
Research article

Modulation laser-induced melt pool dynamics and morphology control in directed energy deposition

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Abstract: Continuous-wave (CW) laser directed energy deposition (LDED) is inherently constrained by the rigid coupling between heat accumulation and laser power. Elevated power levels frequently induce melt pool overheating and surface oxidation, thereby hindering independent control of bead geometry and deposition quality. In this study, we proposed a morphology control strategy based on rectangular-wave modulated laser processing. Through a transient thermo-fluid coupled numerical model integrated with single-track coaxial powder feeding experiments, the regulatory mechanisms of duty cycle and modulation frequency on melt pool morphology were systematically investigated. Simulation results demonstrated that under a constant average power, reducing the duty cycle from 1.0 to 0.2 increased the melt pool depth-to-width aspect ratio by 60%. This enhancement was attributed to the synergistic effects of intensified recoil pressure during pulse-on periods and suppressed lateral thermal diffusion during pulse-off intervals. Frequency-domain analysis further delineated distinct regimes of mid-frequency resonance amplification and high-frequency attenuation governed by thermal inertia. Experimental validation conducted at a peak power of 810 W confirmed that modulated laser processing enables continuous and controllable variation of bead width solely through duty cycle adjustment, while consistently maintaining superior surface quality and mitigating overheating oxidation compared to CW operation at equivalent power. This work demonstrates that temporally structured energy deposition via laser modulation effectively decouples instantaneous power density from time-averaged heat input, providing a novel pathway for precise melt pool engineering in LDED.

Keywords: laser directed energy deposition; modulated laser; melt pool dynamics; duty cycle control; thermo-fluid coupling; process optimization

1. Introduction

Metal laser additive manufacturing enables the direct fabrication of dense and geometrically complex three-dimensional metallic components through selective melting and layer-by-layer deposition of metal powder using a high-energy laser beam [1–3]. This technology has demonstrated considerable promise in critical sectors such as aerospace, biomedical engineering, and high-performance tooling [4,5]. However, under conventional continuous-wave (CW) laser operation, the strongly nonlinear thermo-fluid coupling within the melt pool readily induces dynamic instabilities, leading to stochastic surface undulations and geometric deviations along the deposited track [6]. Such irregularities severely compromise the consistency and controllability of dimensional accuracy, surface finish, and resultant mechanical properties [7]. Consequently, achieving active and precise control over melt pool morphology has emerged as a fundamental scientific challenge in the advancement of laser additive manufacturing.

Temporal modulation of laser power has opened a novel technological pathway for programmable control of melt pool morphology. The WaveShape process developed by the Fraunhofer Institute for Laser Technology demonstrates that continuous modulation of laser power dynamically alters melt pool volume, enabling the direct, material-removal-free generation of periodic surface structures via pointwise solidification of the free surface. Within laser powder bed fusion (LPBF), pulse-width modulated lasers and CW lasers exhibit complementary advantages; the former being better suited for fabricating fine features with high precision, while the latter promotes superior densification [8,9]. Rupp et al. [10] identified resonance-like behavior in melt pools subjected to sinusoidally modulated laser intensity, revealing a pronounced frequency-locking phenomenon between the periodic surface morphology and the applied modulation frequency. Furthermore, Calta et al. [11] employed high-speed X-ray imaging to uncover distinct melt pool dynamics under modulated laser irradiation, demonstrating that even at extremely high duty cycles, modulated waveforms can elicit melt pool behaviors that diverge markedly from those observed under CW conditions.

Despite these advances, investigations have predominantly entailed sinusoidal or simple pulsed waveforms [12,13]. Compared with sinusoidal-wave modulation, which primarily excites a single frequency component, rectangular-wave modulation contains rich odd-order harmonics. This multi-frequency excitation offers additional degrees of freedom for melt pool control and introduces more complex resonance behaviors. This work reveals that these harmonics can couple with melt pool natural frequencies in the transitional regime (200 Hz–1 kHz), producing resonance effects that are not accessible with pure sinusoidal modulation. A systematic understanding and quantitative description of rectangular-wave modulation—a waveform intrinsically suited to digital generation and embedded system implementation—for melt pool morphology control remains conspicuously absent. Moreover, key open questions persist: how do the rich harmonic components inherent to a rectangular wave, as revealed through Fourier decomposition, translate into multi-frequency thermo-mechanical excitation of the melt pool? Does an analytically describable quantitative mapping exist between modulation parameters (peak power, frequency, duty cycle, scan speed) and the resulting melt pool geometric attributes and surface topography? How can such a mapping inform the construction of an adaptive control framework based on real-time melt pool monitoring to achieve precise, programmable shaping toward arbitrary target morphologies? These unresolved issues constitute a theoretical bottleneck impeding the translation of modulated laser shaping technology into robust engineering practice [14].

To address these scientific challenges, we propose an intermittent energy deposition control methodology based on rectangular-wave modulated laser processing. An analytical description of the spectral energy distribution of the modulated laser is first established through Fourier series expansion of the rectangular waveform [15]. Subsequently, a transient thermo-fluid coupled numerical model is developed to simulate melt pool evolution under intermittent rectangular-wave energy input, thereby systematically elucidating the influence of modulation parameters on melt pool cross-sectional geometry and surface morphology [16]. In this work, we aim to provide systematic theoretical underpinnings and methodological guidance for the customized regulation of melt pool morphology in metal laser additive manufacturing.

2. Materials and methods

2.1. Fourier expansion and spectral characteristics of rectangular-wave modulation

Consider a rectangular-wave modulated laser with period $T = 1/f$. The instantaneous output power can be expressed in Eq 1:

$$P(t) = \begin{cases} P_{peak}, & 0 \leq t < D \cdot T \\ 0, & D \cdot T \leq t < T \end{cases} \text{ (Model T)} \quad (1)$$

where P_{peak} denotes the peak power, T is the period, f is the modulation frequency, and $D \in (0,1]$ represents the duty cycle. The equivalent average power is given by $P_{avg} = P_{peak} \times D$, P_{avg} is the average power. The rectangular waveform can be expanded into a Fourier series as given by Eq 2 [17,18]:

$$P(t) = P_{avg} + \sum_{n=1}^{\infty} \frac{2P_{peak}}{n\pi} \sin(n\pi D) \cos(2\pi nft) \quad (2)$$

This expansion reveals the fundamental physical nature of rectangular-wave modulation [19]: the laser power is composed, in the frequency domain, of a direct-current (DC) component P_{avg} and an infinite series of alternating-current (AC) harmonic components. The amplitude of the n -th harmonic is $2P_{peak}/n\pi|\sin(n\pi D)|$, and its phase is determined by the sign of $\sin(n\pi D)$.

Figure 1 presents the time-domain power output of the rectangular-wave laser for duty cycles (D) = 0.2, 0.5, and 0.8. The intermittent energy injection characteristic of the “on-off” modulation is illustrated: at $D = 0.2$, the pulse width is extremely narrow, concentrating energy within a very short temporal window; and at $D = 0.8$, the waveform closely approaches continuous-wave output, with a significantly shortened off-period. These three waveforms, plotted on a common time base, directly demonstrate the regulatory effect of the duty cycle on the temporal distribution of laser energy (a smaller duty cycle yields higher energy density per pulse but extends the inter-pulse interval).

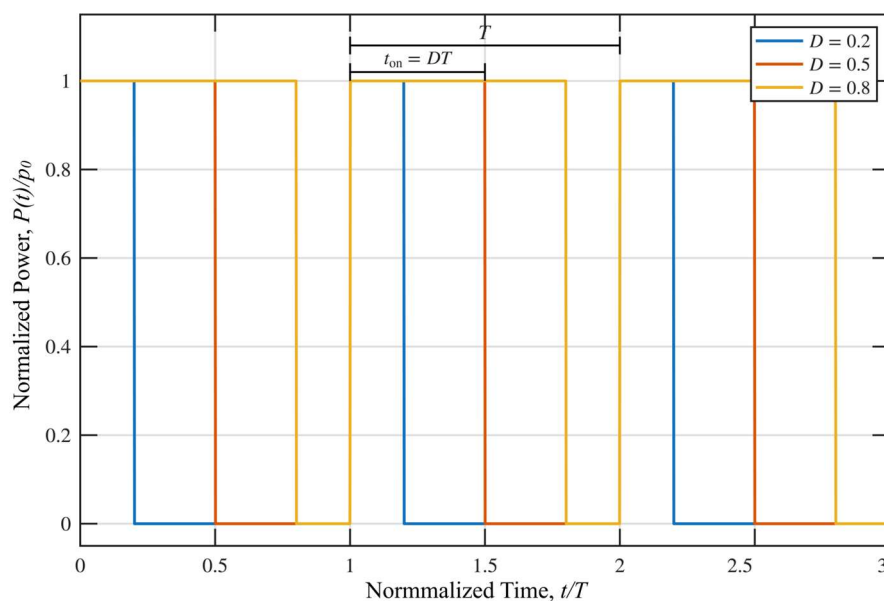


Figure 1. Time-domain waveforms of rectangular-wave modulated laser power at different duty cycles.

