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Formation of Inward Tilt of Vertical Outer Walls in Laser Solid Forming Parts and Post-Print Model

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Abstract

Bulk specimens with progressively increasing layer counts were fabricated using laser solid forming, and the causes for the inward inclination of part vertical outer walls were analyzed. Based on a method for reconstructing single-track cladding cross-sectional profiles using powder accumulation height, an analytical model describing the layer-by-layer evolution of vertical outer wall profiles was constructed. This model was employed to reconstruct vertical outer wall profiles under varying single-track cladding aspect ratios and effective laser beam interaction zones, and the effects of these two parameters were investigated. The results demonstrate that during the layer-by-layer buildup process, previously deposited cladding layers influence the formation of subsequent layers; due to the arc-shaped cross-section of single-track claddings, the boundary melt pool formed at the intersection with the laser beam contracts toward the part interior, thereby inducing inward contraction of boundary single-track claddings and inward inclination of vertical outer walls; as deposition height increases, this inclination diminishes and gradually vanishes. With a constant initial single-track cladding width, reducing the effective laser beam interaction zone facilitates vertical alignment of the outer wall but increases its deviation; the influence of single-track cladding aspect ratio on the outer wall is essentially negligible.

Full Text

Formation and Modeling of Inward Inclination of Vertical Outside Walls in Laser Solid Forming

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Abstract

The vertical outside wall in laser solid forming (LSF) is prone to incline inward, which deteriorates dimensional precision and process stability. To address this problem, samples with varying numbers of deposited layers were prepared to investigate the evolution of boundary single-track clad shape and the formation mechanism of inward-inclining vertical walls. Based on a method for reconstructing the cross-section profile of single-track clads using powder accumulation height, an analytical model was developed to describe the evolution of vertical outside walls during multilayer superimposition. Using this model, vertical outside walls were reconstructed under different width-to-height ratios of single-track clads and critical defocus distances to analyze their respective influences.

Results indicate that deposited clads significantly influence the formation of subsequent clads during layer-by-layer superimposition. Due to the arc-shaped cross-section profile of single-track clads, the boundary molten pool intersecting with the laser beam shrinks inward, causing the boundary single-track clad edges to contract and the vertical outside wall to incline inward. However, this inclination decreases with increasing deposition height and eventually disappears. For an initial single-track clad with fixed width, reducing the critical defocus distance helps the outside wall become more vertical but increases its dimensional offset. The width-to-height ratio of single-track clads has almost no effect on the outside wall profile.

Keywords: laser solid forming, vertical outside wall, inward inclination, analytical model

1. Introduction

Laser solid forming (LSF) integrates the freeform fabrication capability of rapid prototyping with the high-performance cladding characteristics of synchronous powder feeding laser cladding, representing an advanced digital additive manufacturing technology for metals [?]. LSF enables rapid fabrication and repair of high-performance metal components and has found applications in aerospace, energy, and power generation industries [?]. For LSF technology, ensuring geometric accuracy and process stability represents a critical objective. LSF constructs two-dimensional planes through lateral overlapping of single-track clads, which are then stacked layer-by-layer to form three-dimensional components. Consequently, the formation of single-track clads and their inter-track and inter-layer overlapping fundamentally affect forming precision. Numerous studies have investigated the effects of process parameters—including power, scanning speed, powder feed rate, and spot size—on single-track clad shape [?] and surface flatness [?], as well as the influence of overlap rate on surface quality [?, ?].

During layer-by-layer superimposition, boundary single-track clads constitute the component's outside wall, whose profile accuracy directly reflects the geometric precision of the part. Deviation of the outside wall profile from the intended shape not only reduces dimensional accuracy but can also cause process instability and surface quality deterioration [?]. Depending on the deposition path, outside wall formation in LSF can be categorized into three types: (1) composed of single-track clad end faces; (2) composed of longitudinal side surfaces of single-track clads; and (3) alternating combinations of end faces and longitudinal side surfaces. Bi et al. [?] and Tan et al. [?] reported and analyzed the collapse of single-track clad ends and the resulting inward inclination of the first wall type. Zhu et al. [?] studied the effects of laser beam and powder stream defocusing on top surface flatness and process stability. However, in practical LSF processes, the second wall type—composed of longitudinal side surfaces of clads—frequently exhibits inward inclination, particularly pronounced in steel components, yet the underlying mechanisms remain unreported.

