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**LASER POWDER DED PARAMETER SELECTION FOR HIGH-QUALITY
Ti6Al4V DEPOSITIONS**

Guilherme Rosati Mecelis, guilherme.mecelis@ifsp.edu.br¹
Eraldo Jannone da Silva, eraldodasilva@usp.br²
Cleiton Lázaro Fazolo de Assis, fazolocla@ifsp.edu.br¹
Reginaldo Teixeira Coelho, rtcoelho@sc.usp.br²

¹Instituto Federal de São Paulo - Campus Votuporanga, Av. Jerônimo Figueira da Costa, 3014, Pozzobon, CEP 15503-110, Votuporanga - SP

²Escola de Engenharia de São Carlos – Universidade de São Paulo, Av. Trabalhador São-Carlense, 400, Pq Arnold Schmidt, CEP 13566-590, São Carlos - SP

Abstract: Titanium alloys are renowned for their exceptional mechanical and chemical properties, such as high strength-to-weight ratio, stiffness, and corrosion resistance, making them ideal for industrial applications, especially in biomedical and aerospace sectors. However, machining titanium alloys is challenging due to their high strength, poor thermal conductivity, and high chemical reactivity, compounded by the high cost of titanium feedstock. This has led to significant interest in Additive Manufacturing (AM) as a cost-effective alternative, particularly Laser Powder Directed Energy Deposition (LP-DED), that produces near-net-shape parts. This study investigates the influence of LP-DED process parameters (laser power, scanning speed, and powder feed rate) on the single track geometry of Ti6Al4V. The experimental setup utilized a BeAM MODULO 250 machine with a 1 kW continuous-wave Nd:YAG fiber laser and a coaxial powder feeder. Parameters were selected based on pretesting and literature, with ranges of 300-450 W for laser power, 800-1200 mm/min for scanning speed, and 1-2 g/min for powder feed rate. A full factorial design of experiments (DOE) was employed to optimize the parameter window. Results showed that laser power exhibited a strong linear correlation with dilution and track width, but not with track height. Scan speed influenced track height, and powder feed rate was the most significant factor affecting track height. Analysis of variance (ANOVA) confirmed the significant impact of all parameters and their interactions on track geometry. Laser power had the strongest effect on dilution, while powder feed rate predominantly influenced track height. Regression modeling with polynomial regression and stepwise methodology was used to develop predictive models for track geometry. The models achieved high adjusted R² values, indicating good fit and reliable predictions within the chosen parameter window. The dilution model achieved an adjusted R² of 0.974, the growth model 0.953, and the width model 0.980. This research highlights the importance of optimizing LP-DED parameters to control single track geometry, providing a foundation for further process optimization in additive manufacturing. Future studies should explore the relationship between optimized single track geometries and the subsequent stages of the additive manufacturing process, such as multilayer deposition and part fabrication, to develop comprehensive process guidelines.

Keywords: additive manufacturing, titanium Ti-6Al-4V, laser powder directed energy deposition, LP-DED, parameter optimization

1. INTRODUCTION

Titanium alloys are highly valued for their exceptional mechanical and chemical properties, including high strength-to-weight ratio, stiffness, and corrosion resistance. These attributes enable various industrial applications. Notably, their biocompatibility makes them ideal for biomedical applications, while their high-temperature strength makes them suitable for aerospace applications. However, machining titanium alloys is challenging because of their inherent material properties, including high strength, poor thermal conductivity, and high chemical reactivity. Furthermore, the high cost of titanium feedstock makes machining particularly challenging for cost-sensitive applications, which are often characterized by high buy-to-fly ratios (significant material waste). This economic burden is where Additive Manufacturing (AM) emerges as a compelling alternative, offering the ability to produce near-net-shape parts, helping to reduce material waste and production costs (Zhang *et al.* 2023).

Recent research on Laser Powder Directed Energy Deposition (LP-DED) of Ti6Al4V has focused on understanding the influence of various process parameters on the resulting material properties, particularly porosity, track geometry, and microstructure, according to the following studies.

