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Research Progress and Development Trends in Energy-Field-Assisted Laser Additive Manufacturing of Titanium Alloys

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Abstract

Titanium alloys are known for their high specific strength, excellent corrosion resistance, and good high-temperature mechanical properties. They have extensive applications in fields such as aerospace, high-end equipment, and biomedicine. However, during the laser additive manufacturing of titanium alloys, rapid melting and solidification behavior, combined with complex thermal cycling, tend to induce coarse columnar grain structures, residual stress accumulation, and defects such as porosity and cracks. It constrains further improvement in the comprehensive performance of the components. In recent years, energy-field-assisted technologies have emerged as a crucial approach to enhancing the quality and performance of laser additive manufacturing of titanium alloys. By introducing external fields, such as ultrasonic, thermal, plastic deformation, and electromagnetic fields, during the forming process, these technologies enable effective control over molten pool flow, heat and mass transfer, and the evolution of solidified microstructures. This paper provides a comprehensive review of research progress on laser additive manufacturing of titanium alloys assisted by single and multi-energy fields. It focuses on summarizing the process characteristics, microstructure control mechanisms, and performance enhancement principles associated with various energy fields, while elucidating the underlying mechanisms by which these fields influence molten pool evolution, grain refinement, defect suppression, and residual stress regulation. Finally, the future development directions of energy-field-assisted laser additive manufacturing of titanium alloys are outlined. This paper provides a theoretical reference for the development and engineering application of additive manufacturing technology for titanium alloys.

Keywords

laser additive manufacturing, titanium alloys, energy field assistance, microstructure and property control

1. Introduction

Titanium alloys offer advantages such as high strength, excellent corrosion resistance, a low elastic modulus, and good biocompatibility [1], and are widely used in fields including aerospace, medical devices, and nuclear energy equipment. However, traditional subtractive manufacturing processes, such as forging, casting, and machining, involve complex workflows and suffer from issues like low material utilization and long production cycles. Consequently, they struggle to simultaneously meet the requirements for high strength, lightweight design, and structural integration when manufacturing complex components. Laser additive manufacturing technology enables the direct near-net-shape fabrication of complex structural components using powders or wire. It overcomes the limitations of traditional processes and demonstrates broad development prospects and immense application potential.

The mainstream additive manufacturing technologies currently used for the fabrication of titanium alloys primarily include laser additive manufacturing (LAM) and wire arc additive manufacturing (WAAM). Laser additive manufacturing technologies, exemplified by Laser Powder Bed Fusion (LPBF) and Laser Directed Energy Deposition (LDED), offer significant advantages such as high energy density, excellent focusing capabilities, rapid response, and high processing precision. Capable of producing ultrafine microstructures with outstanding mechanical properties and dimensional accuracy, these technologies represent a major focus of current research [2, 3]. However, this process still suffers from microstructural non-uniformity. Rapid solidification and cyclic thermal effects tend to induce coarse columnar grains and structural heterogeneity, thereby limiting the stability and reliability of the components [4].

To address this challenge, existing research has increasingly turned its attention to external-field-assisted laser additive manufacturing technology. External field-assisted technologies can effectively regulate the solidification behavior, grain growth mode, and microstructural evolution of the molten pool by introducing ultrasonic, electric, or magnetic fields. This paper focuses on research into external-field-assisted laser additive manufacturing of titanium alloys. It systematically reviews the mechanisms and application effects of external-field-assisted technologies and analyzes how different external fields regulate the microstructure and properties of titanium alloys, aiming to provide theoretical support and technical reference for the efficient fabrication of high-performance titanium alloy components.

2. Current Research Status of Ultrasonic-Assisted Laser Additive Manufacturing of Titanium Alloys

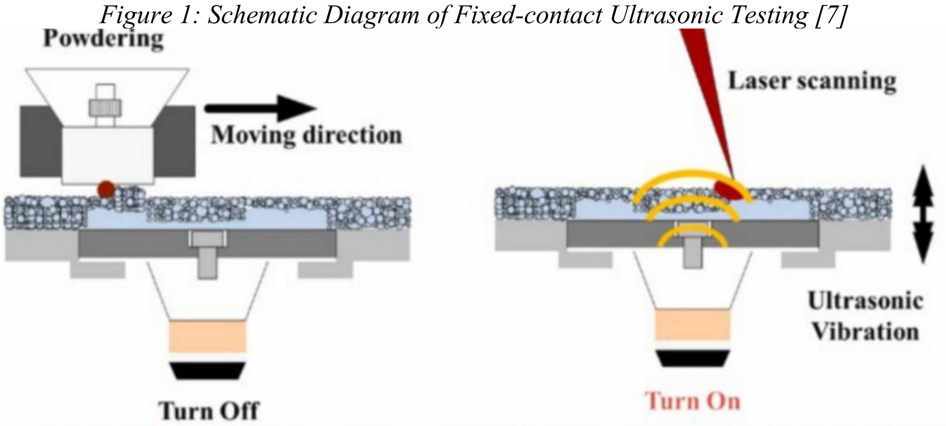
Ultrasonic-assisted energy fields involve coupling high-frequency ultrasonic vibrations (typically 20–60 kHz or higher) into the molten pool and deposited layer via a specialized system [5]. This modulates the solidification process through mechanisms such as acoustic streaming [6], acoustic cavitation [7], and thermodynamic coupling [8], thereby mitigating defects associated with conventional processes. Depending on the mode of ultrasonic field application, they can be classified into fixed-contact, moving-contact, and non-contact types [9].