This work investigates the inward inclination phenomenon of vertical outside walls composed of longitudinal side surfaces of single-track clads in LSF. The fundamental formation process and mechanism of inward inclination are analyzed. Based on a method for reconstructing single-track clad cross-section profiles using powder accumulation height, a theoretical model describing the evolution of vertical outside walls is established. The influences of single-track clad width-to-height ratio and laser beam effective range on wall evolution are discussed.

2. Experimental Methods

To investigate the formation process of vertical outside walls, rectangular cross-section samples with progressively increasing layer numbers were designed. To reveal the complete contour of boundary clads, after depositing the predetermined number of layers, the laser was elevated by one additional layer and an extra track was deposited at the first track position, as shown in [Figure 1: see original paper].

Experiments were conducted on a self-developed LSF-VI system at the State Key Laboratory of Solidification Processing, Northwestern Polytechnical University. The system comprises a CO₂ continuous laser, a five-axis four-linkage CNC worktable, a high-precision powder feeder, and an atmosphere-controlled glove box. The deposition material was 2Cr13 stainless steel powder prepared by rotating electrode process, with particle sizes of 45–160 μm and chemical composition (wt.%): C 0.24, Cr 12.47, Mn 0.6, Si 0.4, Ni 0.32, Fe balance. Substrates were 2Cr13 stainless steel plates approximately 8 mm thick. Prior to experiments, powder was dried at 120 °C in a vacuum oven to remove adsorbed moisture. Substrate surfaces were ground to remove oxide layers and cleaned with acetone. Process parameters were: laser power 2.8 kW, scanning speed

600 mm/min, spot diameter ~2 mm, powder feed rate 7.38 g/min, overlap rate 45%, vertical increment 0.2 mm, using a unidirectional scanning path. Experiments were performed under Ar protective atmosphere with O₂ partial pressure controlled during processing.

After deposition, samples were sectioned perpendicular to the laser scanning direction. Cross-sections were mounted, ground, polished, and electrolytically etched in 10% (mass fraction) ammonium persulfate aqueous solution at 6 V for 120 s. The outside wall and boundary single-track clad morphologies were examined using an OLS4000 laser confocal microscope.

3. Results and Analysis

[Figure 2: see original paper] shows cross-sectional morphologies of LSF samples with 1, 7, 15, and 36 layers. The outside wall did not form the intended vertical shape but inclined inward, making the cross-section approximately trapezoidal. The inward inclination gradually decreased with increasing deposition height, showing a tendency toward verticality. Since the outside wall composed of longitudinal side surfaces forms through layer-by-layer superimposition of boundary single-track clads, its shape is determined by the geometry of these boundary clads. Based on metallographic features reflecting solid/liquid and solid/gas interfaces, the cross-section profiles of boundary clads can be traced, as shown in [FIGURE:2b-d]. However, interlayer superimposition allows only the top clad profile to be fully revealed. As samples were prepared under identical parameters, the shape of the additionally deposited top track reflects the shape of boundary clads at corresponding layers during forming. Measured profiles of these top boundary clads are presented in [Figure 3: see original paper], where the outer edge of the initial single-track clad is defined as the coordinate origin, and the x-coordinates of left edges represent their horizontal offset from the origin.

[Figure 2: see original paper] and [Figure 3: see original paper] demonstrate that boundary single-track clad shapes evolve progressively with deposition height: (1) outer edges gradually shrink inward; (2) cross-section profiles deviate from symmetry about the laser beam center axis, with inner edges rising relative to outer edges and expanding inward; (3) the slope of the outer half-profile (from outside to inside) gradually increases, making the outer half of boundary clads steeper. This progressive inward contraction of outer edges creates the inward-inclining outside wall during layer stacking. The mechanism behind this gradual contraction is analyzed below.

Single-track clad formation involves powder accumulation, melting, and solidification in the molten pool, with shape determined by substrate geometry, powder accumulation, and deformation. In LSF, when process parameters are fixed, the laser energy distribution and powder concentration distribution are constant, but the substrate—the carrier for cladding—does not remain planar. During

track overlapping and layer stacking, deposited clads become substrates for subsequent clads. Substrate shape changes alter molten pool geometry, affecting powder accumulation and deformation, thereby changing clad shape and ultimately influencing component geometry.