Ahn (2021) reviewed recent research trends in DED processes and their applications. The paper discussed principles, key technologies, and the state-of-the-art related to the development of processes and systems, the optimization of deposition conditions, and the application of the DED process. While discussing the effects of deposition parameters in DED processes that uses powder as feedstock, the author identifies that the three main parameters affecting bead formation are laser power, scanning speed, and powder feed rate.

A study by Lee *et al.* (2017) studied the influence of the laser power, scanning speed, powder feed rate, powder gas flow rate, and coaxial gas flow rate on the deposit geometry in direct energy deposited SISI M4 specimens. They found that laser power affected the overall size of the deposited bead, whereas the scanning speed mainly influenced the deposited height. The powder feed rate also influenced mainly the deposition height.

Another paper discussed the optimization of DED process parameters for the enhancement of directed energy deposition powder efficiency based on single-track geometry evaluation (Kim *et al.* 2022), seeking to minimize porosity. They found that the influential factors for porosity were the laser power, powder feed, and number of paths and proposed a method for detecting and quantifying pores using machine learning to detect pores in Inconel 718 products fabricated by DED.

Srekanth *et al.* (2020) investigated the effect of three important process parameters, namely laser power, scanning speed, and laser stand-off distance, on the deposit geometry, microstructure, and segregation characteristics in direct energy deposited alloy 718 specimens. They found that laser power and laser stand-off distance notably affected the width and depth of the deposit, while the scanning speed influenced the deposit height.

Two studies from Saboori studied single tracks depositions of Ti6Al4V. Saboori *et al.* (2017) investigation showed that all combinations used in this study produced consistent and no interrupted single tracks, and they concluded that using high laser power and high scan speed could result in a higher deposition rate while maintaining appropriate melt pool characteristics. In their next paper, Saboori *et al.* (2018) analyzed single track depositions to determine the correct layer height that should be used in the multilayer deposition. They found that increasing the laser power, and decreasing the scan speed, both results in an increase in the track height.

Narayana *et al.* (2021) enhanced the geometric accuracy and density of the deposited Ti6Al4V using neural networks. They could identify two parameters sets using this method, producing samples as desired. This study also identified that all parameters influenced the build height and the porosity.

Conclusions from Carrozza *et al.* (2021) point out to a cost and time-effective methodology for identifying a viable process window by depositing single tracks while varying the laser power and scan speed. They used two parameters, linear energy density (LED) and powder efficiency (P_e), to help identify this parameter window while agreeing that a higher LED value is correlated with lower cooling rates.

Despite significant advancements in Directed Energy Deposition (DED) technology, knowledge gaps remain, especially regarding Laser-DED (L-DED) applied to Ti6Al4V. While some studies have explored the impact of process parameters on the microstructure and mechanical properties of L-DED Ti6Al4V (Zhang *et al.* 2022), a deep understanding of a generalized process-structure-property relationship is lacking. This absence hinders the development of universally applicable L-DED process guidelines. Furthermore, standardized methodologies for optimizing these parameters are scarce, making it challenging to compare results across studies. Models to predict the geometry for single tracks depositions are in progress for LP-DED using different approaches as Finite Elements (Gonnabattula *et al.* 2024), Finite Volumes (Katinas, Liu, and Shin, 2019), Regression (Li *et al.* 2024), and Multi-Physics (Biyikli *et al.* 2023) modelling.

In addition, current models for predicting porosity in L-DED, particularly for complex geometries or multi material depositions, are often insufficient. Moreover, most research relies on post-process characterization. Development of real-time monitoring (Khanzadeh *et al.* 2019) and control (Zhang *et al.* 2022) techniques during the L-DED process is crucial to ensure consistent quality of the deposited tracks .

This research investigates the relationship between process parameters and single-track geometry during LP-DED of Ti6Al4V, aiming to optimize the parameter window. Starting from an initial guess guided by literature and manufacturer's advice, this study establishes a foundation for improved control over subsequent stages of the additive manufacturing process.

