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Detection of Nozzle Wear in High-Speed Directed Energy Deposition Using Multispectral Process Emissions

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Abstract

In High-Speed Directed Energy Deposition, nozzle wear affects powder stream symmetry and energy coupling, leading to reduced deposition stability and impaired surface integrity. In this study, the influence of nozzle wear on multispectral process emissions and the resulting track morphology is investigated. Single-track deposits were produced using new and worn coaxial nozzles under identical process conditions and monitored by a coaxial multispectral photometric sensor covering the visible and near-infrared spectral range.
Multispectral emission signals were analyzed using feature selection and clustering methods to distinguish nozzle conditions and identify sensitive spectral descriptors. Tracks produced with worn nozzles exhibited systematically reduced track heights and increased geometric irregularities compared to new nozzles, while penetration depth remained largely unaffected. Clustering based on selected spectral features enabled reliable differentiation between nozzle conditions with an accuracy of approximately 80%.
The results demonstrate that multispectral emission signals provide characteristic indicators of nozzle wear and correlate with surface-related quality features in HS-DED. This highlights the potential of photometric process monitoring for early detection of nozzle degradation and improved process stability in high-speed additive manufacturing.

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Keywords: "High-Speed Directed Energy Deposition; Additive Manufacturing; Photometric Emission; In-process Monitoring;"

1. Introduction

High-Speed Directed Energy Deposition-Laser Beam Metal (HS-DED-LB/M) is an additive manufacturing process that enables high deposition rates and flexible material application for repair, coating, and near-net-shape production of metallic components. In contrast to powder bed-based processes, HS-DED allows processing speeds of up to 200 m/min while maintaining precise thermal control and geometric accuracy [1]. During HS-DED, metal powder is delivered coaxially into the laser interaction zone and melted together with the substrate surface, forming a metallurgically bonded track. A defining characteristic of the process is the controlled spatial overlap between laser beam and powder stream, which governs powder catchment efficiency and melt pool stability. Consequently, process stability and resulting surface integrity are strongly influenced by the alignment and symmetry of the powder-laser interaction. Figure 1 provides a schematic overview of the HS-DED process configuration and illustrates the spatial relationship between laser beam, powder stream, and substrate. Deviations in powder stream geometry or energy coupling can lead to irregular track morphology, reduced layer uniformity, and defects

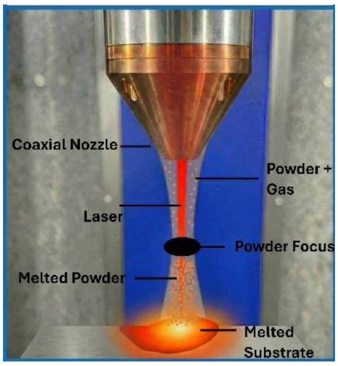

Fig. 1: Schematic illustration of the HS-DED Process

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affecting functional performance, such as fatigue resistance or coating quality.

Conventional approaches for nozzle wear assessment rely on visual inspection, empirical maintenance intervals, or ex-situ measurements, which do not provide real-time information during the process. Established in-situ monitoring techniques for Directed Energy Deposition, such as coaxial imaging, pyrometry, or thermography, offer valuable insights into melt pool behavior but often face limitations under high-speed processing conditions due to restricted spatial resolution, limited field of view, or insufficient temporal bandwidth [2,3].

Multispectral emission sensing provides an alternative monitoring approach by capturing thermal radiation and process-related optical emissions from the melt pool and interacting particles in the visible and near-infrared spectral range. Previous studies have shown that spectral characteristics and intensity variations are sensitive to changes in energy absorption, particle heating, and melt pool dynamics, making them suitable indicators of process stability in DED [4]. However, the systematic application of multispectral emission analysis for detecting nozzle wear and linking optical signatures to surface-related quality features in HS-DED has not yet been comprehensively addressed.

The objective of this study is to investigate the influence of nozzle wear on multispectral process emissions in HS-DED-LB/M and to correlate characteristic spectral signatures with changes in track morphology and surface integrity. By comparing single-track deposits produced with new and worn nozzles under identical process conditions, this work aims to identify spectral indicators of nozzle wear and assess their suitability for in-process monitoring and early detection of nozzle wear.

2. State of the Art

Directed Energy Deposition (DED) is governed by the interaction between a high-power laser beam and a stream of metallic powder delivered into the processing zone. The resulting melt pool dynamics and track geometry are primarily influenced by laser power, processing speed, and powder feed rate, which together determine the local thermal input and consolidation behavior [5].

