was observed in the melting zones. The initial melting zone (CGMZ) produced larger grains, while the re-melting zone (FGRZ) produced smaller grains. Thus, the variation in grain size leads to a clear change in the microstructure, and this method is useful for facilitating additive manufacturing. It was observed that the grains in the melting zone (CGMZ) were coarse, while in the re-melting zone (FGRZ) they were fine. It was discovered that the δ-ferrite shape in the (CGMZ) could change under high pulsed currents, such as those produced by high-frequency laser beams or heat treatment. In contrast, the δ-ferrite shape remained ribbon-like in the (FGRZ). It was also observed that using a high-frequency laser with varying beam angles improved elongation and strength, resulting in different properties. The best horizontal yield strength (YS) is 363 MPa, which is higher than the yield strength of the sample that was put down without a laser beam, which is about 318 MPa. The YS anisotropy that comes with it has dropped from 7.5% to less than 2.0%. Research results have shown that strengthening the microparticles gives better properties than sedimentation or strengthening the solution, as demonstrated when modeling the yield strength. The yield strength increase was due to contributions of 166.6, 27.7, and 3.3 MPa, in that order. The greatest influence leading to variation in tensile properties is the extent of FGRZ and the Taylor factor. The range of FGRZ has a bigger effect than the Taylor factor. The research is further expanded [28] to develop entities characterized by exceptional efficiency and mechanical superiority through an enhanced deposition technique in oscillating laser-arc hybrid additive manufacturing. The microstructure and mechanical properties differ according to the deposition methods employed and the heat accumulation. This study examines the extent to which the shaping, tensile properties, and microstructure of (100x100x70) mm O-LHMed are affected by deposition methods where a speed of 18 m/s can be used, which represents the maximum speed. A continuous reciprocating deposition method that doesn't use arc extinguishing in the same layer has been shown to be a good way to keep the actual shape from being different from the planned shape. The deposition efficiency reached 848 cm^3/h, which is 2.25 times higher than the previously achieved deposition efficiency for CMT-AHed fractions. Using these deposition methods, no change in the microstructure was observed in the wide sections. It was noted that the solution's heat treatment was better when using high, continuous currents, resulting in a change from a ferrite-austenite crystal-setting mode to a fully austenite mode. While the tensile properties are not significantly affected by the deposition method, the continuous deposition method at a 90° angle provides a better balance between microstructure, morphology, and performance because it allows for more random heating. The elongation values were 34.2%–47.5% and 518–544 MPa, respectively, which conform to ASTM A479. The results greatly increase the possible uses of O-LHAM, which makes it easier and faster to make metal parts. This speeds up the process of industrialization. Quality, microstructure, and mechanical characteristics of Al-Mg-Sc alloy produced using laser-arc hybrid additive manufacturing were investigated by Ma et al. (2024) [29] Regarding the effect of the beam high frequencies . Active zone expanded with each mm increase or decrease in oscillation amplitude. At first, this improved the stirring impact of the laser beam on the metal pool. As the laser approached the pool's edge, however, its impact gradually diminished. The forming quality, porosity, and microstructures were all improved with a 4 mm amplitude. It was the inverse when the amplitude was 6 mm. After experimenting with several amplitudes, we settled on 4 mm for our mechanical needs. The vertical tensile strength was 354 MPa UTS and the yield stress was 24% EL. The 0 mm condition is 13.5 and 50 percent more than these figures, respectively. As the laser power increases, the titanium, aluminum, and vanadium alloy wire must be consumed, and the power reaches a maximum of 1500 watts, then it decreases. This was demonstrated by Chin et al. (2024) [30] through the mechanical characteristic and the structure of titanium alloys manufactured by the hybrid laser addition manufacturing method. The LAHAM samples have less acicular martensite α′ as the laser power goes up, but the α phase goes up and makes the samples coarser. The tensile strength rises in a straight line as the laser power rises, reaching a maximum of 1080 MPa for horizontally orientation and 1100 MPa vertically orientation . But as the laser gets stronger, it gets shorter. As the laser's power increases, the micro-hardness decreases. When you turn up the power of the laser, the deposition layers stick together better which makes the specimens much stronger in tension.