2. MATERIALS AND METHODS

This section describes the experimental setup, reasoning for parameter selections, and data collection techniques.

2.1. LP-DED Machine Configuration

The machine used in this study was a MODULO 250 from BeAM (Figure 1). This commercial machine uses a 1 kW continuous-wave Nd:YAG fiber laser, mounted in a coaxial deposition head integrated with a powder feeder system. The coaxial nozzle employs three Argon flows: material carriers, equipment protection, and shielding gas. The machine has optimum conditions for deposition with a spot laser diameter of 0.8 mm at a focal length (standoff distance from the

substrate) of 3.5 mm. The machine has an inert chamber that was used with an O₂ content below 200ppm. The depositions were conducted using only three-axis mode with the substrate resting in the machine's table.



Figure 1. BeAM machine (left), coaxial deposition head during the process (right).

2.2. Parameters Selection

The variable parameters considered in this study were the laser power, scanning speed, and powder feed rate. For selecting the parameter window, previous pretesting considering the machine manufacturer's advice was considered. Adding up to this, references from literature for the deposition of Ti6Al4V by the same processes and configurations as close as possible to our machine were also considered. From the pretesting, the parameters around 400 W, 1200 mm/min, and 2 g/min were considered viable for depositions and optimization. From the literature, (Narayana *et al.* 2021) *et. al.* found two optimized parameters sets: 350 W, 1200 mm/min and 1.2 g/min, and 295 W, 1000 mm/min and 2 g/min.

Therefore, this study in the optimization used the ranges of parameter of 300-450 W, 800-1200 mm/min, and 1-2 g/min.

The experimental matrix for these parameters was built with the aim of a full matrix DOE, using four levels for Power and three levels for scanning speed to optimize the distributions. For the powder feed rate, 1g/min and 2 g/min were established, once it was expected that for each powder feed rate there would be a proper window of Power and Scanning Speed that would work better for each one.

In conclusion, considering the machine configurations and limitations with the above-mentioned considerations, the experimental matrix was defined as shown in Table 1.

Table 1. Parameter for the LP-DED process.

Power [W]	300 , 350 , 400 , 450
Scanning Speed [mm/min]	800 , 1000 , 1200
Powder Feed Rate [g/min]	1 , 2

For further reference, Table 2 summarizes the parameters of all samples.

Table 2. Samples names and process parameters.

Sample	Powder Feed Rate [g/min]	Laser Power [W]	Scan Speed [mm/min]	Sample	Powder Feed Rate [g/min]	Laser Power [W]	Scan Speed [mm/min]
E1	1	300	800	E13	2	300	800
E2			1000	E14			1000
E3			1200	E15			1200
E4		350	800	E16		350	800
E5			1000	E17			1000
E6			1200	E18			1200
E7		400	800	E19		400	800
E8			1000	E20			1000
E9			1200	E21			1200
E10		450	800	E22		450	800
E11			1000	E23			1000
E12			1200	E24			1200

2.3. Materials

The powder used was manufactured by Carpenter Additive, under the product name PowderRange Ti64 E. Its particles range from 45 μm to 106 μm in diameter, and the composition is shown in Table 3. This powder has spherical particles with few satellites and very low porosity, as shown in the Figure 2.

Table 3. Titanium alloy powder composition.

	Ti	Al	V	Fe	O	C	N	H	Y	Other
wt%	Balance	5.5-6.5	3.5-4.5	0.25	0.13	0.08	0.03	0.0125	0.005	< 0.40