In high-speed variants of DED, these interactions become particularly sensitive due to shallow melt pools and increased particle velocities. Under such conditions, small deviations in energy coupling can lead to pronounced changes in track geometry and surface quality [1].

The powder stream plays a central role in energy transfer. When particles intersect the laser beam, a fraction of the laser energy is absorbed or scattered, resulting in powder-induced attenuation and a reduced net energy input at the substrate surface [10]. The efficiency of this interaction strongly depends on the spatial distribution and symmetry of the powder jet [16].

Nozzle wear directly affects powder stream convergence and symmetry. Progressive nozzle wear caused by abrasive powder flow alters the annular gap and particle trajectories, which can shift the effective powder focus and disturb melt pool stability even under constant nominal process parameters [4]. While the influence of powder–laser misalignment on track quality has been investigated, the specific impact of nozzle wear on process emissions and surface integrity remains insufficiently quantified.

In-situ monitoring techniques have been widely studied to improve quality assurance in DED processes. Coaxial optical imaging enables real-time observation of melt pool geometry but is often limited by line-of-sight constraints and spatial resolution at high processing speeds [3]. Infrared thermography and pyrometry provide temperature-related information but typically lack sensitivity to changes in powder stream symmetry and energy coupling [19].

Multispectral emission sensing has emerged as a promising alternative for high-speed process monitoring. By capturing thermal radiation and characteristic emission signatures from the melt pool and interacting particles in the visible and near-infrared spectral range, multispectral sensors provide indirect access to energy absorption and dynamic process behaviour [17]. Previous studies have shown that characteristic spectral features respond sensitively to changes in melting conditions and process stability [21]. To extract relevant information from high-dimensional spectral data, feature extraction and selection methods are commonly applied. Dimensionality reduction approaches such as principal component analysis and information-theoretic measures have proven effective in identifying discriminative spectral descriptors for process monitoring applications [18]. More recently, physics-informed machine learning approaches have been proposed to enhance robustness and interpretability by embedding physical constraints into data-driven models [24]. Despite these advances, a systematic correlation between nozzle wear, multispectral process emissions, and surface-related quality metrics in high-speed DED has not yet been established. Addressing this gap is essential for the development of robust in-process monitoring strategies capable of detecting nozzle wear and maintaining consistent surface integrity.

3. Materials and Methods

This section describes the experimental setup and data analysis methods used to investigate the influence of nozzle wear on HS-DED-LB/M. Controlled deposition experiments with new and worn nozzles are combined with quantitative wear characterization, track geometry analysis, and in-situ multispectral emission sensing. The applied methods are detailed in the following subsections.

3.1 Experimental setup and process parameters

The experimental investigations were carried out using a PE3D Directed Energy Deposition system (Ponticon GmbH, Wiesbaden, Germany) operated in three-axis mode, where the build platform moves in X, Y, and Z while the processing head remains stationary. The system enables processing speeds of up to 200 m/min with a positioning accuracy of 0.03 mm. A diode laser source (LDF 6000-40, Laserline GmbH, Germany) with a maximum output power of 6 kW and a fiber core diameter of 400 μm was employed. The laser beam was focused to spot diameters between 1.0 mm and 3.2 mm, resulting in a top-hat intensity distribution at the interaction zone.

Powder was delivered coaxially using a continuous annular gap nozzle, generating a convergent powder–gas stream with a defined powder focus above the substrate surface. Gasatomized AISI 316L stainless steel powder with a particle size range of 20–63 µm was used throughout the experiments. Carrier gas and shielding gas flow rates were kept constant to isolate the influence of nozzle wear from other process parameters.

Single-track deposits with a length of 20 mm were produced under identical nominal process conditions. Laser power was varied between 1600 W and 2000 W, while the powder supply was adjusted using discrete powder feeder levels (3–10) according to the parameter matrix. All experiments were conducted at a constant processing speed of 30 mm/s.

3.2 Quantitative nozzle wear characterization

The behavior of a new nozzle was compared to that of a worn nozzle to investigate nozzle wear. The worn nozzle had been exposed to prolonged operation under abrasive powder flow, leading to visible signs of erosion at both the inner and outer nozzle surfaces.

To quantitatively characterize nozzle wear, the inner and outer nozzle geometries were additionally measured prior to the deposition experiments. Wear profiles were acquired along the nozzle axis as well as in the circumferential direction to capture axial wear gradients and angular asymmetries. The resulting datasets were evaluated in terms of local material removal, circumferential variation, and axial wear progression.