Figure 2 displays the Fourier series expansion results for the condition $D = 0.5$ (ideal square wave), illustrating the amplitude distribution of the first 15 harmonic components.

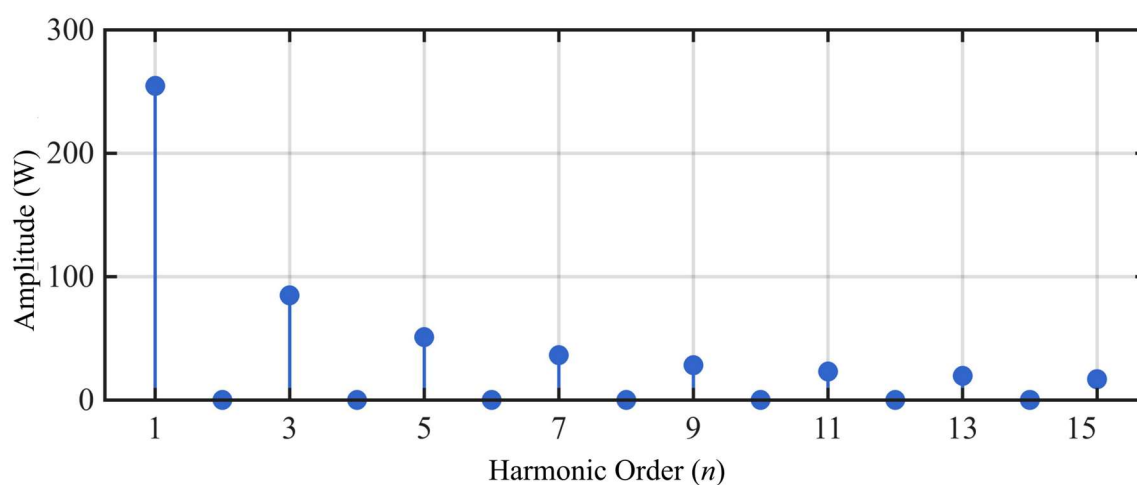


Figure 2. Fourier harmonic amplitude spectrum for a $D = 0.5$.

As evident from the Figure 2, the spectrum of square-wave modulation exhibits the following distinctive features:

Dominance of odd-order harmonics: only the odd harmonics (1st, 3rd, 5th, 7th, 9th, etc.) possess non-zero amplitudes; all even-order harmonic amplitudes are strictly zero.

Amplitude attenuation with harmonic order: the fundamental frequency ($n = 1$) exhibits the maximum amplitude. The 3rd harmonic amplitude decays to one-third of the fundamental, and the 5th harmonic further attenuates to one-fifth. This decay law indicates that the AC energy of the modulated laser is predominantly concentrated in low-order harmonics, with the contribution of high-frequency components to the melt pool being relatively limited.

Implicit DC component: the DC component $P_{avg} = P_{peak} \times D$ from the Fourier expansion is not displayed in the amplitude spectrum; yet, it constitutes the primary portion of the heat input to the melt pool and governs the quasi-steady-state macroscopic dimensions of the melt pool.

2.2. Partitioning of the frequency-duty cycle parameter space

The modulation frequency (f) and the duty cycle together constitute a two-dimensional parameter space. The melt pool response to the modulated laser can be delineated into three characteristic regimes based on the relationship between the modulation frequency and the characteristic time scales of the material [20]. As indicated by the harmonic amplitude formulation, variations in D systematically alter the harmonic energy distribution across the spectrum.

Two intrinsic characteristic time scales of the melt pool system are introduced: the thermal diffusion characteristic time, $\tau_{th} = L_c^2/\alpha$ (where L_c is the characteristic length, typically taken as the laser spot radius, and α is the thermal diffusivity), and the melt pool convection characteristic time, $\tau_c = L_c/v_{max}$ (where v_{max} is the maximum surface velocity of Marangoni convection) [21,22]. For typical laser additive manufacturing processes (spot radius $\sim 50 \mu\text{m}$, thermal diffusivity $\sim 5 \times 10^{-6} \text{ m}^2/\text{s}$), the thermal diffusion characteristic time τ_{th} is approximately 0.5 ms (corresponding to a critical frequency of $\sim 2 \text{ kHz}$); the melt pool convection characteristic time τ_c is approximately 1–5 ms (corresponding to critical frequencies ranging from $\sim 200 \text{ Hz}$ to 1 kHz). Using the relative magnitude of the modulation period $T = 1/f$ with respect to these characteristic times as a criterion, the parameter space can be partitioned into three distinct regimes:

Regime I—Quasi-static regime ($T \gg T_{th}$, i.e., $f \ll 1/\tau_{th}$, approximately $< 200 \text{ Hz}$): the melt pool has sufficient time within each pulse period to approach thermal equilibrium. As D varies, P_{avg} and P_{peak} change either synchronously (if P_{peak} is held constant) or inversely (if P_{avg} is held constant). The melt pool morphology resembles that produced by an equivalent continuous wave but with superimposed periodic pulsations. In this regime, a reduction in duty cycle (under constant P_{avg}) increases the peak power, thereby enhancing recoil pressure and driving the melt pool to extend in the depth direction. The duty cycle exerts a dominant regulatory influence on melt pool morphology.

Regime II—Transitional coupling regime ($T \sim \tau_c$, i.e., f in the range of 200 Hz–1 kHz): when the time scale of the energy pulsation is comparable to that of melt pool convection, the transient response of the melt pool becomes strongly coupled with the modulation waveform. For sinusoidal modulation, resonance-like behavior of the melt pool has been observed at a specific frequency of approximately 250 Hz, where frequency coupling between the modulation frequency and the melt pool's natural frequency causes the surface morphology to transition from a random distribution to a periodic pattern. Under rectangular-wave modulation, multi-frequency coupling may occur not only at the fundamental frequency but also at odd harmonic frequencies.

Regime III—High-frequency filtering regime ($T \ll \tau_c$, i.e., $f \gg 1/\tau_c$, approximately $> 1 \text{ kHz}$): the thermal inertia of the melt pool filters out high-frequency pulsations, and the system primarily responds to the DC component P_{avg} . Moreover, while rapid power modulation at frequencies up to 10 kHz can influence keyhole dynamics, the ability to regulate macroscopic melt pool morphology diminishes as frequency increases. In this regime, the melt pool morphology approaches that of an equivalent continuous wave, and the regulatory capacity of the duty cycle on morphology gradually weakens with increasing frequency.

2.3. Harmonic restructuring effect induced by duty cycle variation

A change in the duty cycle is not merely a variation of the “on” versus “off” time ratio; more importantly, it restructures the energy distribution of the modulated signal in the frequency domain.

Figure 3 presents a three-dimensional surface plot illustrating the joint influence of D (ranging from 0.1 to 0.9) and harmonic order (n , 1 to 20) on the harmonic amplitude $2P_{peak}/n\pi|\sin(n\pi D)|$.