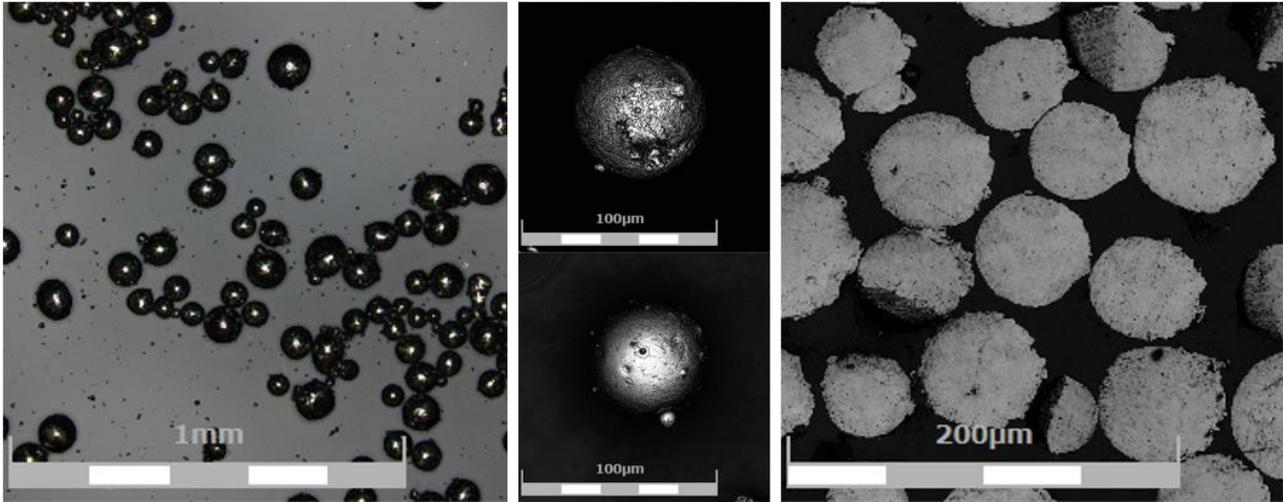


Figure 2. Ti6Al4V powder morphology showing spherical particles, with little satellites (left and middle), and low to none internal porosity (right).

The substrate used was small plates of pure Titanium, grade 2, measuring 25 x 50 x 5 mm, sandblasted to lower reflectiveness and increase security against laser reflections during deposition.

2.4. Track Geometry Analysis

For measuring the geometries of the deposited single tracks, a 3D measuring laser microscope was used, a LEXT OLS4100 made by Olympus. Two types of measurements were taken for comparison: The full track height measurements and the tracks' cross-section geometries. While height measurement is a nondestructive method, cross-section measurements need the cutting and preparation of the samples.

When measuring the full track height with a depth confocal image, it was possible to measure the bead height and width. The measurement of the cross section, on the other hand, also makes possible the measurement of the track's dilution.

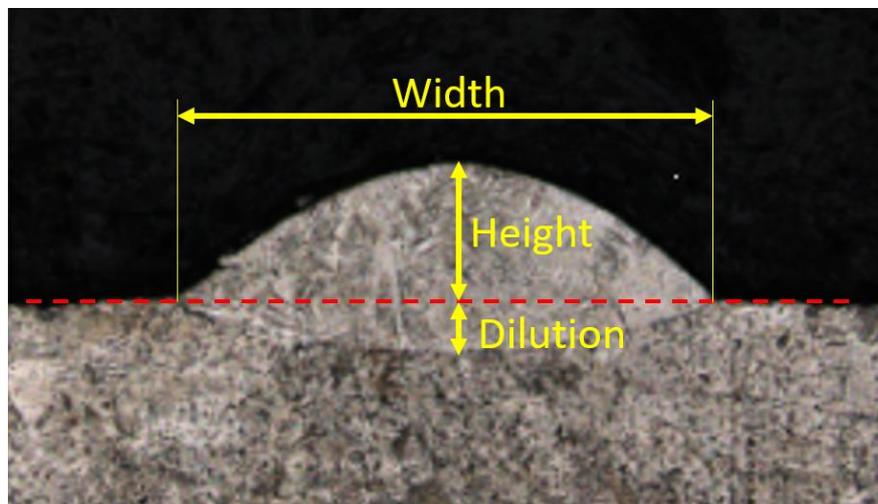


Figure 3. Track geometries measurement example.

As the measurements were made manually, the same taken images were measured three times, and the mean of these measurements was used in the data table for analysis, to minimize human error while not influencing the statistical analysis with duplicated data.