3.3 Multispectral emission sensing

The laser-powder interaction zone was monitored using a multispectral photometric sensor (4D.TWO, 4D Photonics GmbH, Germany) integrated coaxially into the optical beam path of the processing head. This configuration enables real-time acquisition of process emissions along the same optical axis as the laser beam without interfering with powder delivery or energy input. The sensor system consists of an array of photodiodes covering discrete wavelength bands in the visible (VIS) and near-infrared (NIR) spectral range. The photodiode signals were sampled at rates exceeding 1 MHz and synchronized with the process start via a hardware trigger. All spectral data were recorded as time-resolved multichannel signals and stored in a synchronized SQLite database. Each spectral channel corresponds to a predefined central wavelength that remains constant during operation. The acquired dataset therefore represents a multivariate time series capturing the temporal evolution of emission intensities associated with melt pool radiation, particle heating, and dynamic energy coupling in the interaction zone.

3.4 Feature extraction and data analysis

Due to the high dimensionality of the multispectral emission data, feature extraction and selection were applied prior to clustering. Principal Component Analysis (PCA) was selected to reduce feature dimensionality while preserving the dominant variance of the multispectral emission data and mitigating multicollinearity between highly correlated spectral features. Mutual Information was included to identify non-linear dependencies between individual spectral features and nozzle condition without assuming a specific model structure. In addition, Random Forest feature importance was chosen due to its robustness against overfitting, its ability to capture non-linear data boundaries, and its suitability for high-dimensional feature spaces without requiring extensive parameter tuning. The combination of these complementary methods allows robust identification of discriminative spectral features while minimizing method-specific bias. Based on the selected feature sets, clustering was performed to group samples according to spectral similarity. The clustering results were subsequently compared to the known nozzle conditions to evaluate classification performance and assess the sensitivity of the multispectral signals to nozzle wear.

3.5 Track morphology and surface integrity characterization

To evaluate the influence of nozzle wear on track geometry and surface integrity, the deposited single tracks were analyzed using confocal three-dimensional surface topography measurements. A commercial confocal microscope system (Nanofocus µsurf, NanoFocus AG, Germany) was employed to acquire high-resolution surface height maps of the deposited tracks. From these measurements, track height profiles were extracted as a quantitative and reproducible metric for track geometry. In addition, selected samples were prepared for metallographic cross-section analysis. The specimens were ground, polished, and etched prior to optical microscopy to assess melt pool geometry, penetration depth, and internal defects such as pore formation. The combination of surface topography measurements and metallographic cross-sections provides a comprehensive assessment of both external and internal quality features and serves as the basis for correlating track morphology with multispectral emission signatures and measured nozzle wear characteristics.

4. Results and Discussion

The results are presented following a cause-and-effect structure. First, nozzle wear characteristics are analyzed, followed by their impact on track morphology. Finally, changes in multispectral emission signals and the discrimination between new and worn nozzle conditions are discussed.

4.1 Quantitative nozzle wear characteristics

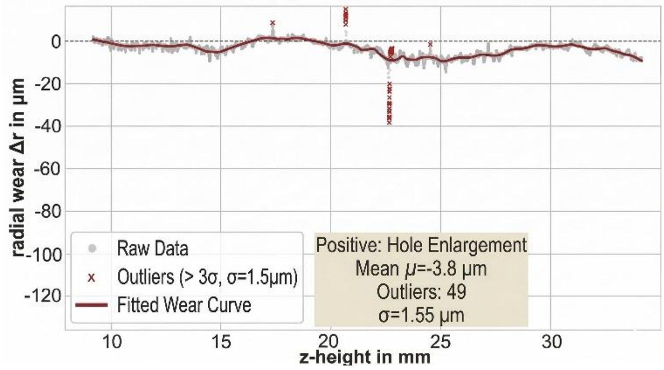

Fig. 2: Axial wear profile of the outer nozzle surface obtained from quantitative wear measurements.

The quantitative wear analysis reveals distinct differences between the inner and outer nozzle surfaces. As shown in Fig.2, the outer nozzle exhibits comparatively moderate material removal characterized by a shallow axial wear gradient. The longitudinal wear profile indicates a gradual increase in material loss towards the lower nozzle region, suggesting limited axial wear progression for the outer nozzle under the investigated operating conditions. In contrast, the inner nozzle surface shows a pronounced and systematic wear pattern (Fig. 3), characterized by a strong monotonic increase in material removal along the nozzle height.

