Laser Shock-Enabled Hybrid Additive Manufacturing Strategy for Molten Pool Modulation in Fe-Based Alloys

Authors: Jian Liu, Shusen Zhao, Xiaohan Zhang, Xuechun Lin, Yaowu Hu, Yaowu Hu

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Abstract

A novel hybrid laser additive manufacturing process based on laser shock modulation of molten pool was proposed in this work. The flow behavior residual stress, and microstructure of the molten pool were comprehensively characterized by a combination of experiments and simulations. The relationship between the convection behavior, evolution of microstructure, and enhancement of residual stress induced by laser shock modulation was established. Laser shock modulation assisted additive manufacturing process exhibits high efficiency in residual stress control. The hidden mechanism in microstructure evolution and residual stress enhancement was expected to be related to intensified molten pool convection, uniform solute distribution and improved cooling rate induced by shock wave. The hybrid additive manufacturing process strategy based on laser shock modulation provides a new approach for heat and mass modulation in hybrid manufacturing.

Full Text

Preamble

A Laser-Shock-Enabled Hybrid Additive Manufacturing Strategy with Molten Pool Modulation of Fe-based Alloy

Jian Liu a#, Shusen Zhao b#, Xiaohan Zhang a, Xuechun Lin b*, Yaowu Hu a*

a The Institute of Technological Sciences, Wuhan University, Wuhan, 430072, China
b The Institute of Semiconductors, Chinese Academy of Sciences, Beijing, 100083, China

Jian Liu and Shusen Zhao contributed equally to this work.

*Corresponding author: Yaowu Hu
E-mail: yaowuhu@whu.edu.cn

*Corresponding author: Xuechun Lin
E-mail: xclin@semi.ac.cn

Abstract

This work proposes a novel hybrid laser additive manufacturing (LAM) process based on laser shock modulation of molten pool (LSMMP). Through a combination of experimental and simulation approaches, we comprehensively investigate residual stress, heat transfer, and mass transfer behaviors, along with microstructure evolution. The relationship between convection behavior, microstructure evolution, and residual stress enhancement induced by LSMMP is established. Compared with traditional post-treatment processes, the LSMMP-assisted LAM process demonstrates higher efficiency in residual stress control under the same pulsed laser energy input. The underlying mechanism for microstructure evolution and residual stress enhancement appears to be related to intensified molten pool convection, uniform solute distribution, and improved cooling rate induced by LSMMP. This hybrid LAM strategy provides a new approach for applying short-pulse lasers in hybrid manufacturing.

Keywords: Additive manufacturing; Laser shock; Molten pool; Residual stress; Microstructure

1. Introduction

Compared with subtractive manufacturing, laser additive manufacturing (LAM) represents a promising process that integrates knowledge from mechanics, materials science, and machinery, offering inherent advantages in direct forming and remanufacturing applications [1-3]. While the typical layer-by-layer construction principle of LAM facilitates the fabrication of complex structural components, it also introduces unavoidable challenges, including geometric accuracy [4,5], metallurgical defects [6-8], and residual thermal stress [9,10]. The forming accuracy and surface roughness of LAM directly influence manufacturing efficiency and the quality of complex parts or dies. Metallurgical defects are primary contributors to part failure, while residual stress significantly impacts material fatigue properties.

Generally, residual stress is inevitable in LAM processes due to the layer-by-layer construction strategy and complex thermal history [11,12]. Research has revealed that residual stress in LAM parts comprises two distinct zones: a compressive stress zone in the middle region and a tensile stress zone in the outer region [13]. The distribution characteristics of residual stress are influenced by part geometry, raw material thermophysical properties, and deposition path, as these factors directly affect molten pool solidification behavior. Specifically, part geometry and deposition path alter heat transmission and diffusion processes, while thermophysical properties primarily influence phase structure, microstructure, and composition distribution—all of which are sensitive to molten pool heat and mass transfer behaviors. For instance, studies on AISI H13 tool steel layers have shown that compressive stresses are significantly magnified by the martensite phase, though this can be mitigated through appropriate heat treatment [14].