This study focused on the measurements of bead growth, width, and dilution, and their relationships. However, there are two common methods for measuring growth and dilution: by line height, and by area. After some comparison tests, as both methods show good agreement for the samples produced, the use of linear height measurements was defined due to its simplicity and speed, as show in Figure 3.

3. RESULTS AND DISCUSSION

The results presented shows a qualitative analysis from visual inspection of the single tracks cross-sections, arranged side-by-side in Figure 4, the statistical analysis that relates the input parameters with the measured dimensions, and the final regression modeling based on all data collected.

3.1. Impact of Process Parameters on the Geometries

Figure 4 presents cross-sectional images of all the deposited tracks for comparison. The images illustrate the significant influence of feed rate on track morphology (shape and size). Visual comparison of the dilution results suggests that optimal processing conditions are dependent on the powder feed rate. Furthermore, minimal porosity was observed within the tracks, indicating a dense material.

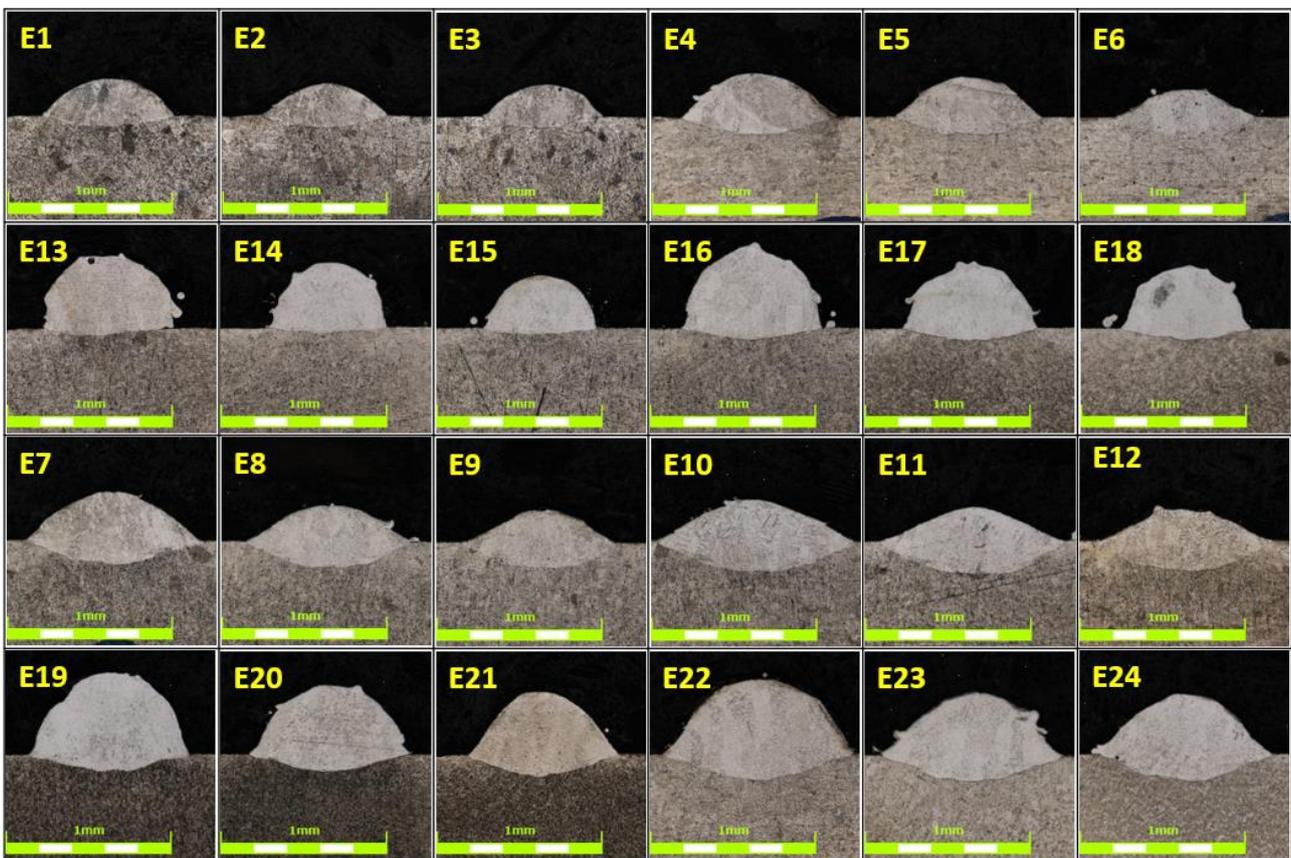


Figure 4. Side-by-side comparison of all 24 experiments.

To gain a deeper understanding, the effects of individual parameters were first investigated. Subsequently, a combined analysis was conducted to assess the potential interactions between them.