For boundary clads, the influence of previously deposited material on subsequent clads during superimposition is illustrated in [Figure 4: see original paper]. First, single-track clads possess curved outer surfaces (determined by powder accumulation height distribution in the molten pool) that rise gradually from outside to inside ([Figure 4a: see original paper]). When serving as a substrate, the current clad shape is determined by this substrate geometry plus powder accumulation height, so the curved substrate features alter the current clad geometry. Second, molten pool shape changes. Ignoring heat transfer effects, the molten pool can be considered as the intersection line between the laser beam (within its effective range where critical energy density for melting is met) and the substrate. For the initial clad on a planar substrate, the molten pool is circular. Typically, the energy density at the substrate exceeds the minimum required for melting, so melting can occur within a certain range below the substrate surface. Due to the curved clad surface, the actual molten pool shape at increased deposition heights appears as shown in [Figure 4a: see original paper].

Assuming ideal track and layer overlapping (i.e., minimal inter-track unevenness approximated as planar, with layer increment equal to clad height), the actual molten pool projection is shown by the solid line in [Figure 4b: see original paper]. [Figure 4a: see original paper] and [Figure 4b: see original paper] reveal that even with ideal overlapping, the outer half of the molten pool (outside the laser beam center axis) undergoes changes compared to the initial planar substrate case: (1) the outer edge of the molten pool (intersection of the critical-energy-density spot with the substrate outer surface) shrinks inward relative to the boundary clad serving as substrate; (2) the outer edge acquires a finite length rather than being zero; (3) with large laser beam divergence angle, the molten pool projection diverges in a “trumpet” shape from inside to outside, approaching but always exceeding the initial pool size as the divergence angle decreases.

These molten pool changes cause corresponding alterations in boundary clad shape: (1) inward contraction of outer edges causes the outside wall to incline inward as shown in [Figure 2: see original paper]; (2) the finite length of the molten pool outer edge creates a “step” where powder accumulation height drops to zero beyond the edge, making the boundary clad steeper at its outer edge (though in reality, heat transfer and deformation smooth this step); (3) ignoring pre-solidification deformation, when the molten pool projection approaches the initial case, powder accumulation height within the current pool becomes consistent with the initial condition, making the current boundary clad profile an integer multiple superposition of the initial profile. Since the increment is typically set to the initial clad height (maximum height of the initial cross-section), the slope of the outer half-profile increases ([FIGURE:4c, case I]). As the molten

pool projection enlarges, powder accumulation height exceeds the initial value, gradually reducing the profile slope ([FIGURE:4c, case II]). When the projection becomes trumpet-shaped, all points in the outer half-pool approach the central length, yielding powder accumulation heights near the initial clad height and making the outer half-profile approach the initial shape ([FIGURE:4c, case III]). With further trumpet-shaped divergence, powder accumulation heights exceed the initial clad height, reducing the slope below the initial case ([FIGURE:4c, case IV]). When powder accumulation height far exceeds the initial clad height, the outer half-profile may even rise from inside to outside, opposite to the initial case ([FIGURE:4c, case V]). Notably, corresponding to cases I-V, the “step” at the outer edge gradually increases, enhancing outward flow deformation of the boundary clad in its liquid stage and promoting verticality or even outward expansion of the outside wall [?]. As shown in [Figure 4d: see original paper], a sample’s outside wall remains nearly vertical in the middle-lower section while expanding outward at the top.

Based on this analysis, during superimposition, the curved clad surface as substrate causes inward shrinkage of the boundary molten pool, leading to progressive inward contraction of boundary clads. In practice, laser beams have very small divergence angles, so boundary molten pool projections approach the initial case. Combined with the finite length of the molten pool outer edge and abrupt drop in powder accumulation beyond it, these factors increase the slope of the outer half-profile. Given a fixed increment for the critical laser spot, the inward shrinkage of the molten pool outer edge decreases layer by layer, causing the outside wall inclination to diminish and approach verticality.

4. Model Development

Based on the above analysis, an analytical model was established to describe the evolution of vertical outside wall profiles by constructing the outer half-profiles of boundary single-track clads layer-by-layer using the powder accumulation height method [?]. For model simplification, the following assumptions were made:

1. The substrate is located below the laser beam focal point during forming.
2. Linear beam approximation: the laser beam below the focal point is treated as a cone with its apex at the focal point, with uniform energy density distribution within the spot.
3. In LSF, molten pool size is typically comparable to laser beam diameter; thus, heat transfer effects are neglected and the molten pool shape is defined as the intersection line between the laser beam within its effective range and the substrate.
4. Powder concentration distribution within the powder stream is assumed uniform, with all powder entering the molten pool being captured and melted.

5. Ideal track overlapping is assumed, making the clad surface planar except for the outer half of boundary tracks.
6. The increment along the deposition direction equals the initial clad layer height.
7. Liquid-phase flow deformation of clads is neglected.