To address these residual stress challenges in LAM processes, various post-treatment methods have been developed, including heat treatment [15], shot peening [16], ultrasonic surface mechanical grinding [17], ultrasonic impact [18], ultrasonic surface mechanical rolling [19], friction stir processing [20], and laser shock peening (LSP) [21-24]. In particular, LSP utilizes ultra-high-pressure plasma generated by short-pulse lasers, which is transmitted to the workpiece through shock waves, inducing ultra-high-strain-rate plastic deformation in metals [25]. LSP has proven effective at inducing compressive stresses and grain refinement, thereby improving mechanical properties [26-28]. However, post-treatment approaches compromise process continuity and manufacturing efficiency in additive manufacturing. Consequently, synchronous hybrid AM technologies that can reduce metallurgical defects and enhance microstructure and residual stress without increasing total manufacturing time are highly desirable, such as laser metal deposition assisted with warm ultrasonic impact (LMD+WUI) [29] and LAM+LSP [30]. A key limitation of existing residual stress control technologies like WUI and LSP is their reliance on plastic deformation of the solidified surface, which requires substantial shock pressure exceeding the elastic limit. The shock pressure in LSP heavily depends on the confinement layer' s effectiveness in restricting laser-induced plasma.

Unfortunately, applying a confinement layer during continuous LAM processes is challenging. Although one could transfer the deposited layer from the AM platform to an LSP platform after each layer, this approach prevents real-time residual stress control and extends total processing time [31]. To address the poor synchronicity and low efficiency of existing hybrid LAM processes, we report for the first time a hybrid manufacturing strategy that combines LAM with laser shock modulation of molten pool (LSMMP). While short-pulse lasers are commonly used for material property enhancement, to our knowledge, no research has investigated synchronous hybrid LAM processes based on LSMMP. This method enhances cladding layer structure and residual stress by shifting the pulsed laser irradiation area from the solid surface to the fluid molten pool, significantly reducing shock pressure requirements and eliminating confinement layer challenges. In this paper, we investigate molten pool morphology and microstructure of LAM+LSMMP manufactured cladding layers through experimental observation and numerical simulation, while also examining residual stress distribution characteristics. We establish the relationship between convection behavior changes, microstructure evolution, and residual stress enhancement induced by LSMMP, and discuss the underlying mechanisms through which LSMMP achieves residual stress control and microstructure evolution.

2.1 Process and Experimental Design

As shown in Fig. 1(a), traditional LSP is performed on solidified cladding layers during LAM+LSP hybrid manufacturing. In contrast, the LAM+LSMMP hybrid process developed in this work (Fig. 1(b)) shifts the pulsed laser irradiation area into the liquid molten pool. Fe-based cladding layers were fabricated using a LAM+LSMMP platform consisting of a 3 kW continuous-wave (CW) fiber laser for LAM, a 3 J pulsed laser for LSMMP, and a 6-axis ABB robot arm for implementing the scanning path. The axes of the CW laser beam and pulsed laser beam are symmetrically oriented, deviating from the vertical direction by +5° and -5°, respectively. Raw material was supplied as pre-placed powder with a thickness of 0.7 mm. To suppress oxidation during laser processing, high-purity argon was used as shielding gas at an empirically determined flow rate of 3 L/min.

The CW laser power was set to 1500 W, while the pulsed laser parameters were: pulse energy of 2 J and repetition frequency of 5 Hz. The beam diameters of the CW laser and pulsed laser spot were 3 mm and 1.3 mm, respectively, with the CW laser scanning speed set to 4 mm/s.

Fig. 1. Schematic diagram of LAM+LSMMP: (a) Traditional LAM+LSP process, (b) LAM+LSMMP in this study.