2.1 Fixed Contact Type

In the fixed-contact method, the ultrasonic transducer and horn are rigidly attached to the bottom of the substrate. Ultrasonic energy is transmitted to the molten pool and solidification zone via mechanical contact, utilizing acoustic streaming and cavitation effects to agitate the melt, refine grains, and inhibit the growth of columnar crystals. This method features a simple structure and high stability, making it suitable for conventional multi-layer deposition of titanium alloys [10]. However, significant ultrasonic attenuation occurs during forming, tissue regulation is non-uniform, and the substrate is prone to additional stress, making it difficult to precisely match the energy input to the molten pool [11, 12].

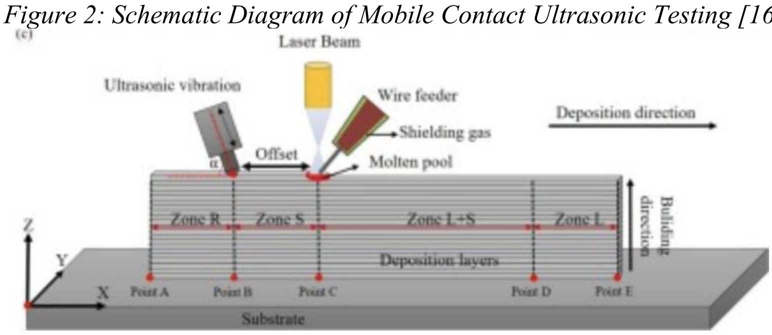
Wang Wei and colleagues [13] investigated the repair of trapezoidal groove bottoms using laser deposition assisted by an ultrasonic field. They found that surface points at the bottom of the trapezoidal groove exhibited periodic motion characteristics under the ultrasonic field, and the repaired specimens showed a 3.2% increase in tensile strength and a 7.1% increase in yield strength. Some other researchers [14] investigated the use of dual ultrasonic vibration (UV) to induce a transition from coarse columnar primary β grains to equiaxed primary β grains (CET). It reduces the average grain size from 1678.4 μm to 467.9 μm. The ultimate tensile strength (UTS), yield strength (YS), and elongation of the Ti-6Al-4V alloy increased by 26.7%, 24.7%, and 104%, respectively. Also, Biswas et al. [15] investigated ultrasonic vibration-assisted laser surface treatment. The laser treatment triggered the transformation of globular α into acicular α and martensitic α'. It results in a significant reduction in the friction coefficient of the textured surface.

Figure 1: Schematic Diagram of Fixed-contact Ultrasonic Testing [7]



2.2 Mobile Contact Type

Figure 2: Schematic Diagram of Mobile Contact Ultrasonic Testing [16]



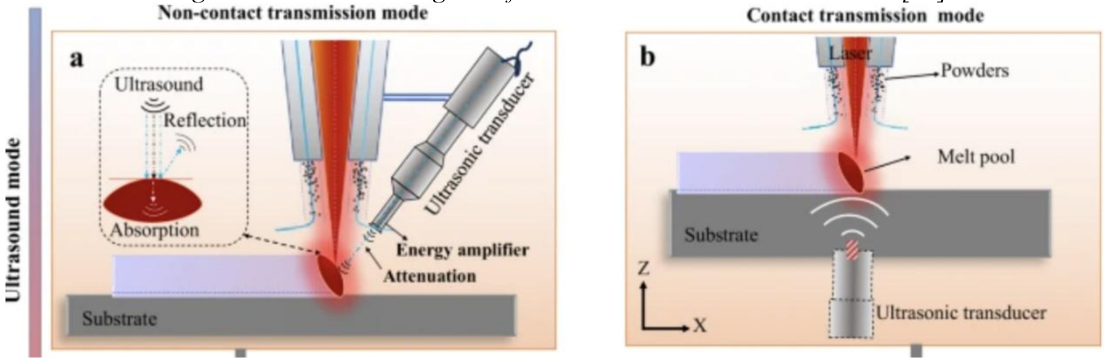
The mobile contact method involves mounting the ultrasonic device coaxially or off-axially with the laser printhead, applying ultrasonic vibration to the molten pool and solidification front at close range [16]. This method has low energy consumption and direct interaction between cavitation and acoustic flow. The grain refinement effect is significant, capable of weakening texture, enhancing interlaminar bonding, and optimizing the strength and ductility of the titanium alloy [16, 17]. However, the equipment features a complex structure and poor dynamic stability. It is prone to disturbing the molten pool and scratching the workpiece, so it reduces forming accuracy and makes it difficult to process components with complex curved surfaces [9, 17].