As shown in [Figure 5: see original paper], a coordinate system is established with the initial substrate surface as the x-y plane, the intersection point of the laser beam center axis at the start position for the first clad as the origin, and the scanning direction as the y-axis. Let the laser spot radius on the substrate plane (i.e., the width of the initial single-track clad) be r , the half-divergence angle of the laser beam be β , and the distance from the maximum forming spot to the substrate plane within the effective range be H (larger H indicates greater forming range). Under linear beam approximation, the laser beam surface geometry is expressed as:

$$y_{Li} - y^* = \cot \beta \cdot \sqrt{(x_{Li} - x^*)^2 + (z_{Li} - z^*)^2}$$

where x_{Li}, y_{Li}, z_{Li} are coordinates of the i th layer laser beam surface, x^*, y^*, z^* are corresponding coordinates of the beam center axis, and $z^* = (i-1)\Delta h$ is the elevation of the i th layer.

Additionally:

$$x_{Li} - x^* = \cot \beta \cdot (z_{Li} - z^*)$$

Under ideal overlapping and the assumption that increment equals initial clad height, for the sample cross-section shown in [Figure 1: see original paper], the middle overlapping region is approximated as planar, with symmetric outer half-profiles of left and right boundary clads. Only the left boundary clad is considered herein.

Let the powder concentration at any point in the powder stream be m (g/(m² · s)). The outer half-profile of the i th layer boundary clad is:

$$z_i = \frac{m \cdot y_i}{\rho \cdot v} + (i-1)\Delta h$$

where x_i, y_i, z_i are coordinates of the i th layer boundary clad cross-section profile, y_i is the molten pool length (m) at position x_i (absolute difference between y_{Li} and y^*), v is scanning speed (m/s), and ρ is powder density (g/m³).

When depositing the i th layer, the boundary molten pool shape is the intersection line between the i th layer laser beam and the surface of the $(i-1)$ th layer boundary clad. From Eq.(1):

$$y_i = 2 \cdot \sqrt{[H - (i-1)\Delta h]^2 - (x_{Li} - x^*)^2}$$

where X_i is the intersection point between the laser beam and the outer half-profile of the i th single-track clad. X_i is determined by $|z_{Li} - (i-1)\Delta h| = 0$ when $z_{Li} - (i-1)\Delta h \geq 0$, and by z_i when $z_{Li} - (i-1)\Delta h < 0$.

Considering the interior of the $(i-1)$ th layer cross-section profile as a plane at height $(i-1)\Delta h$ and neglecting the effect of solidified clad height at the rear of the molten pool during scanning (due to small beam divergence and low clad height), the boundary molten pool length is:

$$y_i = 2 \cdot \sqrt{[H - (i-1)\Delta h]^2 - (x_i - x^*)^2} \quad \text{for } x_i \in [x^*, X_i]$$

$$y_i = 2 \cdot \sqrt{[H - (i-1)\Delta h]^2 - (X_i - x^*)^2} \quad \text{for } x_i \in [X_i, r]$$

From Eqs.(3), (4), and (6), the i th layer boundary single-track clad cross-section profile is:

$$z_i = \frac{m}{\rho \cdot v} \cdot 2 \cdot \sqrt{[H - (i-1)\Delta h]^2 - (x_i - x^*)^2} + (i-1)\Delta h \quad \text{for } x_i \in [x^*, X_i]$$

$$z_i = \frac{m}{\rho \cdot v} \cdot 2 \cdot \sqrt{[H - (i-1)\Delta h]^2 - (X_i - x^*)^2} + (i-1)\Delta h \quad \text{for } x_i \in [X_i, r]$$

4.1 Model Evaluation

Based on this model, single-track clad shape, laser beam divergence angle, and effective range directly determine boundary clad shape evolution, with process parameters acting through these factors. Using the model, vertical outside walls were reconstructed for different initial single-track clad width-to-height ratios and laser effective ranges. Parameters are listed in , where R denotes the initial single-track clad width-to-height ratio. Results are shown in [Figure 6: see original paper].

Comparison with experimental results shows the model correctly predicts: (1) gradual inward contraction of boundary clad outer edges causing inward wall inclination; (2) decreasing inclination with increasing deposition height; (3) shape evolution of boundary clads with increasing outer half-profile slope. This validates the proposed mechanism: during superimposition, the curved surface of deposited boundary clads as substrate alters substrate height and molten pool shape, progressively affecting subsequent clad shapes and outside wall formation.