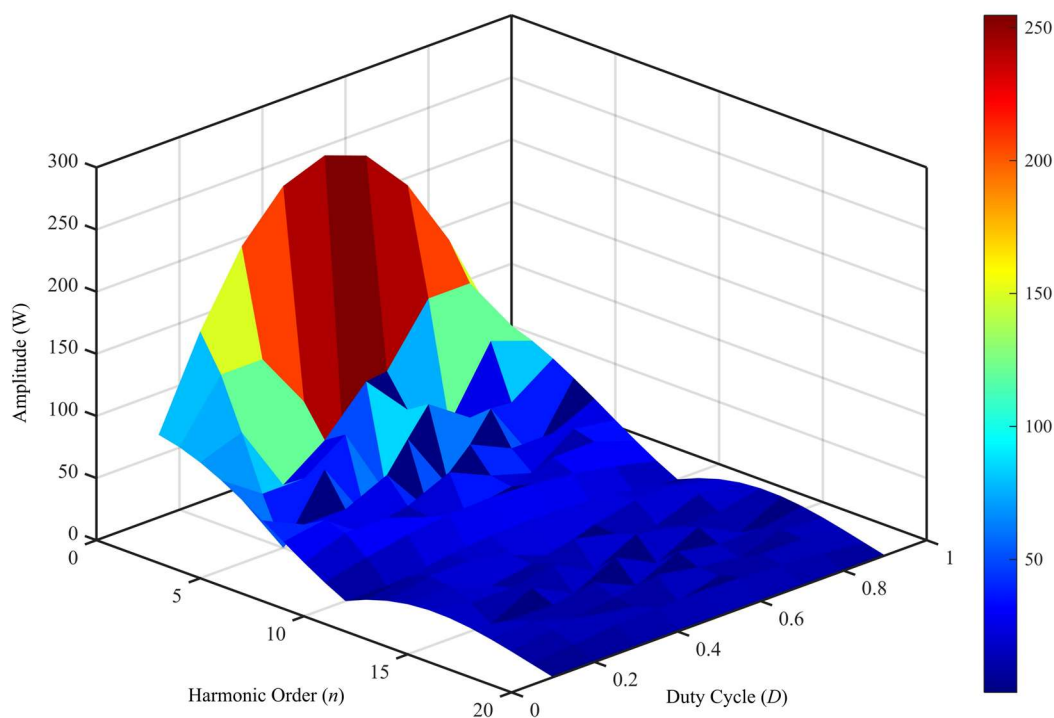


Figure 3. Three-dimensional surface plot showing the combined effect of duty cycle and harmonic order on harmonic amplitude.

Unimodal distribution of the fundamental ($n = 1$) amplitude: the fundamental amplitude attains its maximum at $D = 0.5$ and gradually decreases toward both sides. This behavior arises because $\sin(\pi D)$ reaches its maximum value of 1 at $D = 0.5$.

Multi-peak oscillatory structure for higher-order harmonics: the 3rd harmonic exhibits local maxima at $D = 1/6, 3/6, 5/6$; the peak positions become even denser for the 5th harmonic. This oscillatory characteristic stems from the periodicity of the $|\sin(n\pi D)|$ function.

Overall amplitude decay with increasing order: the surface exhibits a general downward trend toward higher harmonic orders, reflecting the attenuation effect of the $1/n$ factor.

Furthermore, as shown in the Fourier harmonic amplitude spectrum of Figure 2, when $D = 0.5$, $\sin(n\pi D) = \sin(n\pi/2)$, the amplitudes of even-order harmonics are zero, and all energy is concentrated in the odd harmonics (a typical spectral signature of a square wave). As D deviates from 0.5, even-order harmonics begin to appear, leading to a significant alteration of the spectral structure.

Regarding the DC component, $P_{avg} = P_{peak} \cdot D$ increases linearly with D when P_{peak} is fixed, thereby determining the baseline heat input and quasi-steady-state dimensions of the melt pool. For the n -th harmonic, its amplitude $A_n = 2P_{peak}/n\pi|\sin(n\pi D)|$ oscillates periodically with D . Physically, this harmonic restructuring effect implies that under the constraint of constant average power (i.e.,

setting $P_{\text{peak}}=P_{\text{avg}}/D$), reducing D systematically enhances the relative intensity of all harmonic components, with the most pronounced enhancement occurring for low-frequency harmonics. In the modulated mode, as the duty cycle increases, the weld width and penetration depth tend to increase; when the duty cycle exceeds 50%, the welding mode begins to transition from conduction-mode welding to keyhole-mode welding; moreover, the larger the duty cycle, the smaller the influence of frequency on weld width and penetration depth. This phenomenon can be attributed to the attenuation of the relative intensity of high-frequency harmonics: at high duty cycles, the waveform approaches a continuous output, reducing the proportion of harmonic energy, and consequently, the influence of modulation frequency on melt pool dynamics naturally diminishes.

2.4. Frequency selection and the lag effect in melt pool thermal response

The modulation frequency influences the melt pool response through two distinct mechanisms. First, it alters the periodicity of energy injection, directly affecting the heating-cooling dynamics of the melt pool within each pulse cycle. Second, it changes the frequency spacing between harmonics; when a specific harmonic frequency matches a natural frequency of the melt pool, resonance may be excited.

The thermal response of the melt pool to the modulated laser exhibits an inherent phase lag. Treating the melt pool as a first-order thermal system [23,24], Its transfer function can be approximately expressed in Eq 3:

$$H(\omega)=\frac{K}{1+j\omega\tau_{th}} \quad (3)$$

where $\omega = 2\pi f$ is the angular frequency, $H(\omega)$ is the transfer function, K is the system gain, and τ_{th} is the thermal time constant. The amplitude response of the melt pool temperature attenuates with increasing frequency ($|H(\omega)|=K/\sqrt{1+(\omega\tau_{th})^2}$), while the phase lag increases with frequency ($\phi=-\arctan(\omega\tau_{th})$), where ϕ is the phase. When the modulation frequency is much higher than $1/(2\pi\tau_{th})$, the melt pool temperature exhibits negligible response to the AC components and is governed almost entirely by the average power. This frequency-dependent lag effect forms the basis for understanding the frequency dependence of melt pool morphology.

2.5. Melt pool resonance and the synergistic mechanism of frequency and duty cycle

Within the transitional coupling regime, the modulated laser may excite a resonant response in the melt pool. In the case of rectangular-wave modulation, its rich harmonic content implies that multiple frequency components may simultaneously couple with the melt pool.

The occurrence of resonance relies on two critical conditions: frequency matching and energy coupling. Frequency matching is directly determined by f , whereas the efficiency of energy coupling is modulated by D . Since the amplitude of the n -th harmonic is proportional to $|\sin(n\pi D)|$, the intensity of the resonant response depends not only on whether the frequencies match but also on whether the corresponding harmonic possesses sufficient injected energy. If D causes the amplitude of a particular harmonic to approach zero, effective resonance cannot be generated even if that harmonic frequency aligns with a natural frequency of the melt pool. This constitutes the synergistic coupling mechanism between frequency and duty cycle.

Even at extremely high duty cycles, modulated laser processing can induce melt pool behaviors that are markedly different from those observed under continuous-wave laser operation. Such behaviors manifest as fluctuations in vapor depression depth, alterations in complex pore formation mechanisms, and differences in spatter ejection dynamics. This indicates that the melt pool response to modulated laser irradiation is not a simple quasi-static averaging process but rather a highly nonlinear transient phenomenon, wherein small variations in modulation frequency and duty cycle can induce qualitative changes in melt pool flow patterns. High duty cycles can produce weld quality comparable to that of continuous-wave processing, whereas low duty cycles may introduce numerous defects; at intermediate duty cycles, precise control of modulation parameters enables the reproducible and accurate generation of a single pore per laser pulse.

2.6. Quantitative criterion for energy-frequency matching

Synthesizing the preceding analyses, a quantitative criterion for energy-frequency matching in rectangular-wave modulated laser processing can be established. Define the dimensionless frequency $\tilde{f} = f \times \tau_c$ and the harmonic energy efficiency factor $\eta_n(D) = |\sin(n\pi D)|/n$. Thus, the effective energy coupling between the modulated laser and the melt pool can be expressed as in Eq 4 [25]:

$$E_{\text{eff}} = P_{\text{avg}} \cdot \left[1 + \sum_{n=1}^{N_{\text{cut}}} \eta_n(D) \cdot G(\tilde{f}, n) \right] \quad (4)$$

where $G(\tilde{f}, n)$ is a frequency response function describing the response gain of the melt pool to the n -th harmonic. When $n\tilde{f}$ falls within the range of melt pool natural frequencies, G attains a relatively large value; when $\tilde{f}$ is very large, $G \rightarrow 0$.