Some researchers [18] investigated the application of synchronous ultrasonic energy. The microhardness of 5%TiC/Ti6Al4V and 20%TiC/Ti6Al4V increased from 406.5 HV0.2 and 498.4 HV0.2 to 414.2 HV0.2 and 539.1 HV0.2, respectively. Yuan and others [7] investigated the effects of acoustic cavitation and acoustic streaming during metal solidification. They concluded that the introduction of high-intensity ultrasound can effectively disrupt the prevailing epitaxial growth trend. Some other researchers [19] applied ultrasonic field intervention to eliminate the banded microstructure in additively manufactured titanium alloys and induce compressive residual stress, while reducing high-temperature yield strength and ultimate tensile strength. Li Changfu and colleagues [20] investigated the application of an ultrasonic field normal to the substrate surface. They found that it effectively inhibited the growth of β-phase columnar grains and tensile strength increased by 4.2% and yield strength by 3.1% as the amplitude increased.

2.3 Non-contact Type

The non-contact method applies an ultrasonic field to the molten pool via air coupling or medium radiation. It involves no mechanical contact with the workpiece and relies on controllable acoustic streaming to regulate melt flow, thereby avoiding internal defects caused by the intense impact of cavitation [22]. This method causes no surface damage or additional stress, is not constrained by forming height or structural geometry, offers high process flexibility, and is suitable for microstructural control of thin-walled, precision, and large-scale titanium alloy components [9, 22]. However, the utilization efficiency of ultrasonic energy is low and attenuation is rapid, making it difficult to generate strong cavitation effects. Consequently, the grain refinement effect is limited, and the uniformity of the sound field is susceptible to interference from gas flow and temperature fields [22, 23].

Figure 3: Schematic Diagram of Non-contact Ultrasonic Assistance [21]



Han et al. [21] investigated a non-contact ultrasonic method that utilizes the combined effects of acoustic streaming and Marangoni forces to generate high-frequency oscillatory melt flow within the weld pool. This induces fatigue fracture of dendrites, thereby promoting grain refinement. At the same time, it was found that low-intensity ultrasound enables stable melt pool modulation throughout the layer-by-layer processing. It achieves uniform grain refinement in large-scale samples. Other researchers [6] investigated the effects of high-intensity ultrasound on the Ti-6Al-4V melt pool and microstructure during PBF solidification. They found that the acoustic pressure generated during processing, acting through coupled fields, led to a reduction in the grain aspect ratio under ultrasonic excitation, although the effect on the equivalent grain diameter remained inconclusive.

Ultrasonic field-assisted laser additive manufacturing of titanium alloys can improve solidified microstructures, suppress defects, and simultaneously enhance both strength and ductility. By utilizing cavitation and acoustic streaming to fragment dendrites and promote grain equiaxing, this technique addresses challenges such as large columnar grains, crystallographic texture, porosity, and residual stresses [7, 24, 25]. Different methods of applying the ultrasonic field offer distinct advantages: The fixed contact type relies on the substrate to conduct vibration, which can stably achieve grain refinement and reduce residual stress. It is the first choice for universal use, but the vibration energy is significantly attenuated in large-height multi-layer deposition [9, 10]. The mobile contact type has the lowest energy loss and the most prominent grain refinement effect, and is particularly suitable for high-demand scenarios such as aerospace load-bearing components [16, 17]. The non-contact type, with its advantages of no contact and no damage, possesses unparalleled flexibility in the shaping of precision thin-walled parts and large components [9, 22]. Overall, this technology demonstrates significant regulatory effects, yet it still faces challenges such as low coupling efficiency and poor high-temperature stability.

3. Current Status of Plastic Deformation Field-Assisted Laser Additive Manufacturing of Titanium Alloys

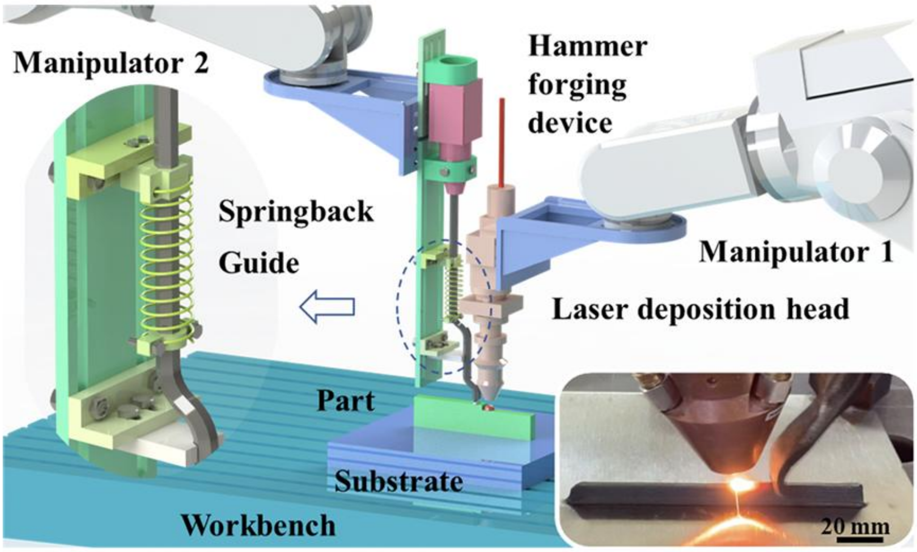
Plastic deformation field-assisted laser additive manufacturing employs a device to apply mechanical loads to the molten pool and deposited layer. By utilizing mechanisms such as extrusion, strain energy storage, dislocation proliferation, and dynamic recrystallization to regulate the entire forming process, it refines grains, repairs defects, and relieves stress. It thereby mitigates issues associated with coarse columnar grains, porosity, stress concentration, and property anisotropy [26, 27]. Based on the load, they can be categorized into high-magnitude pulsed loads, which is exemplified by synchronous hammer forging assistance, and low-magnitude continuous loads, exemplified by roller pressing and rolling assistance.

