Porosity reduction by co-axial laser shock modulation of the molten pool in powder-bed selective laser sintering: A case study on widely-used stainless steel

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Abstract

Powder-bed metal additive manufacturing frequently suffers from high porosity issues arising from gas entrapment and keyhole instability. This study presents, for the first time, a breakthrough methodology: in-situ molten pool modulation via low-pulse-energy coaxial laser shock. By coupling an additional pulsed laser beam into a selective laser melting system, fabrication of low-porosity, high-quality metal components is achieved. In-situ monitoring reveals that the employed laser shock method suppresses severe spattering during the melting process, contributing to low porosity. Computed tomography (CT) enables quantification of pore volume, diameter, and sphericity. The results demonstrate that under optimal pulsed laser conditions, porosity in printed 316L stainless steel blocks is significantly reduced by 86% to less than 0.016%, while the shape and size of pores are favorably controlled.

Full Text

Preamble

Porosity Reduction by Co-Axial Laser Shock Modulation of Molten Pool in Powder-Bed Selective Laser Sintering: A Case Study on Widely-Used Stainless Steel

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Abstract: Powder-bed metal additive manufacturing is frequently plagued by high porosity resulting from gas trapping and keyhole instability. This work pioneers a breakthrough approach: in-situ molten pool modulation via low-pulse-energy co-axial laser shock. By coupling an auxiliary pulsed laser beam to a selective laser sintering system, we achieve low-porosity, high-quality fabrication of metal components. In-situ monitoring reveals that the laser shock method effectively inhibits severe splashing during sintering, thereby contributing to the achieved low porosity. Computed Tomography (CT) quantifies pore volume, diameter, and sphericity, demonstrating that the porosity of printed 316L stainless steel blocks is significantly reduced by 86 percent to less than 0.016% under optimal pulsed laser conditions. Concurrently, the shape and size of pores are beneficially controlled.

Keywords: Laser shock; selective laser sintering; Molten pool; Porosity

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1. Introduction

Additive manufacturing (AM), particularly laser powder bed fusion (L-PBF), enables production of complex geometries with minimal material waste and has found widespread application in aerospace [?], biomedical engineering [?], and other fields. However, porosity issues arising from unstable melt pool dynamics [?], keyhole collapse [?][?], and gas entrapment [?] severely compromise the mechanical integrity, fatigue resistance, and high-temperature properties of fabricated parts [?], limiting broader adoption of L-PBF. While efforts to reduce porosity through process parameter optimization (e.g., laser power, scanning speed) have been pursued, this approach remains insufficient for meeting stringent quality requirements. Recent studies on laser directed energy deposition (L-DED) and wire arc additive manufacturing (WAAM) have demonstrated that external physical fields—such as thermal field modulation [?], ultrasonic vibration [?], and magnetic stirring [?]—can effectively suppress porosity by modulating melt pool behavior. Nevertheless, in-situ, large-scale-applicable, and user-friendly physical field modulation strategies for porosity reduction in L-PBF, which demand high accuracy, efficiency, and scalability, remain lacking.

This work introduces the first breakthrough approach: in-situ molten pool modulation via co-axial low-pulse-energy laser shock during L-PBF processing (LS-L-PBF) to reduce porosity. By introducing an auxiliary coaxial pulsed laser to locally enhance heat and mass transfer, this method accelerates gas escape, stabilizes keyhole dynamics, and reduces peak temperature, thereby decreasing porosity in 3D printing. Using widely-adopted 316L stainless steel as a benchmark, this paper validates the broad engineering applicability of this strategy. This work not only advances L-PBF toward near-fully-dense fabrication but also establishes a new paradigm for multi-physics field control in metallic AM.

2. Experiments and Methods

Fig. 1 [Figure 1: see original paper] illustrates the experimental optical path design featuring double beams coupled through dichroic mirrors. A laser galvo scanning mirror directs the coupled beams for sample processing. Based on preliminary experimental testing, the continuous laser (CL) power was selected at 140 W, 150 W, 160 W, 170 W, and 180 W, with a powder layer thickness of 36 µm and scanning speed of 1100 mm/s. The pulsed laser (PL) current was varied from 7.5 A to 10 A in 0.5 A increments, with a pulse width of approximately 5 ns. At 10 A, the maximum power of the pulsed laser reached 10 W. The temporal distribution of the coupled beams is shown in Fig. 1. The experimental metal powder was 316L stainless steel with particle sizes ranging from 17 to 53 µm. The high-speed camera operated at a resolution of 768 × 480 pixels with a sampling rate of 40,000 fps. Illumination was provided by a 450 nm laser, with interfering light removed by a narrow-band filter. The minimum resolution of Computed Tomography (CT) was 7.5 µm.