This energy-frequency matching model provides theoretical guidance for the selection of modulation parameters: in Regime I, a lower duty cycle can be selected to enhance harmonic energy and utilize low-frequency modulation to generate surface ripple structures; in Regime II, f should be tuned to approach a melt pool natural frequency while choosing a D that maximizes the amplitude of the corresponding harmonic, thereby exciting the strongest resonant response; in Regime III, the regulatory effect of D diminishes as f increases, and melt pool morphology is primarily governed by P_{avg} .

The proposed energy-frequency matching model is validated indirectly through its predictive capability for melt pool geometry. As demonstrated in Section 3.2 (Figure 4 and Table 1), the model captures the monotonic increase in depth-to-width aspect ratio with decreasing duty cycle under constant average power, with simulation results agreeing well with experimental measurements.

3. Results

3.1. Numerical model formulation and validation

To elucidate the mechanistic influence of rectangular-wave modulated laser parameters on melt pool morphology, a two-dimensional transient thermo-fluid coupled numerical model is developed. The underlying theory, governing equations, and validation are detailed below.

3.1.1. Governing equations and physical assumptions

The melt pool dynamics are described by the conservation laws for mass, momentum, and energy. The liquid metal is treated as an incompressible Newtonian fluid with laminar flow, which is valid for the moderate Reynolds numbers encountered in conduction-mode melting. The Volume-of-Fluid (VOF) method is employed to track the time-varying free surface. The set of coupled equations is expressed as: mass conservation is given by Eq 5:

$$\nabla \cdot u = 0 \quad (5)$$

momentum conservation is governed by the Navier–Stokes equation, shown in Eq 6:

$$\rho[\partial u/\partial t + (u \cdot \nabla)u] = -\nabla p + \mu \nabla^2 u + \rho g + f_{st} + f_{recoil} \quad (6)$$

where u is the velocity vector, ρ is the density, p is the pressure, μ is the dynamic viscosity, and g is the gravitational acceleration. The surface tension force f_{st} is modeled by the continuum surface force (CSF) formulation as $f_{st} = \gamma \kappa n \delta_s$, with γ as the temperature-dependent surface tension coefficient, κ as the local interface curvature, n as the interface unit normal, and δ_s as a delta function concentrated at the interface. The recoil pressure force due to evaporation (f_{recoil}) expressed as in Eq 7:

$$f_{recoil} = 0.54 p_0 \exp[(L_v/(RT_b))(1 - T_b/T)] n \delta_s \quad (7)$$

where p_0 is the ambient pressure, L_v is the latent heat of vaporization, R is the universal gas constant, T_b is the boiling temperature, and T is the local interface temperature.

Energy conservation energy conservation is written as in Eq 8:

$$\rho c_p [\partial T/\partial t + (u \cdot \nabla)T] = \nabla \cdot (k \nabla T) + S_{laser} - S_{vap} \quad (8)$$

where c_p is the specific heat, k is the thermal conductivity, and S_{laser} is the laser heat source. The evaporation-induced heat loss $S_{vap} = L_v \dot{m}_{vap} \delta_s$ accounts for the energy carried away by the vapor, with $\dot{m}_{vap}$ being the net evaporative mass flux derived from the recoil pressure. The laser beam is applied as a temporally modulated Gaussian surface heat flux on the evolving free surface, and its instantaneous power is expressed as in Eq 9:

$$q_{laser}(x, t) = (2P(t)/(\pi r_0^2)) \exp(-2|x - x_{center}|^2/r_0^2) \quad (9)$$

with $P(t)$ defined as in Eq 10:

$$P(t) = P_{avg} + \sum_{n=1}^N \frac{2P_{peak}}{n\pi} \sin(n\pi D) \cos(2\pi nft) \quad (10)$$

where r_0 is the spot radius. Eq 9 directly couples the analytically derived spectral characteristics into the numerical model.

The following physical assumptions are adopted, and their justifications are provided:

(1) The flow is laminar, as typical melt pool Reynolds numbers under conduction-mode conditions remain below the transition threshold.

(2) The 2D computational domain represents a transverse (y-z) cross-section of the melt track. This assumes translational invariance along the scanning direction and is appropriate for analyzing quasi-steady cross-sectional melt pool shapes at moderate scan speeds.

(3) Marangoni convection driven by surface tension gradients ($d\gamma/dT$) is fully incorporated, with $\gamma(T) = \gamma_0 + (d\gamma/dT)(T - T_m)$.

(4) Thermophysical properties (k, μ) are temperature-dependent, while density is treated as constant except in the buoyancy term using the Boussinesq approximation.

(5) Multiple reflections, vapor plume absorption, and plasma effects are neglected, confining the model to conduction-mode and incipient keyhole conditions where these phenomena are not dominant.

The reduction from a three-dimensional to a two-dimensional transverse cross-section model is justified by the quasi-steady-state assumption, where the temperature and flow field gradients along the scanning direction ($\partial/\partial x$) are significantly smaller than those in the transverse (y) and depth (z) directions. Under this assumption, $\partial/\partial x \approx 0$, and the 3D governing equations reduce to their 2D forms.

For example, the energy equation simplifies from the 3D form, shown in Eq 11:

$$\rho c_p \left(\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + S_{laser} - S_{vap} \quad (11)$$

to the 2D form, given by Eq 12:

$$\rho c_p \left(\frac{\partial T}{\partial t} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + S_{laser} - S_{vap} \quad (12)$$

This simplification has been widely validated for capturing cross-sectional melt pool geometries in LDED at moderate scanning speeds [26,27]. The 2D approach reduces computational cost while retaining the essential physics of heat transfer and fluid flow that govern the depth-to-width aspect ratio.

3.1.2. Boundary conditions and numerical implementation

Boundary conditions are specified as follows: the bottom and side walls of the substrate are held at a preheating temperature $T_0 = 300$ K with no-slip velocity conditions. The top surface is a free surface subject to a shear stress balance incorporating Marangoni stress ($\mu \partial u_t / \partial n = (d\gamma/dT) \nabla_s T$) and normal stress balance including recoil pressure, surface tension curvature pressure, and ambient pressure. The VOF advection equation for the volume fraction (F) is $\partial F / \partial t + \nabla \cdot (uF) = 0$, and the interface reconstruction is performed with a piecewise linear scheme to maintain sharpness.

The governing equations are discretized using the finite-difference method on a staggered grid. The SIMPLE algorithm is employed for pressure-velocity coupling. Transient terms are discretized with a first-order implicit scheme, and convective terms with a second-order upwind scheme for stability. The time step is adaptively controlled to maintain a maximum Courant number below 0.25, typically resulting in $\Delta t \approx 10^{-8}$ s. A grid independence study was carried out by refining the mesh from 4 to 1 μm in the melt pool region. A uniform grid size of 2 μm was selected, for which the predicted melt depth and width varied by less than 2% compared to the finer mesh.

3.1.3. Model limitations and deviation discussion

The present 2D model has several inherent limitations: it assumes translational invariance along the scanning direction, which is strictly valid only at moderate scanning speeds. It does not explicitly model coaxial powder feeding; the thermal effect of powder is accounted for via an effective absorption coefficient. It is confined to conduction-mode melting and does not capture transient keyhole formation

under low-duty-cycle high-peak-power conditions. Quantitative deviations between simulations and experiments are estimated at 10%–15% for melt width and 8%–12% for melt depth. The model is strictly applicable to conditions where peak power density remains below the keyhole initiation threshold. For $D \leq 0.2$ the simulated melt depth should be interpreted as a lower-bound estimate.

Two critical physical processes are omitted in the model:

(1) Coaxial powder mass feeding: the laser energy attenuation and powder-induced heat sink are not explicitly modeled. Instead, an effective absorption coefficient is used to account for the net energy coupled into the melt pool. This simplification is acceptable for moderate powder feed rates (≤ 12 g/min) but may introduce errors at higher feed rates.

(2) Transient keyhole formation: the model is confined to the conduction-mode regime and does not capture recoil-pressure-driven cavity formation that may occur at peak powers exceeding the keyhole threshold. Therefore, the model predictions are strictly applicable to conditions where peak power density remains below the keyhole initiation threshold. For $D \leq 0.2$ at $P_{peak} = 1000$ W, the instantaneous intensity may approach this threshold, and the simulated melt depth should be interpreted as a lower-bound estimate.

3.2. Regulatory mechanism of duty cycle on melt pool morphology

Given that the formation of a keyhole at excessively high power would introduce substantial complexity into the numerical model, this model is simplified to consider only the conduction-mode welding regime at moderate power levels.