Within the chosen parameter window, laser power exhibited a strong linear correlation with both dilution and track width (Figure 5), but not with track height. In contrast, scan speed displays a linear relationship only with track height, but not with dilution or width. These observations support the suitability of the selected parameter range as there are relationships for dilution, track width, and scan speed that are close to linear. In addition, these clarifies which parameter predominantly influences each track geometry.

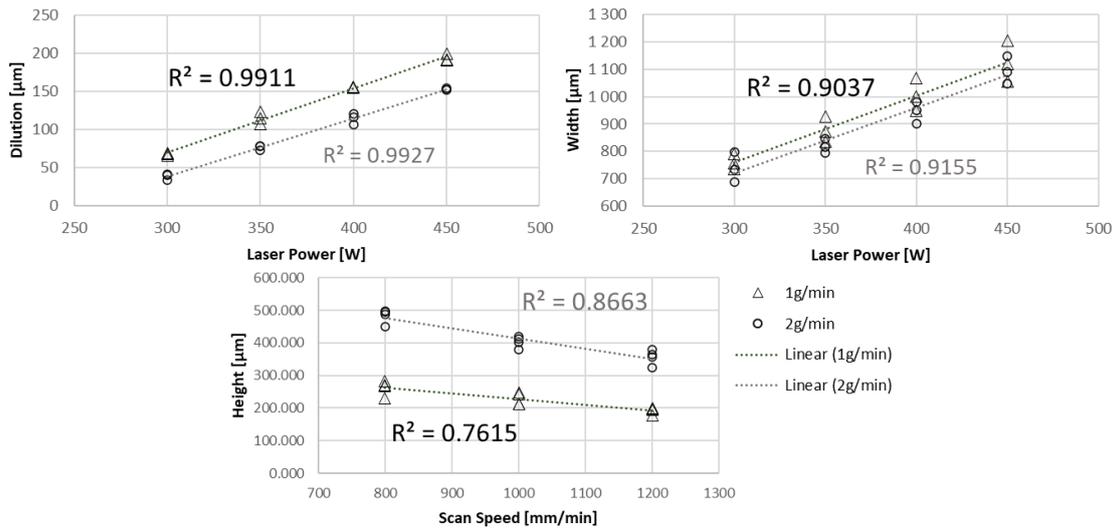


Figure 5. Linear correlation between the process parameters and track geometries.

Using analysis of variance (ANOVA), a comprehensive evaluation of the parameters influencing a specific geometry was conducted. This analysis additionally identified the parameter that significantly influences each geometry. The crucial outcomes of this analysis are the p-value and the F-statistic. The p-value reflects the probability of observing the obtained results under the null hypothesis of no significant difference between group means. A lower p-value indicates a stronger rejection of the null hypothesis, implying that the observed differences are likely not due to random chance. While the F-statistic contributes to the calculation of the p-value, its magnitude alone does not directly quantify statistical significance. However, a larger F-value suggests a greater influence of the tested parameter on the observed differences, potentially leading to a lower p-value if a stricter significance threshold is employed.

Table 4. Analysis of Variance for height.