2.4. Advanced Hybrid Strategies for High-Performance Alloys and Next-Generation Deposition Systems

Liu and his coworkers conducted a study in 2025 [31] that showed that heat treatment makes aluminum-zinc-magnesium-copper alloys made with the WAAM and LAHAM methods stronger. The two methods made the microstructure look very different: The grains in WAAM samples were about 70.4 µm wide and had a rough columnar shape. The grains in LAHAM samples were 68% finer and had a more even distribution of octahedral chemicals. LAHAM-treated samples had particles that were between 10 and 30 nanometers in size. The Al- Cu-Zn-Mg alloy that was treated with LAHAM had a final tensile strength of 590 ± 9 MPa, which was about 87% higher than the specimen that was deposited. It also stretched 8.6 ± 0.2% more, which is almost 169% more than that. Meng et al. (2025) [32] performed a study on the oscillating laser-arc hybrid additive manufacturing of aluminum alloy thin-walls, emphasizing synchronous wire-powder feeding techniques. To modify the mechanical properties of defective, thin-walled aluminum alloys, a wire-powder feeding method was employed, incorporating a hybrid laser-arc additive manufacturing process. Using an additional manufacturing method, namely LAHAM laser arc and MG-Gd-Y-Zr alloys, the texture strength decreased by 27% and the grain size decreased by 26% compared to what was obtained from the WAAM method. This was done by Ge et al. [33] (2025) by modifying the use of magnesium powder, where the droplets were converted into a spray, where the effective wall thickness width increased to 95% and the transport time decreased by 18%, where a clear dendritic deposition was observed.. Similarly, for LAHAM, both the nano β [Mg24 (Gd,Y)5 + Mg5 (Gd,Y)] and β1 [Mg3 (Gd,Y)]phases exhibited a uniform and consistent distribution within the grain boundaries. In WAAM, it was observed that the β nanophase had a distribution around the enriched second phase. The mechanical properties of the alloys were affected by the size of the nanoparticles. For MAAW found that the yield strength and tensile strength were 150 MPa and 228 MPa respectively. In comparison to WAAM, the tensile strength and yield strength of LAHAM exhibited increases of approximately 12% and 15%, respectively, achieving values of 254 MPa and 175 MPa. The strengthening can be enhanced by more than 40%. In conclusion, this study addresses a new method for improving the Mg-Gd-Y-Zr alloy.

In 2025, Ding et al. [34] revealed a progressive enhancement to the Hastelloy C276 by serving LAHAM. The alloy is tempered to more than 1100 °C in a thermo-chemical medium and then rapidly quenched with water. This procedure resulted in a phase transformation within the structure. The method leads to improve the intergranular bonds and minimize the grain size which adapts more resistant structure. The heat treatment organizes the grain propagation during the phase transformation, thus exhibits more uniform crystals allowing for better hardness, toughness and flexibility.

Functionally graded materials (GFM) can be improved by implementing arc laser processes as denoted by Xu et al. (2025) [35] for Ti6Al4V titanium alloy with N2 gas. The alloy has been manufactured through a developed LAHAM method with controlling the nitrogen flow rate. The structure of the alloy and some features has been analyzed based on the data collected from several instruments: optical microscope, scanning electron microscope (SEM), X-ray diffraction (XRD), Vickers hardness testing, friction wear analysis, and an electronic universal testing machine. The results explained that thermal energy of the laser arc strengthening the phases within the alloy. This enhancement is due to increase of the amount of TiN as a result of increase in the nitrogen flow rate. The new method made FGM with layers that withstand wear and still has amount of ductility. Liu et al. (2025) [36] studied the effect of many LAHAM techniques in the development of mechanical properties and structure morphology of Al-Cu alloy. And increase in laser power, there was a significant reduction in hydrogen-induced pores (HIP), while the emergence of keyhole-induced pores (KIP) became evident. In the course of later depositions, the significant reheating effects induced by the laserwhich lead to shift at boundaries of grains from reticular eutectics toled to granular eutectics. Also, the process of recrystallization and the formation of boundaries of coincidence site lattice (CSL) were limited because the residual stress was lower due to slower cooling rates. This helped to reduce stress concentration near pores during deformation. As a result, optimal conductivity was achieved at a laser power of 1 KW. When the laser power was increased from 1.5 KW to 2.5 KW, the average grain size decreased from 41.67 µm to 48.55 µm, and the elongation was 19.6% and 13.8% in the horizontal and vertical orientations, respectively. The maximum tensile strengths were 269.5 MPa and 260.1 MPa, and the elongations were 19.6% and 13.8% in the horizontal and vertical directions, respectively. As the laser power was increased from 1.5 to 2.5 kW, the average grain size of the deposited microstructure reduced from 48.55 to 41.67 µm, which is equivalent to a reduction of 14%. This increase in laser power also fixed the problems with humps, height difference, and too much flow. The porosity improved from 2.42% to 1.79%, and the forming accuracy improved to 38%. This was shown in Guo and his team’s study (2025) [37]. The Max tensile strength and extension of the thin wall both got better. Bubbles could quickly escape from the molten pool because the laser oscillation was better. This caused stirring effects that turned columnar grains into smooth, equiaxed grains, which made the deposits stronger. Wang et al. (2025) [38] worked in his study to find the optimal mix of elements for a multi-stage LAHAM interferometry and the ideal deposited layer. An orthogonal experiment was conducted for this purpose. To fit the perimeter of the multi-stage LAHAM, a parabolic curve and a predictive model were employed. The prediction model's accuracy was assessed through the application of three distinct metrics. In response to the limitations identified in the second-generation non-dominated genetic algorithm (NSGA-II), a refined version of the NSGA-II algorithm has been introduced. The process elements were optimized by developing a specific model using the IOPSIS method. This model automates the optimization of process element configurations by predicting specific sedimentation patterns. A relative error of 2.067% exists between the actual intrusion layer height and the previously determined height calculated using the optimized process element configuration. The optimization model was also confirmed to be useful because the layer's surface became smoother.