Under fixed average power $P_{avg} = 200$ W and $f = 500$ Hz, the influence of the duty cycle on the melt pool cross-sectional morphology is systematically examined. Figure 4 presents the simulated cross-sectional temperature fields and melt pool boundary evolution for single-track deposition over a duty cycle range from $D = 0.2$ to $D = 1.0$ (continuous wave).

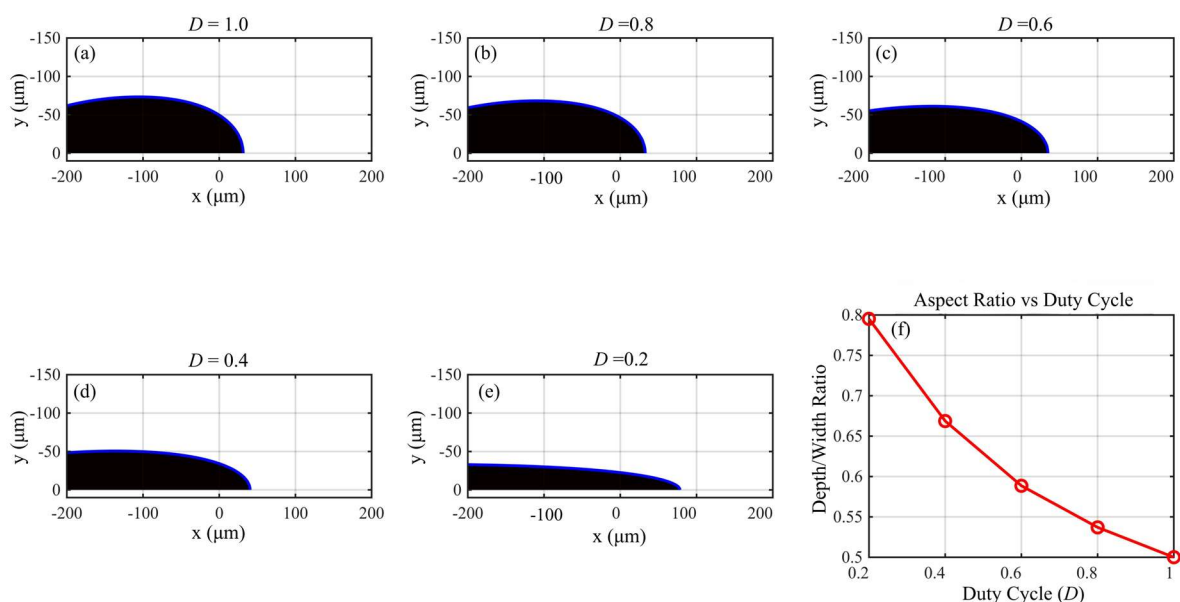


Figure 4. Melt pool cross-sectional morphology at varying duty cycles: (a–e) correspond to cross-sectional temperature fields and melt pool boundaries at $D = 1.0$, 0.8 , 0.6 , 0.4 , and 0.2 , respectively; and (f) variation of the depth-to-width aspect ratio with duty cycle.

The five cross-sectional subfigures in Figure 4 illustrate the morphological evolution from continuous-wave operation ($D = 1.0$) to low-duty-cycle modulation ($D = 0.2$). The temperature field is rendered as a heat map, with the solid blue contour delineating the melting point isotherm ($T = 1600$ K), i.e., the melt pool boundary. The following systematic changes induced by decreasing the duty cycle are discernible:

Monotonic increase in melt depth: at $D = 1.0$, the melt depth is approximately $78\text{ }\mu\text{m}$, and the melt pool exhibits a characteristic shallow, semi-elliptical shape. At $D = 0.2$, the melt depth increases to $108\text{ }\mu\text{m}$, and the melt pool morphology transitions toward a “U”-shape or even an incipient keyhole-like profile. The increased melt depth is a direct consequence of the elevated peak power, which enhances the evaporative recoil pressure.

Slight reduction in melt width: the melt width decreases from $156\text{ }\mu\text{m}$ at $D = 1.0$ to $136\text{ }\mu\text{m}$ at $D = 0.2$. This reduction is attributed to the interruption of heat input during the pulse-off intervals, which suppresses lateral thermal diffusion and effectively constrains the transverse expansion of the molten region.

Significant enhancement of the depth-to-width aspect ratio: the Figure 4f summarizes the variation of the depth-to-width aspect ratio d/w with the duty cycle. The curve exhibits a monotonic decreasing trend; a smaller duty cycle yields a larger aspect ratio. The aspect ratio at $D = 0.2$ (0.80) represents a 60% increase over that of the continuous-wave case (0.50).

Under the constraint of constant average power, the duty cycle modulates the competitive balance between recoil-pressure-driven penetration in the depth direction and lateral thermal diffusion by altering the peak power and the inter-pulse cooling duration. This mechanism enables precise control over the cross-sectional geometry of the melt pool and provides a direct basis for selecting process parameters tailored to specific penetration depth requirements.

Quantitative statistics of the melt pool geometric parameters are provided in Table 1.

Table 1. Melt pool geometric parameters at different duty cycles.

D	P_{peak} (W)	Melt depth (d , μm)	Melt width (w , μm)	Aspect ratio (d/w)
1.0 (CW)	200	78.2	156.4	0.50
0.8	250	82.6	153.8	0.54
0.6	333	88.4	150.2	0.59
0.4	500	96.7	144.6	0.67
0.2	1000	108.3	136.2	0.80

The results demonstrate that, under constant average power, as the duty cycle decreases (i.e., as the peak power correspondingly increases), the melt depth increases monotonically from 78.2 to $108.3\text{ }\mu\text{m}$, while the melt width decreases from 156.4 to $136.2\text{ }\mu\text{m}$. Consequently, the depth-to-width aspect ratio rises substantially from 0.50 for continuous-wave operation to 0.80 at $D = 0.2$. The physical origin of this morphological transition can be attributed to the dual regulatory effect of the duty cycle on the thermo-fluid dynamics of the melt pool:

(1) Foundational dimensional scaling governed by equivalent average power: the quasi-steady-state thermal balance of the melt pool is primarily determined by the DC component P_{avg} . Consequently, the baseline heat input magnitude remains comparable across D values, and the macroscopic dimensions

remain on the same order of magnitude. This explains why the melt pool size does not undergo an order-of-magnitude change.

(2) Instantaneous recoil pressure enhancement induced by peak power: under low-duty-cycle conditions, the instantaneous power density during the laser pulse is drastically elevated, leading to significantly enhanced evaporative recoil pressure and steeper temperature gradients. These factors drive the melt pool to extend deeper into the substrate. Conversely, during the pulse-off intervals, the cessation of heat input enables the molten region to undergo partial cooling and solidification, thereby inhibiting excessive lateral growth that would otherwise result from continued thermal diffusion. The synergistic action of these two effects causes the depth-to-width aspect ratio to increase systematically as D decreases.

This finding is in excellent agreement with the conclusions drawn from the Fourier analysis presented in Section 2.3: under the constraint of fixed P_{avg} , a reduction in D is equivalent to systematically enhancing the relative intensity of all harmonic components, and the increased energy content in the low-frequency harmonics promotes more efficient energy deposition in the depth direction of the melt pool.

3.3. Influence of modulation frequency on melt pool surface morphology and flow characteristics

With the duty cycle fixed at $D = 0.5$, $P_{peak} = 400$ W, and scanning speed (v) = 10 mm/s, the modulation frequency is varied over the range of 100 to 2000 Hz. The simulated melt pool free surface morphologies corresponding to these conditions are presented in Figure 5.