Source	DF	SS	MS	F	P
Laser Power	3	81727	27242	61,48	0,000
Scan Speed	2	699885	349943	789,77	0,000
Powder Feed Rate	1	3751700	3751700	8467,09	0,000
Laser Power*Scan Speed	6	21833	3639	8,21	0,000
Scan Speed* Powder Feed Rate	2	63982	31991	72,20	0,000
Laser Power* Powder Feed Rate	3	14695	4898	11,06	0,000
Error	414	183440	443		
Total	431	4817262			

The results in Table 4 reveal a statistically significant influence of all process parameters and their interactions on the deposited track height. As anticipated, the powder feed rate exerts the strongest effect, evident from its higher F-value. This aligns with the previous explanation, from the visual evaluation, that increasing the powder feed rate directly contributes to a larger quantity of deposited material, leading to a higher track profile. The scan speed also exhibits a significant impact, potentially exceeding the influence of laser power.

Table 5. Analysis of Variance for dilution.

Source	DF	SS	MS	F	P
Laser Power	3	870143	290048	4924,16	0,000
Scan Speed	2	1312	656	11,14	0,000
Powder Feed Rate	1	151587	151587	2573,50	0,000
Laser Power*Scan Speed	6	1469	245	4,16	0,000
Scan Speed* Powder Feed Rate	2	867	433	7,36	0,001
Laser Power* Powder Feed Rate	3	2731	910	15,45	0,000
Error	414	24386	59		
Total	431	1052494			

Table 5 confirms the significant influence of all processing parameters and their interactions on dilution. As illustrated in Figure 5, the powder feed rate exhibits a negative correlation with dilution. This can be attributed to process characteristics as an increased powder flow rate can partially block the laser, reducing the effective power delivered to the substrate and melting pool formation. Laser power is identified as the most influential factor in increasing dilution. As the process heat source, higher laser power tends to melt a greater volume of material within the melt pool, affecting both the powder and substrate.

Table 6. Analysis of Variance for width.

Source	DF	SS	MS	F	P
Laser Power	3	7885913	2628638	8364,72	0,000
Scan Speed	2	640032	320016	1018,34	0,000
Powder Feed Rate	1	197520	197520	628,54	0,000
Laser Power*Scan Speed	6	29639	4940	15,72	0,000
Scan Speed* Powder Feed Rate	2	6645	3322	10,57	0,000
Laser Power* Powder Feed Rate	3	34743	11581	36,85	0,000
Error	414	130101	314		
Total	431	8924593			

Similar to the previous observations, Table 6 confirms the significant influence of all processing parameters and their interactions on single-track width. While laser power exhibits the strongest effect based on the F-value, the observed magnitude differences are insufficient to definitively conclude a greater influence compared to the other two parameters. Moreover, the laser spot diameter, which defines the incident laser power area, could be a crucial factor for track width because it directly affects melt pool size. This is supported by the observed track width range (690-1200 μm) falling close to the laser spot diameter of 800 μm . However, further investigation is needed.

The combined analysis of the figures and ANOVA results shows that all three parameters influence all track geometries. However, specific parameter choices can be advantageous for controlling individual geometries. Modifying the powder feed rate followed by optimization of laser power and scan speed appears most efficient for height control. Conversely, adjusting laser power is recommended for manipulating dilution and width.

It is important to acknowledge that altering one parameter will induce adjustments to the others due to their interconnected influence on geometries and overall process success. Therefore, identifying a suitable process parameter window, as employed in this study, where all conditions yield acceptable depositions, is crucial for optimized control.

3.2. Regression Modeling for Optimization

Regression modeling stands out as a robust method for optimizing process parameters in Laser Powder Directed Energy Deposition (LP-DED) systems due to the observed linear correlation, significant influence, and independence among the process parameters. In this study, polynomial regression with stepwise regression methodology was employed to develop three distinct models tailored for optimizing geometries in LP-DED processes.

In the modeling framework, denoting laser power as P , scanning speed as V , and powder feed rate as f , the final model equations were crafted to achieve simplicity, optimal data fitting, and statistical significance of all terms ($p < 0.05$). Model performance was evaluated using metrics such as Adjusted R^2 , Root Mean Square Error (RMSE), and Mean Absolute Relative Error (MARE).