3.1 Synchronous Hammer Forging Assistance

Synchronous hammer-forging assisted manufacturing utilizes integrated hammer-forging and laser equipment to subject the deposited layer to high-temperature impact immediately after deposition [28].

Instantaneous plastic deformation breaks down coarse columnar grains, compacts interlaminar voids, and eliminates lack-of-fusion defects, thereby increasing density and mitigating anisotropy [29]. This process is highly versatile, allowing for layer-by-layer control to optimize the strength and toughness of the component [30]. However, high-frequency impact can lead to dimensional deviations in the surface layer and damage thin-walled precision parts, which makes it difficult to control forming accuracy [28].

Figure 4: Schematic Diagram of Synchronous Hammer-forging-assisted Additive Manufacturing [31]

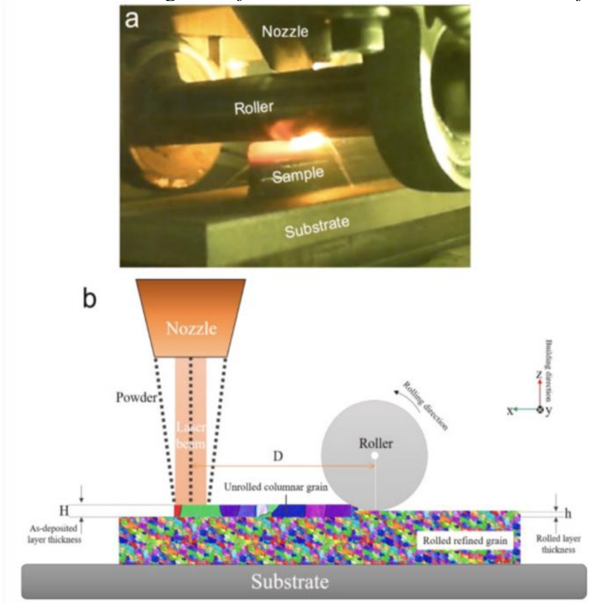


Xu Weiwei and others [32] explored the microstructure morphology of titanium alloys after three heat treatments and found that the content of the equiaxed α phase in the heat affected zone on the forging side increased significantly under the influence of heat input. A large number of fine layered α phases were formed in the heat affected zone on the additive side. Some [33] proposed a hybrid manufacturing route that yields spherical α-grains with an average diameter of approximately 0.8–2.3 μm. Some [34] studied the effect of micro forging on LDED-TC4 and found that micro forging can obtain 70-140 μm equiaxed crystals. Also, the lateral plasticity of the sample is significantly improved, and the anisotropy is less than 10%. Jan Roman Honnige and colleagues [35] used a new type of machine hammering tool as a cold working technology to process interconnected nozzles on the Ti-6Al-4V WAAM wall. They obtained refined grains that were in line with expectations. Some other researchers [36] used point forging combined with laser forming to prepare TC11 titanium alloy thick-walled parts. The forging was refined to obtain an average 48.7 μm equiaxed grain, and a 1.5 mm plastic deformation zone with a deformation rate of 20% was generated on the surface of the component.

3.2 Rolling and Rolling Assistance

In roller-assisted processing, a roller mechanism moves coaxially or off-axially with the laser print head [37]. This process compresses the high-temperature deposited layer, compacting pores, healing micro-cracks, and refining grains through plastic slip, thereby improving the interlaminar microstructure [38]. It offers uniform loading and high control precision, relieves residual tensile stress, and is suitable for large, flat titanium alloy components [39]. However, it struggles to process complex curved surfaces, irregular geometries, and confined forming zones, which demonstrates poor adaptability for complex-shaped components [37].