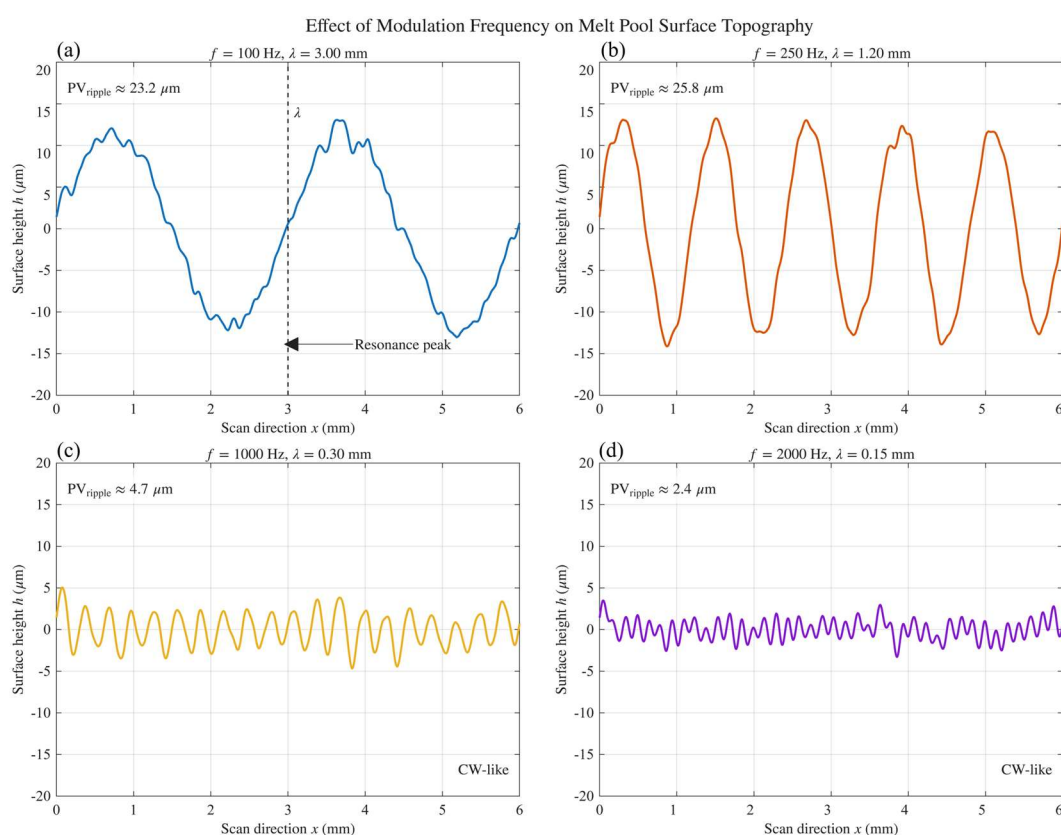


Figure 5. Influence of modulation frequency on melt pool free surface morphology: (a) 100 Hz; (b) 250 Hz; (c) 1000 Hz; and (d) 2000 Hz.

In the low-frequency regime ($f = 100$ Hz), the melt pool surface exhibits a defined spatially periodic undulating structure. The spatial wavelength is $\lambda = v/f = 3000$ μm , which is in perfect agreement with theoretical prediction. This periodic morphology arises from the synchronous coupling between the “on-off” cadence of the laser pulses and the motion of the solidification front: during each pulse cycle, the melt pool undergoes a complete expansion-contraction cycle, leaving a corresponding ripple imprint along the scan path.

As the frequency increases to approximately 250 Hz ($\lambda = 1200$ μm), the amplitude of the surface ripples is significantly amplified, with the peak-to-valley height difference reaching approximately 25 μm —substantially larger than the ~ 10 μm observed at 100 Hz. This amplitude amplification indicates a resonant coupling between the modulation frequency and a characteristic frequency of the internal flow within the melt pool. As discussed in Section 2.5, the odd harmonic components inherent to rectangular-wave modulated laser irradiation can, at specific frequencies, enhance energy transfer to the intrinsic oscillatory modes of Marangoni convection, thereby inducing the melt pool into a stable, periodic pulsatile state.

When the frequency is further increased beyond 1000 Hz ($\lambda \leq 300$ μm), the periodic surface structures tend to vanish, and the melt pool surface morphology gradually approaches the random undulations characteristic of equivalent continuous-wave conditions. The attenuation of the melt pool response in the high-frequency regime is attributable to the low-pass filtering effect of thermal inertia on the energy pulsations. As deduced from the thermal response transfer function analysis in Section 2.4, when the modulation frequency is significantly higher than $1/(2\pi\tau_{\text{th}})$, the melt pool temperature exhibits negligible response to the AC harmonic components, and its macroscopic thermal state is governed solely by the average power P_{avg} . Consequently, the efficacy of high-frequency modulation in regulating melt pool morphology diminishes markedly.

Figure 6 further presents the amplitude-frequency response characteristics and phase lag curves of the melt pool subjected to modulated laser irradiation at various frequencies. Within the transitional range of 100–500 Hz, the melt pool response exhibits a distinct resonance amplification peak (peak frequency at approximately 250 Hz), while the phase lag increases monotonically with increasing frequency. The resonance-enhanced melt pool fluctuation observed at $f \approx 250$ Hz promotes several detrimental phenomena: (1) gas bubble entrapment: vigorous free-surface oscillation entrains shielding gas into the melt pool; rapid solidification traps these bubbles, resulting in porosity. (2) Surface rippling: periodic expansion-contraction at resonance produces peak-to-valley heights exceeding 25 μm (Figure 5b), leading to uneven layer thickness in multi-layer depositions. (3) Spatter generation: intensified recoil pressure and surface oscillations eject molten droplets, causing material loss and contamination.

This frequency response characteristic provides a quantitative basis for the optimal selection of modulation frequency: when the objective is to impart a pronounced periodic structure onto the deposited track surface, the modulation frequency should be set in the vicinity of the resonance peak; conversely, when the goal is solely to regulate the melt pool depth-to-width ratio without introducing surface ripples, parameter combinations within either the high-frequency regime ($f > 1$ kHz) or the quasi-static regime ($f < 100$ Hz) are preferable.

Figure 6a illustrates the amplitude-frequency response characteristics of the melt pool system to modulated laser irradiation in semi-logarithmic coordinates. The black dashed curve represents the theoretical response of a first-order thermal system, $|H(f)| = 1/\sqrt{1+(2\pi f\tau_{\text{th}})^2}$, reflecting the attenuation of high-frequency components by thermal inertia. The solid blue curve depicts the effective response incorporating the melt pool resonance enhancement effect, revealing a distinct, protruding resonance

peak near $f \approx 250$ Hz (with an amplitude enhancement of approximately 30%). The two vertical dashed lines in red and green denote the characteristic frequencies.

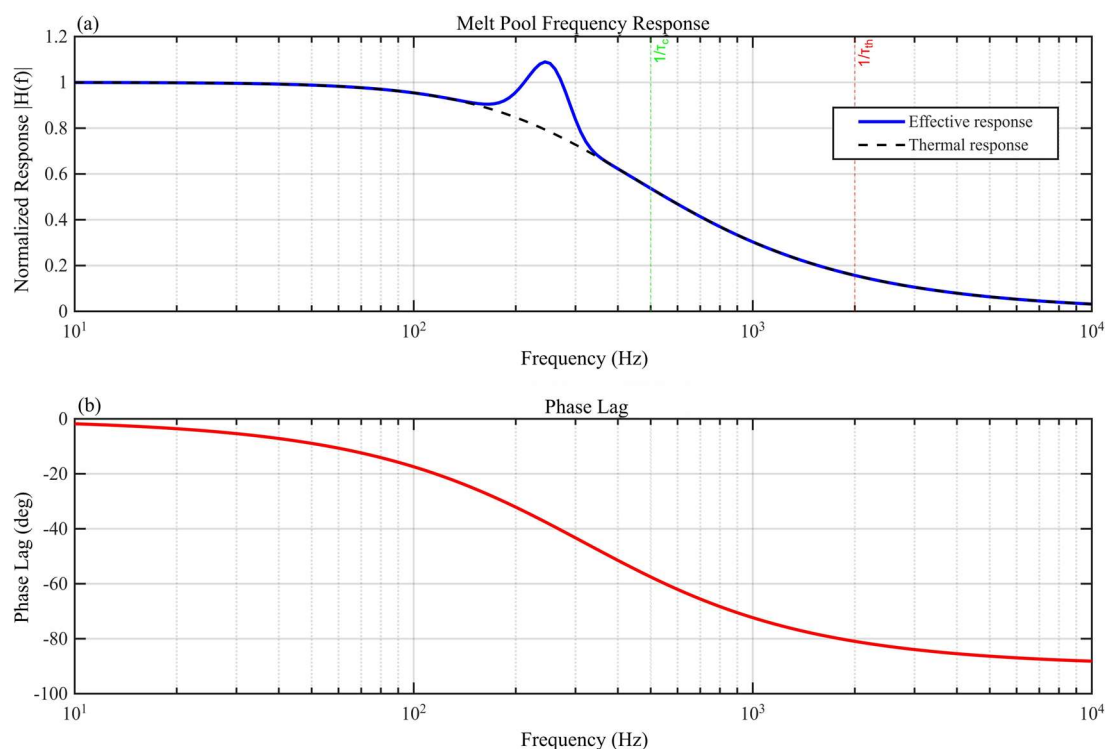


Figure 6. Melt pool frequency response and phase lag: (a) normalized amplitude-frequency response curve of the melt pool to modulated laser irradiation; and (b) phase lag as a function of frequency.