3. Conclusions

The study analyzes previous research works involving new trends in the laser arc additive manufacturing processes that develop the mechanical, thermal, and chemical characteristics of some alloys such as: stainless steel, Hastelloy C276, 2219 aluminum alloy, Ti-6Al-4V, Al- Cu -Zn-Mg, and Al-Sc-Mg. The study analyzes the works and concluded that the new techniques can:

- suggest a well heat treatment method to improve the additive manufacturing (AM) for metals and alloys.
- Improve the efficiency of the materials processed by additive manufacturing (AM).
- Develop the processes in AM methods.
- Optimize the mechanical characteristics, such as yield strength, ultimate stress, fracture resistance, wear resistance, hardness, and formation accuracy.
- Enhance microstructural features, such as grain dimensions, eutectic distribution, and reduce anisotropy.
- Present a method for predicting the morphology of deposition layers.
- Improve surface quality and minimize porosity.
- Strengthen the adhesion between deposition layers.
- Enhance the transfer of droplets.
- Address the challenges associated with the instability of conventional metallurgy processes.

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Abbreviations

AM	Additive Manufacturing
AZ	Arc Zone
BPNN	Back Propagation Neural Network
CGMZ	Coarse-Grained Melting Zone
CMT	Cold Metal Transfer
CSL	Coincidence Site Lattice
EL	Elongation
FGM	Functionally Graded Materials
FGRZ	Fine-Grained Remelting Zone
GP-II	Guinier-Preston Zone II
HAZ	Heat-Affected Zone
H.F.	High Frequency
HLAM	Hybrid Laser Additive Manufacturing
HIP	Hydrogen-Induced Porosity
KIP	Keyhole-Induced Porosity
LAAM	Laser Arc Additive Manufacturing
LAHAM	Laser-Arc Hybrid Additive Manufacturing
LMD	Laser Metal Deposition
LZ	Laser Zone
NSGA-II	Non-dominated Sorting Genetic Algorithm II
O-LHAM	Oscillating Laser-Arc Hybrid Additive Manufacturing
PSO	Particle Swarm Optimization
PTA	Plasma Transferred Arc
SVR	Support Vector Regression
SEM	Scanning Electron Microscope
TIG	Tungsten Inert Gas
UTS	Ultimate Tensile Strength
XRD	X-Ray Diffraction
XCT	X-ray Computed Tomography
YS	Yield Strength
WAAM	Wire Arc Additive Manufacturing

Conflict of interest

"The authors declare that there are no conflicts of interest regarding the publication of this manuscript."

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

Author Contribution Statement

A.K. Muhammad and **T.W. Mohammed**: proposed the research problem. **K.K. Resen** and **A.K. Muhammad**: verified the investigated specific aspects. **T.W. Mohammed** and **K.K. Resen**: discussed the outcomes and contributed to the final manuscript. All authors participated in the discussion of the results and contributed to writing the manuscript.

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