The LAM+LSMMP experiments were conducted on commercial AISI 1045 steel substrates, which were cleaned with acetone and alcohol to remove surface impurities. Fe-based alloy powder (0.5 wt% C, 1.2 wt% Si, 1.6 wt% B, 0.8 wt% Mo, 13 wt% Cr, balance Fe) served as the raw material. The distance between the two laser centers, defined as spot spacing, was varied from 0 mm to 4 mm. A control sample without laser shock processing was also prepared. As shown in Fig. 2, when spot spacing is 0 mm, the pulsed laser irradiates completely within the molten pool; as spot spacing increases, the effective area of pulsed laser action on the molten pool decreases progressively. Spot spacing greater than 2 mm essentially corresponds to the traditional LAM+LSP hybrid process depicted in Fig. 1(a). Samples were designated as 0 J-0 mm, 2 J-0 mm, 2 J-1 mm, 2 J-2 mm, and 2 J-3 mm accordingly. Real-time molten pool morphology during LAM+LSMMP was captured using a high-speed camera. Specimens ($10\times10\times10 mm^{3}$) for macroscopic morphology and microstructure characterization were sectioned from the cladding layers. Three-dimensional profile data were obtained using a white light interferometer, while microstructure observation was performed via scanning electron microscopy (SEM). Residual stress was measured by X-ray diffraction (XRD). Finite volume method (FVM) simulations were employed to analyze convection behaviors and temperature distribution in the molten pool induced by LSMMP, using non-conforming meshes with a unit size of 0.4 mm. Residual stress calculations were performed using finite element method (FEM), establishing a thermodynamic coupling model for the LAM+LSP hybrid additive manufacturing process. PLANE13 quadrilateral four-node and SOLID5 hexahedron eight-node three-dimensional coupled field elements were selected, with the overall model mesh size also set to 0.4 mm.

Fig. 2. Diagram of spot distribution of continuous and pulsed lasers.

3.1 Residual Stress

Fig. 3(a) plots the residual stress curves for cladding layers with various spot spacings. The original coating without pulsed laser assistance exhibits a residual compressive stress of 332$±$18 MPa. Notably, the cladding layer with 2 mm spot spacing shows the highest residual compressive stress, suggesting that pulsed laser irradiation occurs in a mushy zone that is more susceptible to plastic deformation than fully solidified regions.

For the studied conditions, the LSMMP-assisted LAM hybrid process (spot spacing = 0 mm and 1 mm) demonstrates higher residual stress control efficiency than solid surface treatment (spot spacing = 3 mm). The contribution of LSMMP to compressive stress in the upper cladding zone diminishes significantly when spot spacing exceeds 2 mm. This phenomenon arises from variations in the surface state of the laser-irradiated region. As the pulsed laser progressively deviates from the molten pool center, the irradiated area transitions from molten to semi-solidified and finally to fully solidified states. This rapid increase in surface strength consequently weakens the effectiveness of the limited-energy pulsed laser. Furthermore, Figs. 3(b) and 3(c) reveal that the compressive residual stress region in the central zone contracts while tensile stress in the substrate decreases. These results demonstrate the effectiveness of the LSMMP strategy, with the underlying mechanism for residual stress control to be discussed later.

Fig. 3. Experimental and simulation results of the cladding layers: (a) Experimental results, (b) Simulation results of 0 J-0 mm, (c) Simulation results of 2 J-0 mm.

3.2 Macro-Morphology

Fig. 4 shows the 3D profiles of single-track cladding layers with different spot spacings. The most notable feature is that introducing pulsed laser energy fields during AM promotes perlage formation on cladding layer surfaces under small spot spacing conditions ($ $2 mm). However, the surface morphologies of cladding layers fabricated at large spot spacing (>2 mm) resemble those of the original 0 J-0 mm coating, since the pulsed laser applied to solidified or semi-solidified metal surfaces causes only minimal plastic deformation. The modulation effect on surface morphology is closely related to spot spacing, with LSMMP' s influence on molten pool morphology weakening as spot spacing increases.

Fig. 4. 3D profiles of cladding layers with different spot spacing: (a) 0 J-0 mm, (b) 2 J -0 mm, (c) 2 J -1 mm, (d) 2 J -2 mm, (e) 2 J -3 mm, (f) 2 J -4 mm.

The 2D cross-section profiles (Fig. 5) of cladding layers with various spot distances demonstrate LSMMP' s effectiveness in modifying the molten pool' s width-to-height ratio during AM. Since the molten pool experiences complete laser-induced shock wave pressure, sample 2 J-0 mm shows pronounced improvement. Specifically, compared with the original 0 J-0 mm sample, the height of sample 2 J-0 mm decreased by approximately 43% while width increased by about 7%. In contrast, the 2 J-3 mm and 2 J-4 mm samples show only slight height reduction, consistent with the residual stress variation trend.