Figure 6b presents the phase lag of the melt pool temperature response as a function of frequency. In the low-frequency region, the phase lag is relatively small (approximately -10° at $f = 10$ Hz), indicating that the melt pool can follow the modulation signal almost synchronously. As the frequency increases, the phase lag grows monotonically, reaching approximately -70° at 1 kHz. Such a significant phase lag implies a substantial temporal mismatch between the expansion-contraction rhythm of the melt pool and the laser pulses. This constitutes another key reason for the disappearance of periodic surface features in the high-frequency regime: even if temperature fluctuations persist, their phase relationship with the laser pulses is no longer capable of driving a well-ordered surface solidification morphology.

From a system dynamics perspective, the regulatory mechanism of modulation frequency on melt pool morphology can be quantitatively interpreted as follows: in the low-frequency quasi-static regime, the melt pool can respond adequately, and its morphology is dominated by thermal equilibrium; in the intermediate-frequency transitional regime, the resonance enhancement effect yields the maximum modulation depth for the surface topography; and in the high-frequency regime, the combined effects of amplitude attenuation and phase lag render modulation ineffective.

4. Discussion

4.1. Experimental system configuration and process parameter design

To systematically validate the mapping relationships between modulation parameters and melt pool morphology derived from numerical simulations, and to quantitatively assess the capability of rectangular-wave modulated laser processing to precisely control melt pool geometric characteristics and surface quality, single-track deposition experiments are conducted on a custom-built coaxial powder-fed laser directed energy deposition (DED) platform, as schematically illustrated in Figure 7. By comparing the morphological features of deposited tracks produced under CW and modulated laser conditions across process parameter combinations, the optimization mechanisms by which the modulation duty cycle governs the temporal distribution of heat input and the solidification behavior of the melt pool are elucidated.

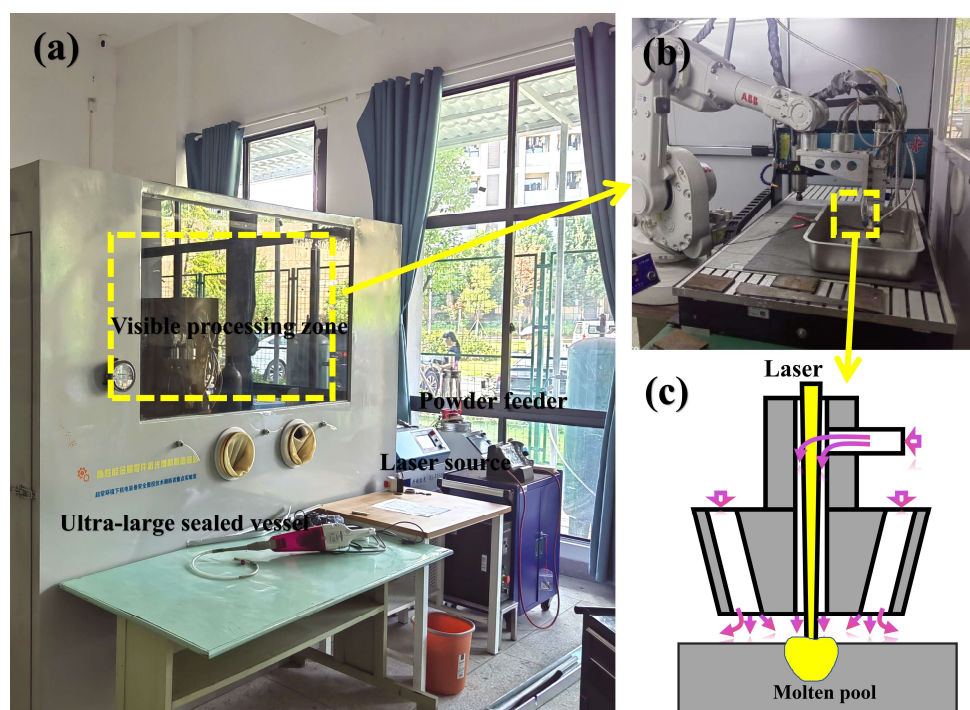


Figure 7. Custom-built coaxial powder-fed modulated laser processing experimental system: (a) overall view of the equipment; (b) laser processing robot; and (c) schematic diagram of laser processing.

The experimental system, depicted in Figure 7, employs a proprietary coaxial powder-fed modulated laser processing apparatus developed at the University of South China. The laser source is a CW1500 quasi-continuous-wave fiber laser (central wavelength: 1060 nm; maximum output power: 1500 W). The modulation waveform is generated by an arbitrary waveform generator (AWG) and fed into the laser driver module via the analog control interface. After passing through collimating optics and a focusing lens assembly, the laser beam impinges perpendicularly onto the surface of a Q235 low-carbon steel substrate, with the focused spot diameter calibrated to 100 μm . Motion control is executed by a five-axis robotic platform, with the scanning speed set within the range of 6–20 mm/s.

according to process requirements. High-purity argon shielding gas is supplied throughout the deposition process at a constant flow rate of 15 L/min to suppress high-temperature oxidation of the melt pool. The powder material is 304 with a particle size distribution of 45–105 μm . The powder feed rate is maintained at 8.1 g/min for all experiments.

To encompass representative continuous-wave process windows and enable direct comparison with modulated laser processing, six distinct sets of process conditions are established, as detailed in Table 2. Groups a–c serve as continuous-wave reference experiments, corresponding to low-power low-speed, nominal-power nominal-speed, and high-power nominal-speed operating conditions, respectively. Groups d–f constitute the modulated laser experiments, wherein the peak power is maintained at $P_{peak} = 810$ W and the modulation frequency at $f = 1000$ Hz, while the duty cycle is set to 0.2, 0.5, and 0.8, respectively. The scanning speed and powder feed rate are kept constant across all six groups to eliminate interference from non-target process variables on melt pool morphology.

Table 2. Experimental groups and corresponding process parameters.

Group	Target characteristic	P_{peak} (W)	D	f (Hz)	v (mm/s)
a	CW—Low speed, lower power	510	-	-	8
b	CW—Nominal speed, nominal power	600	-	-	10
c	CW—Nominal speed, higher power	810	-	-	10
d	Modulated—Low duty cycle	810	0.2	1000	10
e	Modulated—Medium duty cycle	810	0.5	1000	10
f	Modulated—High duty cycle	810	0.8	1000	10

Group a employs a scanning speed of 8 mm/s (0.48 m/min) to maintain a comparable linear heat input to Group b under the lower peak power condition (510 W vs. 600 W). The line energy inputs are $510 \text{ W}/(8 \text{ mm/s}) = 63.75 \text{ J/mm}$ for Group a and $600 \text{ W}/(10 \text{ mm/s}) = 60 \text{ J/mm}$ for Group b, ensuring that the comparison between CW Groups a and b is conducted under approximately equal energy densities.

4.2. Analysis of experimental results and discussion on the morphology control capability of modulation parameters

The macroscopic surface morphologies of the single-track deposited layers obtained under the six process conditions are presented in Figure 8. The morphological differences between tracks produced by continuous-wave and modulated laser processing reflect the regulatory effect of the modulation duty cycle on the thermal history and solidification behavior of the melt pool, thereby corroborating the duty cycle-aspect ratio mapping relationships revealed by the numerical simulations in Section 3.