Figure 1. The experimental double-wavelength beam design routes.

3.1 Low-Pulse-Energy Laser Shock Suppression of Keyhole Instability

Fig. 2 [Figure 2: see original paper] presents high-speed camera images comparing the machining process for single and coupled beams. Severe molten pool splattering occurs during single-beam melting due to temperature fluctuations and keyhole instabilities, as shown in Fig. 2(a). The spatter count reaches approximately 12 per millisecond (Fig. 2(f)), and residual spatter in the powder bed causes defects in subsequent layers. Low-pulse-energy laser shock locally modulates the molten pool, enhances heat transfer and gas escape, and suppresses keyhole instability. The mechanical effect of the PL on the powder bed is detailed in Appendix A (Supplementary Material). During LS-L-PBF, the plasma plume first decreases then increases as the pulsed laser current rises. At a PL current of 10 A, the splash count per millimeter approximates 13, similar to single-beam melting. The molten pool stabilizes as shown in Fig. 2(b) and (c), with spatter counts reducing to approximately 7 at PL currents of 8.5 A and 9.0 A. Importantly, powders near the molten pool remain undisturbed by the short-pulse, low-pulse-energy laser during LS-L-PBF.

Figure 2. High-speed camera images of low-pulse-energy laser shock suppressing keyhole instability.

3.2 Pore Distribution Under Coupled Beam Processing

For each printed sample, a volume of 3000 × 4000 × 1000 µm was sectioned for pore analysis, as shown in Fig. 3 Figure 3: see original paper. Under single-beam processing at the optimal CL power of 180 W, 440 pores remained, with a maximum pore volume of $1.88 \times 10^5 \mu m^3$ (Fig. 3(b)). Through molten pool modulation, LS-L-PBF processed samples exhibited significant pore reduction. Pore counts decreased to 302, 344, 197, 244, 303, and 322 for PL currents from 7.5 A to 10 A (Fig. 3(c)-(h)), respectively. Corresponding maximum pore volumes were $3.02 \times 10^5 \mu m^3$, $2.50 \times 10^5 \mu m^3$, $2.14 \times 10^5 \mu m^3$, $1.33 \times 10^5 \mu m^3$, $1.02 \times 10^5 \mu m^3$, and $1.43 \times 10^5 \mu m^3$, demonstrating the effectiveness of the LS-L-PBF method.

Figure 3. (a) Sectioned samples and 3D rendered pore models under different pulsed laser currents: (b) 0 A and (c)-(h) 7.5 A to 10 A.

3.3 Effect of Local Laser Shock on Porosity

Under single-beam processing, porosity decreased from 3.58%, 1.06%, 0.59%, 0.1115% to 0.0510% as CL power increased from 140 W to 180 W. Additional CT statistics are available in Appendix A (Supplementary Material). Fig. 4 Figure 4: see original paper illustrates the effect of PL current on porosity at CL powers of 170 W and 180 W, achieving minimum porosities of 0.0158% and 0.0216%, respectively, at the optimal PL current of 8.5 A. Fig. 4(b)-(h) shows the sphericity and equivalent diameter of pores in the samples from Fig. 3(b)-(h). Under the optimal CL power of 180 W, pore sphericity disperses between 0.5 and 1, with equivalent diameters ranging from 10 to 100 µm (Fig. 4(b)). Through molten pool modulation at PL currents of 8.5 A to 9.5 A, the sphericity and equivalent diameter distributions concentrate in the upper-left region (Fig. 4(e)-(g)), indicating beneficial control of pore shape and size at lower porosity levels in LS-L-PBF.

Figure 4. Porosity reduction through local laser shock modulation of molten pool in LS-L-PBF.

4. Conclusion

Low-pulse-energy laser shock locally modulates the molten pool in powder-bed selective laser sintering, yielding several important conclusions: (1) The LS-L-PBF approach enables higher-quality additive manufacturing of metal parts with reduced porosity. (2) In-situ monitoring demonstrates that local laser shock inhibits keyhole splashing, with short-pulse, low-pulse-energy lasers modulating the molten pool without disturbing adjacent powders. (3) The porosity of additively manufactured stainless steel is significantly reduced by 86 percent to less than 0.016%.

CRediT Authorship Contribution Statement

Heng Lu: Investigation, Visualization, Integration, Writing-Original draft.
Dingyi Guo: Investigation, Visualization, Integration, Resources.
Yi He: Resources.
Yaowu Hu: Conceptualization, Methodology, supervision, Funding acquisition.

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Note: Figure translations are in progress. See original paper for figures.