Figure 5: Schematic Diagram of Roller-assisted Additive Manufacturing [39]



Some researchers [40] investigated the fabrication of titanium alloy components using a combination of laser deposition and hot rolling. They found that the Vickers hardness of the bonding zone was approximately 375 HV, slightly higher than that of the hot-rolled zone (340 HV) and the deposited zone (355 HV). Yan Taiqi and other researchers [41] investigated the effects of rolling combined with laser deposition on the fabrication of TC4. The results showed significant microstructural changes in the heat-affected zone on the rolled side, characterized by the formation of substantial transformed β phase, a gradual transition from columnar grains to equiaxed grains, and the presence of clustered martensitic α'. On the laser-deposited side, the β grains retained a columnar morphology and martensitic α formed, but no equiaxed grains were observed. F. Martina and colleagues [42] studied the additive manufacturing of TC4 components by high-pressure interlayer rolling. They found that the warpage deformation of the sample was reduced by more than 50% after rolling modification, the peak tensile stress at the junction of the deposition area and the substrate reached 500 MPa, and the overall stress level was reduced by 60%.

Plastic deformation-assisted laser additive manufacturing of titanium alloys enables the control of solidified microstructures, the repair of defects, and the optimization of mechanical properties [27, 43]. It addresses issues inherent in conventional processes, such as coarse columnar grains, anisotropy, porosity, and residual stress concentration, by utilizing mechanical impact and extrusion to promote dislocation proliferation, grain refinement, and dynamic recrystallization, thereby homogenizing the microstructure [43]. While hammer forging is suitable for most conventional structural components, it faces challenges regarding precision control [28, 30]. Conversely, roller pressing offers effective stress relief and suits large flat parts but is ill-suited for complex curved surfaces [37, 39]. Although this technology offers distinct advantages in grain refinement, defect compaction, and stress regulation, it suffers from limitations such as poor structural adaptability and difficulties in controlling precision components [44].

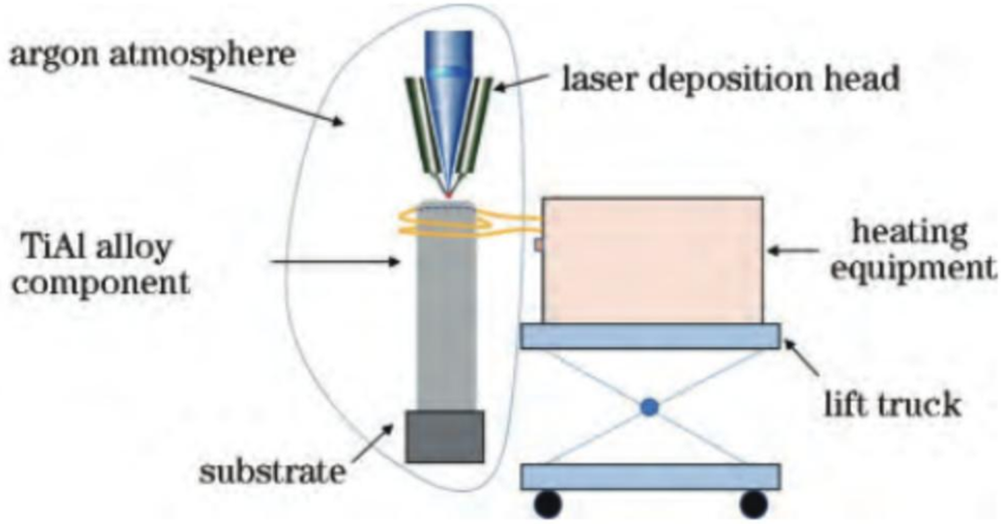
4. Current Status of Temperature Field-Assisted Laser Additive Manufacturing of Titanium Alloys

Temperature-field-assisted laser additive manufacturing introduces a temperature gradient through preheating or precooling. By leveraging the synergistic effects of heat flow within the temperature-gradient melt pool and solidification kinetics [45], it regulates the solidification process to refine grains, suppress defects, and reduce residual stress, thereby overcoming various limitations of conventional processes. Based on the method of temperature field regulation, these techniques can be categorized into preheating and precooling types [46].

4.1 Preheating

Substrate preheating can effectively mitigate the accumulation of thermal stress by raising the initial substrate temperature, thereby moderating thermal gradients during deposition and reducing the cooling rate of the molten pool [47]. Simultaneously, it improves the quality of interlayer metallurgical bonding, regulates grain growth behavior, and reduces microstructural anisotropy, ultimately leading to a significant enhancement in the overall performance of the fabricated components [48].

Figure 7: Schematic Diagram of Substrate Preheating Assistance [49]