Fig. 5. 2D cross-section profiles of cladding layer: (a) 0 J-0 mm, (b) 2 J-0 mm, (c) 2 J-1 mm, (d) 2 J-2 mm, (e) 2 J-3 mm, (f) 2 J-4 mm.

3.3 Microstructure Evolution

The cross-sectional SEM image in Fig. 6(a) reveals excellent forming quality in the cladding layer, with no typical metallurgical defects such as cracks or voids observed in the dense coating. Fig. 6(b) shows that the Fe-based cladding layers exhibit a typical dendritic structure. The enlarged SEM image in Fig. 6(c) demonstrates that the interdendritic region (IR) consists of a continuous network-shaped eutectic phase, while the dendritic region (DR) comprises residual austenite and lath martensite, consistent with previous studies [32]. The IR phase forms through eutectic reaction between austenite and boride, as boron tends to segregate and precipitate at austenite grain boundaries—a phenomenon confirmed by chemical composition analysis (DR: 38.35 at.% C, 0.39 at.% Si, 1.21 at.% Cr, 0.70 at.% Mo, 59.36 at.% Fe; IR: 34.41 at.% C, 0.18 at.% Si, 1.90 at.% Cr, 0.73 at.% Mn, 45.03 at.% Fe, 17.75 at.% B). Additionally, the eutectic borides in Fe-based alloys exhibit an M2B crystal structure (where M is Fe, Cr, or Mn) [33].

Fig. 6. SEM images of cladding layers: (a) cross-section SEM image, (b) microstructure image, (c) Enlarged SEM image.

Fig. 7 presents comprehensive microstructural observations at different depths along the cladding layer cross-section to investigate the influence of laser shock modulation of molten pool on solidification behavior. Observation positions are indicated in the corresponding SEM image illustrations. Figs. 7(a) and 7(c) show that both samples exhibit columnar dendrites perpendicular to the bonding interface in the bottom region, with no significant microstructural differences near the interface, implying negligible pulsed laser effects on bottom molten pool morphology and solidification. However, dendrite morphology distribution characteristics in the middle and top regions differ significantly between samples 0 J-0 mm and 2 J-0 mm. In sample 0 J-0 mm, adjacent eutectic phases display parallel distribution determined by steady heat flow diffusion, whereas in sample 2 J-0 mm, eutectic phases in the top and middle regions exhibit disordered distribution characteristics, indicating that pulsed laser energy fields disrupt the growth behavior of preferentially oriented grains. Molten pool oscillation destabilizes the solid-liquid interface front, inhibiting directional dendrite growth. Additionally, external energy field influence on solidification is evident in eutectic phase distribution characteristics and volume fractions. Comparing Figs. 7(b) and 7(e), or 7(c) and 7(f), reveals transformation of the continuous network-shaped eutectic phase into a discontinuous, refined state. Volume fraction calculations show IR fractions of 6.41%, 17.03%, and 16.55% in the bottom, middle, and upper regions of sample 0 J-0 mm, compared to 6.20%, 10.17%, and 9.96% in sample 2 J-0 mm, respectively. This indicates that LSMMP primarily influences microstructure in the middle and upper cladding regions. We believe that forced molten pool oscillation-induced changes in heat transfer behavior are the critical factor driving these phenomena. While slow cooling rates favor boride precipitation [34], we speculate that increased martensite matrix volume fraction relates to enhanced cooling rates caused by molten pool oscillation [35]. In this study, LSMMP-driven molten pool oscillation promotes thermal diffusion in the middle and upper molten pool regions, increasing solidification rate, inhibiting eutectic reaction, and accelerating martensitic transformation.

Fig. 7. Cross-section SEM images of the cladding layers along different depths direction: (a)-(c) 0 J-0 mm, (d)-(f) 2 J-0 mm.

