Experimental Identification of Stable Deposition Regimes for Adaptive Layer-Wise Control in Laser Directed Energy Deposition

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ABSTRACT

Directed Energy Deposition (DED) is increasingly adopted for the manufacture, repair, and reconditioning of high-value components; however, process variability remains a significant barrier to repeatable and adaptive production. This study presents an experimental foundation for adaptive manufacturing through systematic single-track characterisation of SS316L laser metal deposition. A full-factorial design of experiments comprising 45 parameter combinations was used to investigate the influence of process parameters on deposition stability. Process outcomes were classified into stable, instability, lack-of-fusion, and overmelting regimes using specific energy and material input metrics. A stable process window was identified and subsequently used in stepover investigations to establish relationships between track geometry and layer height evolution. The results demonstrate how single-track features can support layer-wise correction and adaptive manufacturing strategies.

KEYWORDS: *Adaptive Manufacturing; Process Window; Layer-wise Correction; Laser Metal Deposition*

1. INTRODUCTION

Directed Energy Deposition (DED) has emerged as a key additive manufacturing technology for component manufacture, repair, and reconditioning owing to its capability to deposit material selectively onto existing geometries. Despite its industrial potential, deposition quality remains highly sensitive to processing conditions, often resulting in geometric deviation, defect formation, and instability during multi-layer manufacturing [1]. Recent advances in adaptive manufacturing have highlighted the importance of integrating sensing, process understanding, and decision-making within manufacturing systems. For DED, the geometric characteristics of early deposited tracks directly influence the behaviour of subsequent layers. Deviations introduced during initial deposition stages may accumulate throughout the build, resulting in dimensional inaccuracies and increased post-processing requirements [2]. The present study aims to experimentally identify stable deposition regimes for laser metal deposition of SS316L and establish an experimental basis for future adaptive layer-wise correction strategies.

2. MATERIALS AND METHODS

A full-factorial Design of Experiments (DoE) consisting of 45 single-track deposits was conducted using SS316L powder. The investigated process variables were Laser Power (P), Powder Feed Rate ($\dot{m}$) and Scan Speed (v). To facilitate process-window analysis, two derived process indicators were calculated from the primary deposition parameters. The Specific Energy Input (SEI) represents the energy delivered per unit track length and Specific Material Input (SMI) represent the amount of powder supplied per unit track length, these variables were calculated as follows:

$SEI = \frac{P}{v}$ (J/mm) and $SMI = \frac{\dot{m}}{v}$(g/m)

Each deposit was classified based on visual assessment and geometric quality into: Stable, Unstable Lack of Fusion, Overmelting. Stable parameter combinations were subsequently selected for stepover investigations at 0.8 mm, 1.2 mm, and 1.6 mm. The experimental methodology forms the first stage of a broader adaptive manufacturing framework, where deposition geometry obtained from monitoring can be used to inform future parameter correction decisions as shown in Figure 1.



Figure 1. Framework linking single-track deposition behaviour with future adaptive layer-wise correction

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D. Nikam et al. (eds.), *Proceedings of the Global Symposium on Adaptive Manufacturing (GSAM 2026)*, Advances in Engineering Research 308,
https://doi.org/10.2991/978-94-6239-813-9_3

3. RESULTS

Deposition outcomes were classified as stable (continuous and uniform tracks), instability (non-uniform geometry despite continuous deposition), lack of fusion (discontinuous or poorly bonded tracks), and over melting (excessive spreading and dilution). Of the 45 parameter combinations investigated, 16 produced stable deposits, 19 resulted in lack of fusion, 9 exhibited instability, and only one condition resulted in over melting. From the 16 stable conditions identified, nine representative conditions were selected to cover both centre and boundary regions of the stable process window while spanning the investigated ranges of laser power, powder feed rate, and scan speed. Lack-of-fusion behaviour was predominantly observed at low specific energy inputs (SEI) between 53-80 J/mm, particularly at 800 W and higher scan speeds. In contrast, stable deposition was generally achieved within a process window of $90 \leq \mathrm{SEI} \leq 144$ J/mm and $11 \leq \mathrm{SMI} \leq 24$ g/m. From the sixteen stable conditions, nine representative parameter combinations were down selected to capture both the centre and boundaries of the stable process window while covering the investigated range of laser power, powder feed rate, and scan speed. These conditions were selected for further geometric characterisation as they provide the greatest potential for reliable multi-layer deposition and future adaptive manufacturing studies.

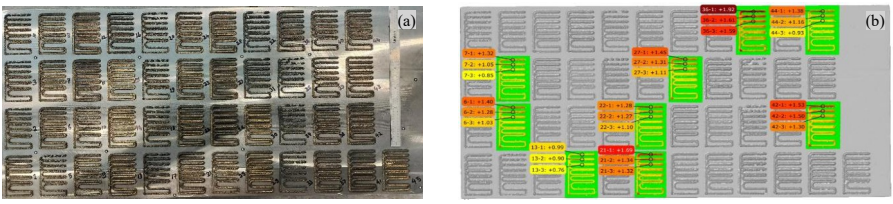


Figure 2. As deposited tracks and corresponding GOM scan reconstructions used for geometric characterisation

The selected conditions were subsequently characterised using a Zeiss ATOS optical scanning system. Figure 2 shows representative deposited tracks and corresponding 3D reconstructions used to extract track height and width measurements. Across all parameter sets, increasing stepover resulted in reduced deposited layer height. For example, Run 21 (1000 W, 10 g/min, 500 mm/min) produced layer heights of 1.69 mm, 1.34 mm and 1.32 mm for stepovers of 0.8, 1.2 and 1.6 mm, respectively. The results demonstrate a clear relationship between process parameters, material accumulation, and resulting track geometry. These geometric features provide an early indication of how future layers are likely to evolve and therefore form a valuable basis for developing layer-wise monitoring and adaptive correction strategies. By linking process conditions to track morphology and subsequent material accumulation behaviour, the study establishes a foundation for future closed-loop control and adaptive DED manufacturing systems.

4. CONCLUSION

This study establishes an experimental foundation for adaptive manufacturing in laser DED through systematic single-track characterisation of SS316L deposits. The work acts as an enabling step towards the development of adaptive manufacturing systems for laser DED. By linking process parameters to track geometry and subsequent layer growth behaviour, the resulting dataset provides the experimental foundation required for future layer-wise correction schemes, closed-loop process control, and intelligent adaptive manufacturing frameworks capable of preventing deviation accumulation during deposition.

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