

Process parameter optimization for porosity reduction in selective laser melting of AlSi10Mg using finite element simulation with response surface methodology

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Abstract. Selective Laser Melting (SLM), a laser powder bed fusion process, enables fabrication of complex AlSi10Mg components with high dimensional accuracy. However, achieving near-fully dense parts remains challenging because porosity is strongly influenced by the interaction of processing parameters. While previous studies have extensively investigated effects of laser power and scanning speed, the influence of laser spot diameter on porosity has received less attention. Moreover, most numerical studies focus on melt pool characteristics without quantitatively assessing porosity tendency. This study proposes a Numerical Porosity Index (NPI) derived from predicted melt pool volume using a three-dimensional transient thermal finite element model developed in ANSYS. A combined Design of Experiments (DOE), Finite Element Method (FEM), and Response Surface Methodology (RSM) framework investigated the effects of laser power, scanning speed, and laser spot diameter on porosity tendency and identified the optimal processing window. Results showed that all three parameters significantly affected the NPI, with laser spot diameter strongly influencing melt pool stability. Optimization identified an optimum processing window of 151–164 W, 804–866 mm/s, and a 0.08 mm laser spot diameter, corresponding to minimum porosity tendency. Numerical predictions agreed well with experimental microstructural characterization and melt pool dimensions, demonstrating the effectiveness of the proposed framework.

1 Introduction

Selective Laser Melting (SLM), a laser-based LPBF process, selectively melts successive powder layers using a high-energy laser beam to fabricate dense metallic components [1,2]. The quality of SLM parts is governed by the complex thermal phenomena occurring during laser-material interaction, where rapid melting and solidification generate steep temperature gradients and transient melt pool behavior. Consequently, the final part quality is highly sensitive to the selected processing parameters. Improper parameter combinations may produce unstable melt pools, resulting in defects. One of the most common defects that has been reported in SLM manufactured components is porosity [3]. Although porosity is important for some applications, such as the medical biology field, it is considered a defect in most mechanical applications, like

additively manufactured parts [4]. Many experimental studies have established that porosity causes a severe transformation in mechanical properties through the loss of load bearing area and stress concentration regions, hence impairing fatigue life and structural reliability.

Experimentally, porosity is commonly defined as the volume fraction of voids within a material and can be characterized using techniques such as X-ray computed tomography (XCT), optical microscopy, and density-based methods [5, 6]. These techniques provide information on pore size, morphology, and spatial distribution and can help identify defect formation mechanisms. In SLM-fabricated aluminum alloys, porosity is commonly classified as lack-of-fusion, keyhole, and gas-induced porosity [7]. Lack-of-fusion pores are generally irregular and associated with insufficient energy input, whereas keyhole pores are typically more spherical and associated with excessive energy input. Gas-induced porosity is related to entrapped gases and is generally characterized by relatively small pores [8]. Several studies have experimentally investigated these defects using different characterization methods. Yusuf et al. [8] evaluated porosity using the Archimedes method and XCT, while Voznesenskaya et al. [9] investigated porosity using optical microscopy and density-based analysis. Pokorný et al. [10] employed computed tomography and computer-aided quality (CAQ) technology for nondestructive porosity characterization and reported a dependence of porosity on scanning direction.

Alongside experimental studies, numerical modeling has emerged as an important approach for understanding porosity formation in SLM. Temperature distributions, melt-pool geometry, and solidification behavior can be predicted using finite element (FE) and computational fluid dynamics (CFD) models and related to experimentally observed porosity trends [11]. In particular, insufficient melt-pool depth or inadequate overlap between neighboring scan tracks is commonly associated with lack-of-fusion porosity, whereas excessively deep and unstable melt pools can promote keyhole-related defects [12]. Cheng et al. [13] used discrete element method (DEM) and CFD models to investigate porosity formation in SLM and reported that pore formation can result from the collapse of an unstable deep keyhole, with their numerical findings supported by experimental observations. Similarly, Tan et al. [14] used a computational model to investigate the effects of process parameters, including laser power, scanning speed, and layer thickness, on porosity formation. Although these numerical approaches have improved the understanding of melt-pool evolution and defect formation mechanisms, they generally evaluate porosity qualitatively or semi-quantitatively rather than providing a direct numerical indicator for quantifying porosity tendency from finite element simulation results.