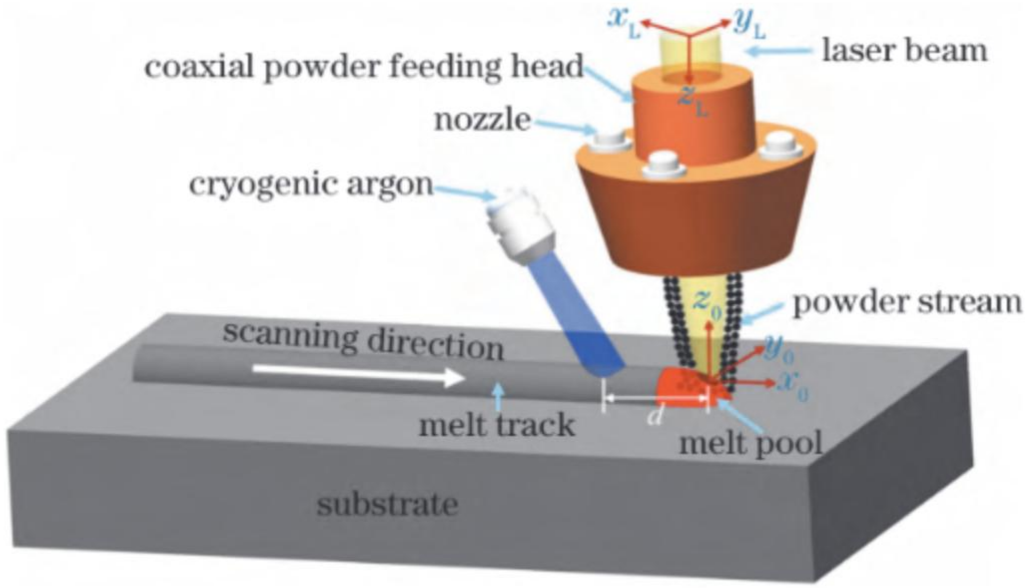


Zhang Feng and others [49] investigated preheated laser melting deposition and obtained a TiAl alloy with a relative density of 99.996%, a microhardness of 350 HV0.5, a room-temperature tensile strength of 497 MPa, and an elongation of 0.49%. Other researchers [50] studied a laser thermal coupling-assisted method and found that after treatment, the residual tensile stress in the sample was transformed into residual compressive stress, and the coarse α' martensite grains were refined and modified. After modification, the ultimate tensile strength and elongation of the alloy reached 1543 MPa and 15.53% respectively. Researchers [51] also relied on a laser deposition repair system equipped with a 6 kW fiber laser to conduct experiments under electromagnetic induction preheating conditions of the substrate at 200 °C and 400 °C. The test results show that increasing the induction preheating temperature will promote the coarsening of the lamellar α structure and the full growth of the primary α phase, and the uniformity of the sample microstructure will be improved. Feng Qigao and colleagues [46] investigated the composite heat source fused deposition process. They found a surface roughness (Ra) of 1.776 μm, an average wall thickness of 0.648 mm, and an average wall thickness deviation of 0.004 mm. Other researchers [53] investigated selected regions of preheated powder bed layers subjected to complete melting. They observed an overall increase in the c/a ratio of the HCP α phase, leading to the relaxation of lattice strain in the local crystal structure.

4.2 Precooling

Substrate pre-cooling enhances heat dissipation during the forming process by lowering the initial substrate temperature, thereby regulating the solidification rate of the molten pool and thermal evolution behavior [54]. This suppresses abnormal grain growth and mitigates the accumulation of thermal stress while optimizing the quality of interlayer metallurgical bonding and microstructural uniformity, ultimately enhancing the dimensional stability and comprehensive mechanical properties of the additive-manufactured components [50].

Figure 8: Schematic Diagram of Substrate Pre-cooling Assistance [55]



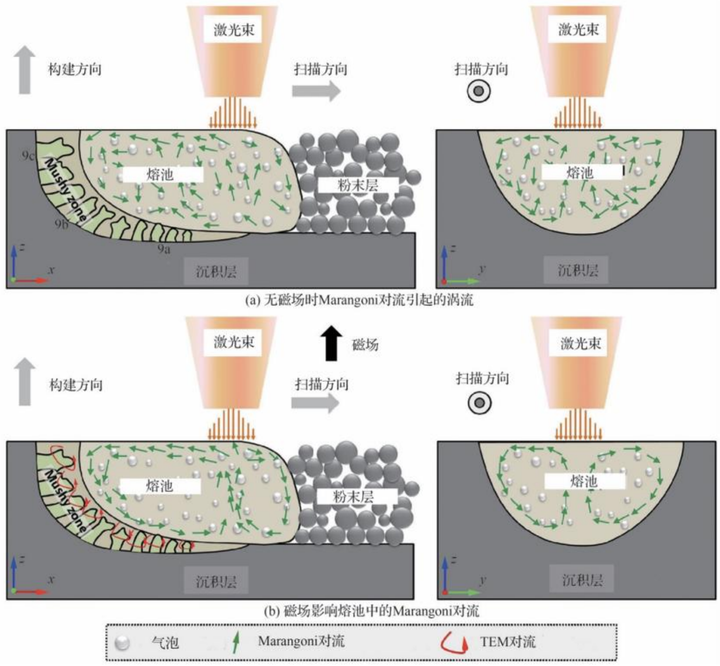
Zhang Hongwei and others [55] investigated synchronous gas-cooled laser directed energy deposition (SGCL-DED) and demonstrated that, in both Laser-DED and SGCL-DED processes, Marangoni convection dominates melt pool flow and induces an outward-flowing toroidal vortex. Liu Bingsen and colleagues [56] studied the effect of interlayer cooling on the grain morphology, microstructure and tensile properties of formed components. They found that increasing the interlayer cooling time will cause the strength of the deposited sample to increase, the plasticity to decrease, and the fracture mechanism to change to cleavage brittle fracture. Some researchers [57] used five interlayer residence strategies and found that the microhardness is the highest when there is no residence time. Appropriate residence (10-20 s) can significantly reduce the TC4 temperature gradient, but too long residence (≥30 s) or forced cooling will weaken the interlayer bonding, induce horizontal cracks and non-fusion defects, resulting in a decrease in mechanical properties. Thampy and others [58] found that the laser power is negatively correlated with the overall cooling rate of the sample. The cooling rate directly affects the residual strain of a small amount of β-Ti phase. The lower the cooling rate, the higher the residual strain of the β phase. While the α-Ti phase undergoes lattice shrinkage, and its degree of shrinkage is basically not affected by changes in the cooling rate.