(1) Limitations of continuous-wave laser processing

Under continuous-wave laser operation, the surface quality of the deposited track exhibits pronounced sensitivity to the combination of laser power and scanning speed. The linear energy input for the condition shown in Figure 8a (510 W, 8 mm/s) is comparable to that of Figure 8b (600 W, 10 mm/s). However, due to a mismatch between the rate of heat accumulation and the heat dissipation conditions, the track surface in Figure 8a displays noticeable undulations and irregular edges, and the surface finish is markedly inferior to that in Figure 8b. When the peak power is elevated to 810 W while maintaining the nominal scanning speed (Figure 8c), the excessive continuous energy input induces severe

overheating of the melt pool, exacerbating melt oxidation and resulting in extensive surface blackening and burning. These observations indicate that the process window for continuous-wave laser deposition is intrinsically narrow. Achieving a specific bead width and surface quality demands stringent, simultaneous optimization of laser power and scanning speed. Moreover, metallurgical defects stemming from thermal overload are virtually unavoidable under high-power CW conditions.

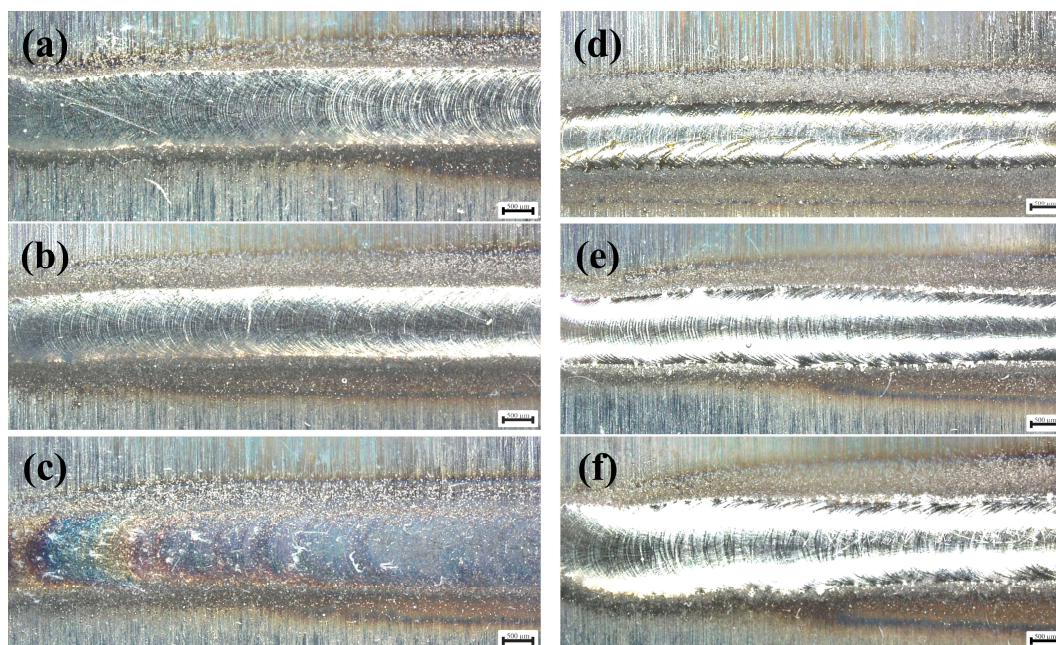


Figure 8. Surface morphologies of single-track melt pools corresponding to the process parameters listed in Table 2: (a–c): continuous-wave laser under three power conditions; and (d–f) modulated laser under three duty cycle conditions.

(2) Optimized regulation of melt pool morphology via modulated laser processing

In stark contrast, the introduction of duty cycle modulation under identical peak power conditions (810 W) fundamentally improves the temporal distribution of heat input to the melt pool. The periodic on-off switching mechanism inherent to modulated laser operation imposes forced cooling intervals, thereby effectively suppressing time-averaged heat accumulation while providing the high instantaneous power density required for complete powder melting. This control philosophy aligns directly with the numerical findings presented in Section 3.2: a reduction in the duty cycle (which corresponds to an increase in peak power under constant average power) enhances evaporative recoil pressure during the pulse-on period, driving increased melt depth, while lateral thermal diffusion is restricted during the pulse-off interval, thereby curbing excessive melt width expansion.

The experimental morphologies provide compelling validation of the effectiveness of this regulatory mechanism. Under the low-duty-cycle condition of $D = 0.2$ (Figure 8d), even though the average power is merely 20% of the equivalent CW peak power, the deposited track exhibits continuous, fully dense formation quality with a narrow bead width and well-defined, regular edges, devoid of any lack-of-fusion or balling defects. This demonstrates that the high instantaneous energy density during the pulse-on period ensures complete melting and adequate wetting and spreading of the metal powder, while the brief heat input duration and the subsequent cooling interval prevent excessive melt pool expansion and overheating-induced oxidation.

Increasing the duty cycle to 0.5 (Figure 8e) prolongs the energy injection duration per period and extends the time the melt pool remains in the liquid state, leading to a corresponding increase in bead width. Nevertheless, the surface retains a smooth, uniform metallic luster, exhibiting none of the thermal overload phenomena observed in the CW case of Figure 8c. Even when the duty cycle is further increased to 0.8 (Figure 8f), resulting in additional bead widening, the track surface still shows no signs of significant oxidation or blackening, and the overall deposition quality remains substantially superior to that achieved with CW processing at the same peak power.

This experimental observation can be rationalized from the perspective of the frequency-domain characteristics of the thermal response. As indicated by the frequency response analysis in Section 3.3, a modulation frequency of 1000 Hz falls within the high-frequency attenuation regime dominated by the thermal inertia of the melt pool. In this regime, the temperature response is governed primarily by the average power, as the ripple amplitude of the pulses has been largely filtered out. Consequently, despite the high peak power of 810 W, the baseline quasi-steady thermal equilibrium temperature of the melt pool is dictated by $P_{avg} = P_{peak} \times D$, which is substantially lower than the superheat experienced under CW conditions. Adjusting the duty cycle thus effectively modulates the time-averaged heat input level, enabling continuous and controllable tuning of the bead width at a fixed scanning speed while minimizing the risk of oxidation associated with peak thermal shock.

In summary, the experimental findings conclusively demonstrate that the modulated laser strategy breaks the rigid coupling between laser power and net heat input inherent to continuous-wave processing. By structurally distributing energy injection in the temporal domain through the duty cycle parameter, this approach enables independent and precise control over the geometric dimensions and the surface quality of the deposited track across a significantly expanded process window. These experimental observations form a closed-loop validation with the duty cycle-aspect ratio mapping relationships and frequency response characteristics unveiled by the numerical model in Section 3, thereby providing a robust experimental foundation for the selection of modulated laser parameters aimed at the synergistic optimization of deposition quality and geometric precision.

5. Conclusions

Through a combined numerical and experimental investigation, this work elucidates the fundamental mechanisms governing melt pool morphology under rectangular-wave modulated laser irradiation in directed energy deposition. The principal conclusions are summarized as follows:

(1) Duty cycle decouples heat input from peak power. Modulated laser processing reduces time-averaged heat input via duty cycle control even at high peak power. The periodic cooling intervals inherent to the off-cycle effectively suppress heat accumulation and surface oxidation, overcoming the intrinsic power-thermal damage coupling limitation of CW processes.

(2) Duty cycle quantitatively regulates melt pool aspect ratio. Under constant average power constraints, decreasing the duty cycle leads to a monotonic increase in melt depth and a concurrent reduction in melt width, resulting in a 60% enhancement of the depth-to-width aspect ratio. Experimental results confirm continuous tunability of bead width across a duty cycle range of 0.2 to 0.8 while preserving stable surface quality.

(3) Frequency response delineates distinct morphology control regimes. Low-frequency operation produces surface ripples synchronized with the pulse cadence. An intermediate frequency regime exhibits a resonance amplification peak (approximately 250 Hz) that maximizes ripple amplitude. In

the high-frequency regime (>1 kHz), the thermal low-pass filtering effect dominates, rendering the melt pool response effectively equivalent to that of a CW laser.

(4) Modulated processing significantly enhances process robustness. In contrast to the narrow defect-free processing window typical of CW laser operation, the modulated approach yields smooth and dense bead morphologies across a broad range of duty cycles. This provides a reliable parameter design basis for the synergistic optimization of high deposition quality and geometric precision.

These findings establish a robust theoretical and experimental foundation for parameter selection and closed-loop control strategies in modulated laser directed energy deposition.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

The work presented here was performed in collaboration among all authors. L.S.: designed, analyzed, and wrote the paper. W.C.: provided and analyzed the experimental data. X.W.: guided the full text. Q.L.: conceived and designed the research. All authors contributed to and approved the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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