Furthermore, most numerical and experimental studies investigating the influence of process parameters on porosity have primarily focused on laser power and scanning speed, while the effect of laser spot diameter has received comparatively less attention. Wang et al. [15] reported that laser power and scanning speed strongly influence porosity, with increased laser power and reduced scanning speed promoting higher energy input and reducing porosity. Nandhakumar and Venkatesan [16] reviewed the effects of major SLM process parameters, including laser power, scanning speed, hatch spacing, and layer thickness, on porosity and other part properties. Similarly, Zhang et al. [17] investigated the effects of laser power, scanning speed, and scanning spacing on porosity and reported that increased energy input and improved track bonding can reduce porosity. Modaresialam et al. [18] further investigated the effects of laser process parameters and scanning strategy on part quality and identified laser spot diameter and powder thickness as important parameters. Podolskyi et al. [19] examined the influence of physical phenomena and material properties on SLM part quality, highlighting the role of melt-pool instability, temperature gradients, and hydrodynamic effects in defect formation. Voznesenskaya et al. [20] investigated the effect of energy density on pore formation and evaluated the influence of hot isostatic pressing (HIP) on pore characteristics using optical microscopy and density-

based analysis. Despite these studies, a systematic quantitative investigation of the interaction between laser power, scanning speed, and laser spot diameter for evaluating porosity tendency remains limited, particularly using FE simulation combined with a numerical porosity indicator. Therefore, a comprehensive evaluation of these process-parameter interactions is needed to establish an effective processing window for porosity reduction.

Therefore, this study develops a three-dimensional transient thermal finite element model in ANSYS to investigate the combined effects of laser power, scanning speed, and laser spot diameter on porosity tendency during SLM of AlSi10Mg. A Numerical Porosity Index (NPI), derived from the predicted melt-pool volume, is proposed as a quantitative indicator for evaluating porosity tendency directly from numerical simulations. The finite element model is integrated with Design of Experiments (DOE) and Response Surface Methodology (RSM) to evaluate the individual and interaction effects of the selected process parameters and determine the optimum processing window for porosity reduction. Finally, the numerical predictions are validated through comparison with experimental melt-pool dimensions and microstructural characterization. The proposed framework provides an efficient computational approach for predicting porosity tendency and optimizing SLM process parameters while highlighting the comparatively underexplored influence of laser spot diameter on melt-pool behavior and defect formation.

2 Finite element thermal model

2.1 Boundary conditions, material and mesh

A three-dimensional transient thermal finite element model was developed in ANSYS 2023 R1 to simulate single-track laser scanning during SLM of AlSi10Mg. The model was implemented using ANSYS Mechanical with the Transient Thermal module. A single-bead finite element model was developed to investigate the effects of process parameters on melt-pool behavior during SLM of AlSi10Mg. The model represents a single linear laser scan along the powder bed, allowing the melt-pool characteristics to be evaluated under different combinations of laser power, scanning speed, and spot diameter. The computational domain consisted of a $1\text{ mm} \times 2\text{ mm} \times 0.1\text{ mm}$ powder bed deposited on a substrate, with the laser scanning along the 2-mm longitudinal direction.

Table 1: Selected process parameters and their corresponding levels.

Parameter	Symbol	Unit	Levels
Laser power	P	W	100, 150, 200
Scanning speed	v	mm/s	800, 1000, 1200
Spot diameter	d	mm	0.06, 0.08, 0.1

The model assumed conduction-dominated heat transfer within the powder bed and substrate, isotropic material behavior, and a Gaussian laser intensity distribution. The lateral surfaces were assumed to be adiabatic. The initial temperature of the computational domain was set to 293.15 K. Heat losses from the exposed surfaces were considered through convection and radiation:

$$-k \frac{\partial T}{\partial n} = h_c(T - T_{\text{amb}}) \quad (1)$$

$$-k \frac{\partial T}{\partial n} = \varepsilon \sigma (T^4 - T_{\text{amb}}^4) \quad (2)$$

where h_c is the convective heat transfer coefficient, ε is emissivity, σ is the Stefan–Boltzmann constant, and T_{amb} is the ambient temperature.

AlSi10Mg alloy was selected as the base material because of its widespread use in SLM and its favorable combination of low density, high specific strength, good castability, and thermal conductivity. The AlSi10Mg material available in the ANSYS 2023 R1 additive manufacturing material database was used in the present study. The model accounts for the temperature dependence of specific heat, thermal conductivity, and density for the powder and solid states. The powder bed was assumed to be a homogeneous medium, and temperature-dependent material properties were employed in the thermal analysis. The material was considered molten when its temperature exceeded the liquidus temperature, whereas temperatures below the solidus temperature represented the solid state.