3.4 Molten Pool Flow Behavior

To investigate pulsed laser modulation effects on the molten pool, real-time evolution images were captured. Figs. 8(a)-(c) document the molten pool advancement in sample 0 J-0 mm, where liquid droplets from laser fusion gradually coalesce into a plump molten pool. In contrast, Figs. 8(d)-(f) show distinct features with LSMMP: bright plasma induced by the pulsed laser is visible (Fig. 8(d)), and most significantly, the pulsed laser effectively drives molten pool morphological transformation from plump to flat (Fig. 8(e)) through shock pressure-induced forced vibration. Additionally, surface tension-dominated slight fluctuations were observed 3-4 ms after pulsed laser application (Fig. 8(f)). Thus, perlage and sub-perlage formation shown in Figs. 4(b)-(d) can be attributed to forced molten pool fluctuation driven by LSMMP and surface tension-dominated slight vibration, respectively.

Fig. 8. Real-time images of molten pool evolution: (a)-(c) 0 J-0 mm, (d)-(f) 2 J-0 mm.

The underlying mechanism of LSMMP for achieving residual stress control and microstructure evolution is discussed from the perspective of molten pool convection state changes. Fig. 9(a) illustrates the molten pool without LSMMP assistance (0 J-0 mm), where a plump pool exhibits symmetrical convection rings traveling down the vertical centerline to the solid-liquid interface before surging upward toward the cladding layer surface on both sides. In contrast, LSMMP-assisted molten pools (Fig. 9(b)) display distinct morphology with a pit forming in the pulsed laser irradiation area. Furthermore, significant changes in molten pool convection occur during the unloading stage of the pulsed laser-induced plasma shock wave, particularly in the sub-central region. Fig. 9(c) reveals that the middle and upper areas of the flattened molten pool form symmetrical convection rings with flow directions opposite to those in Fig. 9(a), while no apparent disturbed flow is observed near the interface. Therefore, microstructure evolution and residual stress enhancement in LAM+LSMMP may be attributed to one or more of the following mechanisms: (i) LSMMP intensifies molten pool flow behavior, increasing solidification rate, suppressing boride precipitation, and accelerating martensitic transformation; (ii) LSMMP-facilitated convection promotes solute diffusion and uniform distribution, reducing grain boundary precipitation; and (iii) accelerated martensite precipitation increases residual compressive stress [14].

Fig. 9. Simulation results of molten pool convection: (a) Convection without LSMMP assistance, (b) Convection with LSMMP loading process, (c) Convection with LSMMP unloading process.

In summary, the LSMMP-assisted LAM hybrid process shifts the pulsed laser irradiation area from solid or semi-solid metal surfaces to the liquid molten pool, achieving more efficient residual stress control under fixed low-energy laser input conditions. Compared with strategies that increase shock pressure on solid surfaces by raising pulse laser energy or applying confinement layers in inconvenient ways, the proposed LSMMP-assisted LAM process may offer lower production costs and reduced total manufacturing time. This relatively simple hybrid process also shows promise for application to highly brittle, crack-prone additive materials susceptible to undesirable grain boundary precipitation phases, owing to the solute convection and uniform distribution promoted by LSMMP.

4. Conclusions

In this work, we enhanced material microstructure and residual stress through molten pool disturbance, proposing a hybrid LAM and LSMMP manufacturing strategy. Unlike traditional LSP processes, the pulsed laser irradiation area is shifted from the solid surface to the liquid molten pool. For the studied conditions and samples, the LSMMP-assisted LAM hybrid process demonstrates higher residual stress control efficiency than conventional LAM+LSP under identical pulsed laser energy input. Based on molten pool morphology observations and simulation results, the underlying mechanism for microstructure evolution and residual stress enhancement appears to involve intensified molten pool convection, uniform solute distribution, and improved cooling rate induced by LSMMP. The LSMMP process intensifies and alters molten pool flow behavior, increasing solidification rate, inhibiting intergranular precipitation, and accelerating martensitic transformation. The proposed LAM+LSMMP hybrid manufacturing process could be implemented to control fluid flow, heat, and mass transfer during fusion joining and additive manufacturing—factors critical to geometric accuracy, composition distribution, precipitation phases, microstructures, stress states, and mechanical properties.

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