Regulating the temperature field through substrate preheating and synchronous pre-cooling is a crucial method for optimizing the forming quality of titanium alloy components produced via laser additive manufacturing [59]. These techniques help mitigate inherent defects, such as coarse columnar grains, porosity, cracking, and high residual stress, by refining grains and homogenizing the microstructure through the control of temperature gradients and solidification rates. While substrate preheating is a mature and widely applicable technology, multi-layer deposition often leads to heat accumulation [60]. Synchronous pre-cooling enables precise control over melt pool solidification behavior and suppresses dendritic coarsening. It offers distinct advantages in the fabrication of highly dense, high-precision components [55]. Although temperature field regulation has proven highly effective in addressing microstructural defects, issues such as the unclear mechanisms of temperature field coupling remain, necessitating further in-depth research.

5. Electromagnetic Field-assisted Laser Additive Manufacturing of Titanium Alloys

Electromagnetic-assisted laser additive manufacturing of titanium alloys employs external devices to apply electric and magnetic fields to the molten pool and high-temperature deposition zone, thereby regulating solidification behavior through the effects of individual fields and their coupling [61]. The electric field generates Joule heat and adjusts the temperature gradient of the molten pool. It also drives solute atom diffusion via electromigration, thereby mitigating elemental segregation and optimizing grain morphology [62]. When the conductive titanium alloy melt is subjected to a magnetic field, the resulting Lorentz force, acting through magnetohydrodynamic effects, constrains chaotic melt flow and breaks up coarse dendrites [63]. The coupling of electric and magnetic fields integrates the advantages of thermal, mass, and flow field regulation. This approach refines grains, reduces defects such as porosity and cracking, lowers residual stress, and alleviates issues inherent in conventional processes, such as coarse columnar grains and microstructural inhomogeneity [64].

Figure 9: Schematic Diagram of Electromagnetic Field Assistance [65]



Note. (a) Vortices induced by Marangoni convection in the absence of a magnetic field; Development direction; Laser beam; Scan direction; Weld pool; Powder layer; Sedimentary layer; (b) Magnetic field affects Marangoni convection in the molten pool; bubble; Marangoni convection; TEM convection

Some researchers [66] studied the thermal fluid characteristics in the titanium alloy molten pool generated under the combined action of DC electric field and PMF during the laser scanning process. They found that combining DC electric field and PMF can reduce the maximum temperature of the molten pool. Liu Chang and colleagues [67] proposed a three-dimensional numerical model of LMD Ti-6Al-4V combined with electromagnetic fields. It was found that a stable electromagnetic field can suppress the flow inside the molten pool. Other researchers [68] proposed the subsequent synchronous electromagnetic induction-laser hybrid directed energy deposition (FEMI-DED). They found that in FEMI-DED, the number of refined dendritic primary TiC was reduced by ~26.2%, and a large amount of granular TiC appeared, with a particle size of approximately 1.45 μm. Some other researchers [69] constructed a mathematical model of magnetohydrodynamics inside a tiny molten pool under the action of a three-phase three-pole rotating electromagnetic stirrer. The test proved that equiaxed crystals appeared in the structure at the top of the molten pool after applying a magnetic field. As it moved away from the center of the magnetic field, the number of equiaxed crystals at the top of the molten pool gradually increased, which is consistent with the analysis trend of the calculation results. Liu Qi and others [70] studied that under the action of a rotating magnetic field, the magnetic induction intensity on the liquid surface in the laser melt pool is proportional to the excitation current and inversely proportional to the frequency. Under the action of the rotating magnetic field, both sides of the surface of the laser-deposited repair part are convex and the aspect ratio of the α/β lamellae of the internal tissue of the repair layer is reduced. Researchers [71] also found that after applying an electromagnetic composite field, a network structure appeared in the cladding layer, and the downward Lorentz force can form a network structure with larger spatial spacing inside the coating.

Electromagnetic field-assisted laser additive manufacturing of titanium alloys enables the regulation of melt pool solidification and microstructure, as well as the improvement of mechanical properties. It addresses issues associated with traditional processes, such as disordered grain structures, elemental segregation, residual stress concentration, and forming defects, that arise from rapid melting and solidification. This technology utilizes electromagnetic forces, stirring effects, and magnetically induced oscillations to control melt pool flow, refine grains, and homogenize the microstructure [72]. Steady-state electromagnetic fields help balance melt pool temperatures and suppress the formation of cracks and porosity [73], while alternating electromagnetic fields agitate the melt pool and fragment dendrites, making the process suitable for fabricating high-performance, precision components [70].