The computational domain was discretized using SOLID279 three-dimensional thermal elements. A mesh-dependence study was performed by progressively refining the element size. The difference between the two finest meshes was below 2%, and an element size of 0.017 mm was therefore selected for the subsequent simulations, resulting in 51,696 elements and 194,734 nodes. A sufficiently small fixed time increment was used to ensure smooth movement of the laser heat source and adequate resolution of the rapid heating and cooling cycles.

2.2 Governing equation

The transient thermal behavior was governed by the three-dimensional heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (3)$$

where T is temperature, ρ is density, C_p is specific heat capacity, k is thermal conductivity, $\mathbf{u}$ is the laser scanning velocity, and Q is the absorbed volumetric heat source.

A moving volumetric Gaussian heat source was used to represent the laser-material interaction. The attenuation of laser energy through the powder bed was described using the Beer-Lambert law:

$$Q(x, y, z) = \frac{Q_0(x, y)}{\delta} \exp\left(-\frac{|z|}{\delta}\right) \quad (4)$$

where δ is the optical penetration depth and Q_0 is the absorbed surface heat flux. The surface heat flux was represented by a moving Gaussian distribution:

$$Q_0(x, y) = \frac{2AP}{\pi R^2} \exp\left[-\frac{2((x - ut)^2 + y^2)}{R^2}\right] \quad (5)$$

where A is the laser absorptivity, P is laser power, R is the effective laser beam radius, u is scanning speed, and t is time. Combining the above equations gives the volumetric heat source:

$$Q(x, y, z) = \frac{2AP}{\pi \delta R^2} \exp\left[-\frac{2((x - ut)^2 + y^2)}{R^2}\right] \exp\left(-\frac{|z|}{\delta}\right) \quad (6)$$

Temperature-dependent thermophysical properties of AlSi10Mg were adopted from Ansari et al. [21]. The solid-to-liquid phase transition was incorporated using temperature-dependent density, thermal conductivity, and effective specific heat capacity. The phase fraction was defined as

$$\theta = \begin{cases} 0, & T \leq T_S, \\ \frac{T - T_S}{T_L - T_S}, & T_S < T < T_L, \\ 1, & T \geq T_L. \end{cases} \quad (7)$$

where T_S and T_L are the solidus and liquidus temperatures, respectively. The effective material properties were calculated from the corresponding solid and liquid properties, with latent heat incorporated into the effective specific heat capacity.

The transient thermal analysis provided the temperature history throughout the computational domain. The maximum temperature was extracted from the thermal field, while elements reaching temperatures above the liquidus temperature were identified as molten elements. The melt pool volume was calculated by summing the volumes of these elements. This melt pool volume was subsequently used to calculate the Numerical Porosity Index described in Section 2.3.

2.3 Numerical porosity index

To quantitatively evaluate porosity tendency from the finite element results, an NPI was defined based on the ratio between the predicted melted volume and the nominal track volume:

$$\text{NPI} = 1 - \frac{V_{\text{melted}}}{V_{\text{track}}} \quad (8)$$

where V_{melted} is the volume of elements reaching or exceeding the liquidus temperature and V_{track} is the nominal volume of the scanned track. The melted volume was calculated as

$$V_{\text{melted}} = \sum_{T_i \geq T_L} V_i \quad (9)$$

where V_i is the volume of element i , T_i is its temperature, and T_L is the liquidus temperature. The nominal track volume was calculated as

$$V_{\text{track}} = LWD \quad (10)$$

where L is the laser scanning length, W is the nominal track width, and D is the nominal track depth.

An NPI value close to zero indicates that the predicted melted volume approximately corresponds to the nominal track volume and represents a balanced melting condition. A positive NPI indicates insufficient melting relative to the nominal track volume and, consequently, a tendency toward lack-of-fusion defects. A negative NPI indicates that the predicted melted volume exceeds the nominal track volume, representing excessive melting and a potential tendency toward thermal instability. Therefore, NPI is used as a porosity tendency indicator rather than a direct measurement of physical void volume. Unlike VED, which represents the nominal laser energy input per unit volume, and melt-pool dimensions, which describe the resulting melt-pool geometry, NPI evaluates the balance between the predicted melted volume and the nominal track volume directly from the finite element results. It therefore provides a complementary FE-based criterion for assessing the tendency toward insufficient or excessive melting under different process conditions. Values closer to zero were considered desirable during process optimization.