The dilution model:

$$-254.2361 + 1.2619 \times P + 0.0105 \times V - 0.0994 \times (P \times f) - 0.004 \times P^2 \quad (1)$$

achieved an adjusted $R^2 = 0.974$, RMSE = 7.99 μm , and MARE = 7.02%.

The growth model:

$$-382.4341 + 2.3744 \times P + 283.0583 \times f + 0.1725 \times (P \times f) - 0.1614 \times (V \times f) - 0.0032 \times P^2 \quad (2)$$

achieved an adjusted $R^2 = 0.953$, RMSE = 22.76 μm , and MARE = 5.96%.

The width model:

$$668.4634 - 84.7146 \times f - 0.0008 \times (P \times V) + 0.0419 \times (V \times f) + 0.0043 \times P^2 \quad (3)$$

achieved an adjusted $R^2 = 0.980$, RMSE = 20.45 μm , and MARE = 1.77%.

All models achieved an adjusted R^2 above 95%, indicating their capability to explain over 95% of the response variability, thereby demonstrating a good fit to the data. Additionally, the relatively low MARE (highest at 7%) suggests an acceptable margin of error for predictions, while the RMSE values are also close to the mean standard deviation of the dataset for these geometries. These evaluation metrics underscore the reliability of the models for predicting geometries within the proposed parameter window.

To validate the models, three sets of additional experiments were conducted using the same scan speeds (800, 1000, and 1200 mm/min) and mass flow rates (1 and 2 g/min) as in the initial study. Two sets extrapolated the window parameter to lower (300W) and higher (500W) laser power values, while one set remained within the window (375W). Comparing the results from the extrapolated sets to the model predictions revealed that the models were ineffective at predicting growth and dilution outside the specified window, indicating that the chosen window probably involve the entire linearity space related to our process. However, predictions for width had a mean absolute relative error (MARE) under 10.5%, suggesting that factors other than the three key process parameters, such as laser spot diameter (as it limits the area of

power input in the process), may influence width. Expanding this model would require significantly more experiments. Conversely, the set within the parameter window performed well, with MAREs of 10% for growth and 5.1% for width, which are acceptable for this model type. However, the dilution parameter showed a MARE of 20%, indicating that while the model remains valid, future studies should consider varying the mass flow beyond just two points to improve model accuracy. Comparing with different models performance, the model proposed by (Katinas, Liu, and Shin, 2019) achieved errors of 3.3% for height and width, and 11.1% for dilution, while comparing experimental result with their model.

The regressions models will be helpful in future experiments for optimizing the geometries of single-track depositions, lowering material consumption while finding optimal parameters for a given study. It is worth mentioning that these models are fitted for one specific machine, but it proves that it is possible to identify a window where the resulting geometries are linearly correlated to the process parameters. Hence, this modeling process should be suitable for any LP-DED machine.

4. CONCLUSIONS

This work tested the relationship between all three main DED process parameters (laser power, scanning speed, and powder feed rate) on the geometries of deposited single tracks of Ti6Al4V. From these comparisons and analyses, it was possible to conclude that it is possible to find a process parameter window where the geometries will behave in linear correlation with the parameters, and it makes possible to perform modeling using regression methods to find fine-tuned parameters showing the best conditions for depositing. In addition, it is possible to identify important relations:

1. Dilution and width increase with laser power, while growth reduces when increasing the scan speed.
2. ANOVA shows that all parameters, and their interactions, significantly affects all the analyzed geometries, and it is possible to consider the F value in the ANOVA table to identify the parameters that would have stronger effects: The height is most affected by the powder feed rate, the dilution is more affected by the laser power and powder feed rate, and the width are most affected by the laser power.

Further research is still needed to relate these optimizations with the further steps in the additive manufacturing process: producing wall, layers, and multilayers parts.

5. ACKNOWLEDGEMENTS

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7. AUTHORSHIP RESPONSABILITY

The author(s) is(are) the only responsible(s) on this work content.