6. Composite-field-assisted Laser Additive Manufacturing of Titanium Alloys

6.1 Ultrasonic Composite Micro-forging Composite Field

During the solidification phase of the molten pool, the ultrasonic field employs cavitation and acoustic streaming effects to agitate the liquid metal, thereby breaking up primary dendrites and refining solidified grains to inhibit the formation of coarse columnar crystals at the source. Subsequently, micro-forging is performed within the high-temperature range of the deposited layer. Impact-induced plastic deformation compacts interlaminar voids, compensating for the limitation that ultrasound alone struggles to eliminate solid-state porosity. Together, these processes synergistically control the manufacturing of the titanium alloy.

Some researchers [74] investigated an ultrasonic micro-forging (UMFT) assisted method. They found that UMFT-treated samples exhibited a large number of equiaxed β grains, with the area percentage of these grains being controllable. The Vickers hardness increased from 360 HV to 520 HV, the nanohardness increased by a factor of 1.54, and the Young’s modulus reached 170 GPa.

6.2 Magnetic Field-Assisted Thermal Processing

The magnetic field utilizes the Lorentz force to agitate the molten pool, fragment dendrites, and mitigate solute segregation. The temperature field enhances the magnetic control effect by smoothing temperature gradients and improving molten pool fluidity. Acting synergistically, they regulate solidification behavior, suppress columnar grain growth and internal defects, and thereby control the manufacturing process of titanium alloys.

Researchers [75] applied high magnetic field (HMF, 3 T) and heat treatment (HT) to L-PBF Ti64 at 800–900°C. This treatment increased the α-phase sub-grain boundary fraction from approximately 7% to about 21%. At 900°C, the HMF-HT further increased the β-phase volume fraction from 6.5% to 13.4% and the lattice parameter to 3.2143 Å, resulting in an enhanced tensile ductility of 15.4 ± 1.3% for the Ti64 alloy. HMF-HT can be effectively used to tailor the microstructure and mechanical properties of L-PBF α-β titanium alloys.

7. Conclusions and Outlook

7.1 Conclusions

This article systematically reviews the research progress of ultrasonic field, plastic deformation field, temperature field, single external field of electromagnetic field and composite energy field assisted titanium alloy laser additive manufacturing technology. It systematically reviews the operating principles, implementation methods, regulatory effects, and application limitations of various external fields.

Ultrasonic fields utilize cavitation and acoustic streaming effects to fragment dendrites in the molten pool. Three loading modes, stationary, mobile, and non-contact, are respectively suited for the deposition of large components, high-precision parts, and precision thin-walled components. While capable of efficiently refining grains and optimizing strength and ductility, the process faces challenges regarding energy attenuation and relatively low coupling efficiency.

The plastic deformation field relies on the plastic deformation and dynamic recrystallization caused by pulse hammering and continuous rolling, which compacts internal pores, breaks coarse columnar crystals, and greatly weakens mechanical anisotropy. It is difficult to achieve integrated control of special-shaped surfaces with the assistance of pulse plastic deformation.

The temperature field regulates the solidification rate and temperature gradient through a dual-control approach involving substrate preheating and synchronous precooling. Preheating helps alleviate thermal stress and suppress cracking, while precooling accelerates cooling to prevent grain coarsening. However, this method faces challenges such as complex parameter matching for the thermal field and a tendency for heat imbalance during multi-layer deposition.

Electromagnetic fields constrain weld pool convection and mitigate solute segregation through Lorentz forces and electromigration. Alternating magnetic fields refine grains via stirring, while steady-state magnetic fields stabilize forming quality, yet the coupling mechanisms among the various field parameters remain unclear.

7.2 Future Outlook

For titanium alloy series such as TC4, TA15, and Ti60, used in applications ranging from aerospace to medical implants, establish a standardized process database for external-field-assisted laser additive manufacturing, and determine the optimal external-field process parameters for each specific alloy grade.

Drive the industrial-scale production of field-support equipment, transitioning from small-scale laboratory sample preparation to the mass production of large-scale aerospace structural components and medical titanium alloy parts; reduce manufacturing costs and accelerate the engineering application of field-support additive manufacturing technologies.

Leveraging in-situ high-temperature observation, synchrotron radiation characterization, and multi-physics numerical simulation, this work deeply analyzes the cross-scale coupling mechanisms among multiple external fields, laser heat sources, and the molten pool. It elucidates the dynamics of atomic diffusion, nucleation and growth, and dislocation evolution driven by the synergy of ultrasonic cavitation, plastic deformation, temperature gradients, and electromagnetic stirring. Furthermore, it establishes a comprehensive theoretical model covering the entire cycle from molten pool solidification to solid-state phase transformation, thereby filling the knowledge gap regarding the microscopic interaction mechanisms of composite energy fields.

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Conflicts of Interest

The authors declare no conflict of interest.

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