The axial wear profile exhibits a strong monotonic increase in material removal along the nozzle height, indicating

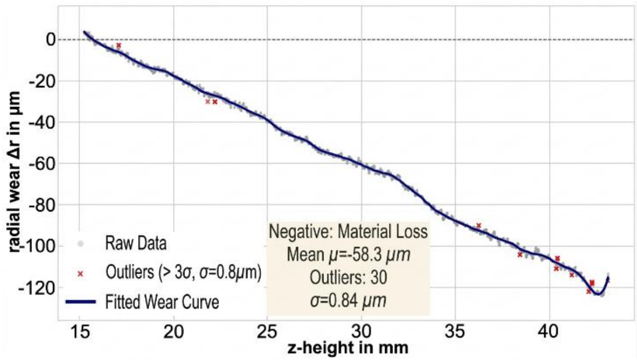

Fig. 3: Axial wear profile of the inner nozzle surface obtained from quantitative wear measurements.

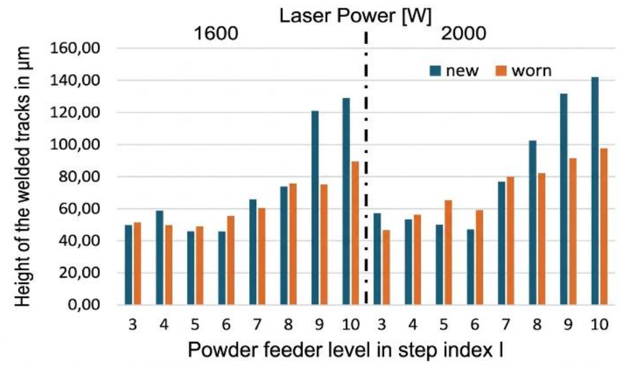

Fig. 4. Quantitative comparison of track heights for single-track deposits produced with new and worn nozzles.

progressive erosion in the direction of powder flow. This pronounced axial wear behavior suggests non-uniform powder-wall interaction and an increasingly distorted powder stream.
Quantitative surface profile analysis reveals systematically increased wear amplitudes at the inner nozzle surface. Peak-to-valley parameters (Rt) reach values of up to approximately 5 µm, while Rz values increase from about 2–3 µm for the new nozzle to approximately 4 µm for the worn nozzle, indicating pronounced localized material removal. The extracted wear metrics quantitatively support these observations. In particular, the inner nozzle exhibits a higher maximum wear depth and a markedly steeper axial wear gradient compared to the outer nozzle. Such asymmetric axial wear is likely to affect powder stream convergence and symmetry, providing a physical basis for the process-related effects discussed in the following sections.

4.2 Influence of nozzle wear on track morphology

The influence of nozzle wear on track morphology is evident from quantitative track height measurements, as summarized in Fig. 4.
The powder feeder level refers to discrete rotation steps of the feeder disk and does not represent a calibrated powder mass flow rate. Across the investigated parameter matrix, tracks produced with worn nozzles mostly exhibit reduced track heights compared to those deposited with new nozzles, with the deviation becoming more pronounced at higher powder feeder levels. On average, a track height reduction of approximately 15 % is observed, while melt pool penetration depth remains

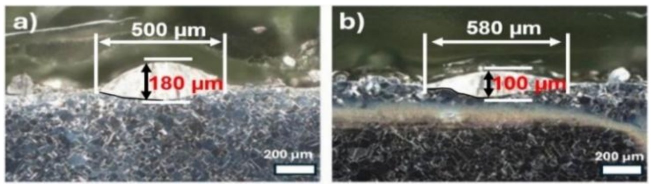

Fig. 5: Metallographic cross-sections of single tracks produced with (a) new and (b) worn nozzles at identical process parameters (P=2000W)

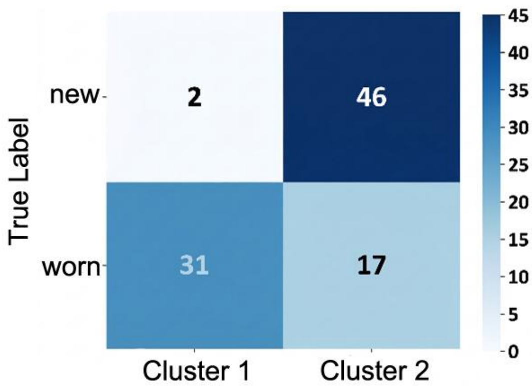

Fig. 6: Confusion matrix for the classification of new and worn nozzle conditions based on optimized multispectral emission features.

largely unchanged. This indicates that nozzle wear primarily affects powder catchment efficiency and lateral material distribution rather than the overall energy input into the substrate. This interpretation is further supported by metallographic cross-sections shown in Fig. 5.
While comparable penetration depths are observed for both nozzle conditions, tracks produced with worn nozzles frequently exhibit irregular track flanks and asymmetric solidification structures. These features are consistent with a disturbed powder–laser interaction caused by altered powder stream geometry due to nozzle wear.