However, single-track clad formation in LSF is complex, and model simplifications affect predictions: (1) The model equates clad cross-section profiles with

powder accumulation on the substrate, neglecting pre-solidification deformation. Song et al. [?] noted that under gravity, boundary clads bulge outward, which can counteract inward contraction or even cause outward expansion. When deformation is small (e.g., large width-to-height ratio, low superheat), powder-accumulation-based profiles approximate reality. (2) Ideal track overlapping assumes a horizontal interior surface, ignoring actual surface unevenness. Improper overlap rates can create wavy or tilted interior surfaces [?], complicating boundary clad formation. As shown in [Figure 3: see original paper], the gradual elevation of inner edges relative to outer edges likely results from higher adjacent interior clads. However, optimized overlap rates minimize this effect. (3) The model assumes equal increment and clad height growth, fixing the relative position between laser beam and clad. In practice, these often differ, continuously changing their relative position and affecting clad shape. The inward expansion of right edges in [Figure 3: see original paper] likely relates to clad growth being smaller than beam elevation, increasing beam-clad spacing. (4) The model simplifies laser energy and powder concentration distributions. Laser spot size varies nonlinearly with defocus, and absorptivity depends on substrate morphology [?, ?], affecting the spatial shape of the effective laser range and molten pool geometry. Powder concentration in the stream follows a Gaussian distribution in planes perpendicular to the axis and diverges with distance from the nozzle [?, ?], resulting in higher accumulation at the pool center and lower at edges.

In summary, the model captures the essential physics of deposited boundary clads influencing subsequent clad shapes. Despite simplifications causing some deviation from reality, it reasonably reflects the layer-by-layer evolution of boundary clads and outside walls. Further refinement incorporating these factors could enable investigation of their effects on geometric evolution.

4.2 Effects of Clad Shape and Laser Effective Range

Based on reconstruction results, the influences of initial single-track clad shape and laser effective range on component geometry and dimensional accuracy were further analyzed. As defined in [Figure 7: see original paper], α represents the interlayer angle and Δf denotes the dimensional offset between each boundary clad outer edge and its preset position, with outer edge heights indicating wall profile elevations. Angle α reflects deviation from verticality and process stability; as α approaches 90° , the wall becomes vertical and processing stabilizes. Offset Δf reflects dimensional accuracy—positive values indicate oversizing, negative values undersizing, with larger absolute values indicating poorer precision.

[Figure 8: see original paper] shows interlayer angle evolution with layer number and deposition height. Results indicate that vertical outside walls gradually approach verticality with increasing layers/height. At the same layer number, smaller width-to-height ratios and smaller laser effective ranges produce larger

interlayer angles. At the same deposition height, width-to-height ratio has negligible effect on α , while smaller laser effective ranges yield larger angles. The initial dip followed by rise in α occurs because when the critical forming spot elevates above the original substrate, the distance between adjacent layers is not the increment; when this distance is too small, the initial interlayer angle becomes large.

[Figure 9: see original paper] shows dimensional offset evolution. The offset is negative and its magnitude decreases with increasing layers/height, indicating progressive inward shrinkage and final undersizing relative to preset dimensions. At the same layer number, smaller width-to-height ratios and smaller laser effective ranges increase shrinkage. At the same height, width-to-height ratio has negligible effect, while smaller laser effective ranges increase shrinkage. Some positive initial offsets occur because the maximum forming radius increases as elevation proceeds above the substrate plane; once elevated beyond the substrate, the beam intersects deposited material instead, after which inward shrinkage begins.

5. Conclusions

1. During LSF layer-by-layer deposition, boundary single-track clad shapes are significantly influenced by underlying deposited clads and cannot be simplified as translations of the initial clad shape. Due to the arc-shaped clad profile and finite laser beam effective range, the molten pool formed by intersection of the laser beam with boundary clads progressively shrinks inward with increasing deposition height, causing vertical outside walls to incline inward.
2. An analytical model describing the layer-by-layer evolution of boundary single-track clad cross-sections and vertical outside wall profiles was established, accounting for the influence of deposited boundary clads as substrates for subsequent clads.
3. Based on model reconstructions, the effects of laser beam effective range and initial single-track clad shape on wall evolution were discussed. Results show that inward inclination decreases and walls approach verticality with increasing deposition height. For a fixed initial clad width, reducing laser effective range and clad width-to-height ratio helps walls become more vertical but increases dimensional offset. At the same deposition height, width-to-height ratio has negligible effect on wall profile.

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