4.3 Multispectral emission signatures and clustering performance

The multispectral emission signals show characteristic differences between new and worn nozzle conditions. When using the full feature set, clustering results already indicate a partial separation between both nozzle states, with worn nozzle samples forming more compact clusters compared to new nozzle samples. This behavior suggests that nozzle wear leads to more distinctive and less stable emission signatures, whereas the spectral response of new nozzles overlaps more strongly with neighboring process states. After feature selection and dimensionality reduction, clustering performance improves significantly.

As shown in Fig. 6, the optimized feature set enables a clear discrimination between new and worn nozzle conditions based solely on multispectral emission data, resulting in an overall clustering accuracy of approximately 80 % with a more balanced classification of both nozzle states.

In addition to overall classification accuracy, the optimized feature set yields balanced precision (approximately 80%) and recall (approximately 78%) for both nozzle conditions, indicating a symmetric classification performance without systematic bias toward either class. This improvement demonstrates that nozzle wear introduces characteristic changes in multispectral emission behaviour that can be captured by targeted feature extraction. The selected spectral features are interpreted as indicators of altered energy absorption and particle heating caused by asymmetric powder delivery, which is consistent with the measured wear patterns and the observed changes in track morphology.

4.4 Correlation between nozzle wear, emission signals, and surface integrity

By combining quantitative wear measurements, multispectral emission analysis, and track morphology characterization, a coherent process–structure relationship emerges. Pronounced axial and circumferential wear on the inner nozzle surface leads to disturbed powder stream symmetry, which manifests as reduced track height and increased geometric irregularity of deposited tracks.

These morphological changes are accompanied by distinct alterations in multispectral emission signatures. The clustering results indicate that emission-based descriptors are sensitive to nozzle-induced process instabilities and can be used to differentiate nozzle conditions even under identical nominal process parameters. The correlation between wear metrics, track geometry, and emission features highlights the potential of multispectral sensing as an indirect but robust indicator of nozzle condition and surface-related quality in HS-DED.

Importantly, the results show that nozzle wear primarily affects deposition efficiency and surface integrity rather than melt pool penetration, emphasizing the relevance of monitoring powder–laser interaction rather than temperature alone. This finding underlines the added value of multispectral emission sensing compared to conventional single-band monitoring approaches. The presented results are based on single-track experiments and represent a first step toward multi-layer and component-scale validation.

5. Conclusion

This study investigated the influence of nozzle wear on powder delivery, track formation, and multispectral process emissions in HS-DED-LB/M. Quantitative wear analysis revealed pronounced and asymmetric wear patterns, particularly at the inner nozzle surface, which directly affect powder stream symmetry. These wear-induced changes result in systematic alterations of track morphology. In particular, a consistent reduction in track height was observed for worn nozzle conditions, while melt pool penetration depth remained largely unchanged. This indicates that nozzle wear primarily reduces powder catchment efficiency rather than altering the overall energy input into the process. In addition to geometric effects, nozzle wear introduces characteristic changes in multispectral emission behavior. Using optimized spectral features, new and worn nozzle conditions can be distinguished based solely on in-process emission signals, demonstrating that nozzle wear leaves a measurable signature in the process radiation. Overall, the results establish a clear causal link between nozzle wear, powder stream behavior, track geometry, and process emission signatures. The presented approach provides a physically consistent basis for data-driven, in-situ monitoring of nozzle condition in HS-DED processes.

6. Outlook

Future work will focus on extending the approach toward continuous, real-time monitoring under industrially relevant conditions. In particular, the integration of temporal wear progression data and longer deposition sequences will allow the assessment of detection sensitivity at early wear stages.

Further studies will address the robustness of the proposed feature set across different materials, nozzle geometries, and process parameter windows. In addition, the combination of multispectral emission sensing with complementary in-situ monitoring techniques, such as high-speed imaging or acoustic emission, represents a promising path toward multi-modal nozzle condition monitoring.

Ultimately, the presented methodology provides a foundation for predictive maintenance strategies in HS-DED, enabling condition-based nozzle replacement and improved process stability in high-rate additive manufacturing applications, such as the coating of brake discs.

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