2.4 Experimental method

AlSi10Mg specimens were fabricated using an Xact Metal XM200G laser LPBF system. Detailed descriptions of AlSi10Mg fabrication using the XM200G have been reported in previous studies [22]. In the present experimental investigation, laser powers of 100 and 200 W, scanning speeds of 800, 1000, and 1200 mm/s, laser spot diameters of 0.05 and 0.10 mm, a layer thickness of 0.10 mm, and hatch spacings of 0.035 and 0.070 mm were employed. These experimental

conditions represent selected combinations of the process-parameter levels considered in the numerical investigation and were used to provide experimental observations for comparison with the finite element predictions.

Prior to scanning electron microscopy (SEM) characterization, the specimens were sectioned and metallographically prepared by sequential grinding and polishing to obtain a suitable surface finish. The polished surfaces were examined in the unetched condition to preserve the original microstructural and defect features. The prepared specimens were subsequently characterized using SEM. Representative SEM images were acquired at a magnification of 500 $\times$, using an accelerating voltage of 20 kV, a 60 μm aperture, and a working distance of approximately 14.3 mm. The images were acquired using the backscattered-electron (BSE) signal and are presented with a 20 μm scale bar.

3 Results and discussion

3.1 Thermal response and numerical porosity tendency

A total of 27 three-level full-factorial FE simulations were performed to investigate the effects of laser power (P), scanning speed (v), and laser spot diameter (d) on the thermal response and numerical porosity tendency of AlSi10Mg during SLM. The predicted maximum temperature (T_{max}) ranged from 346.37 to 2127.6 $^{\circ}\text{C}$, whereas the NPI ranged from -1.18 to 0.898. These wide response ranges demonstrate the strong influence of the investigated process parameters on the thermal state and melt-pool behavior.

The moving laser generated a localized high-temperature region that traveled along the scanning direction, followed by cooling and solidification after the heat source passed. The melted volume was determined by identifying FE elements whose temperature exceeded the liquidus temperature and summing their individual volumes, as illustrated in Figure 1.

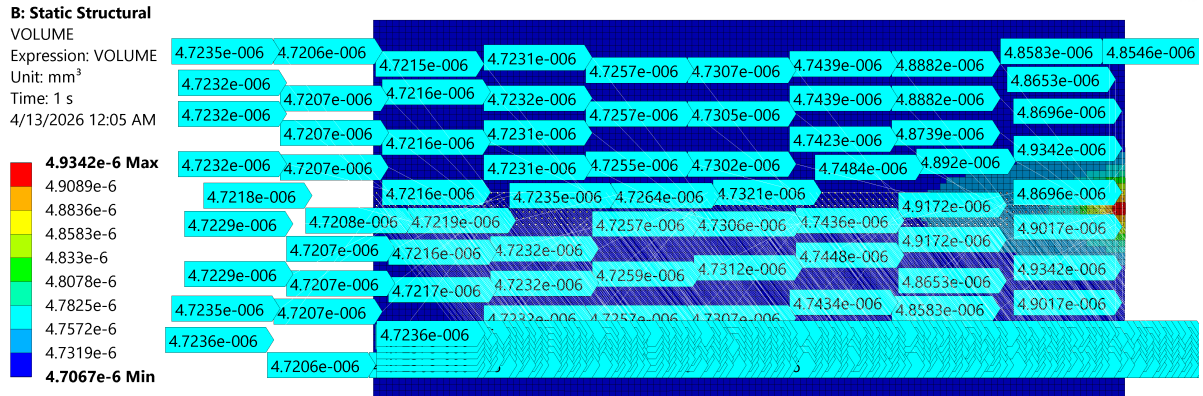


Figure 1: Extraction of melt volume from the FE simulation: elements exceeding the liquidus temperature are identified and used to calculate the total melted volume.

The representative temperature contours in Figure 2 illustrate the transition between insufficient, relatively balanced, and excessive melting conditions. At low energy input, represented by $P = 100$ W, $v = 1200$ mm/s, and $d = 0.10$ mm, the thermal field was relatively weak and localized, resulting in a maximum temperature of 346.37 $^{\circ}\text{C}$ and an NPI of 0.898. This condition indicates insufficient melting and a strong tendency toward lack-of-fusion defects. In

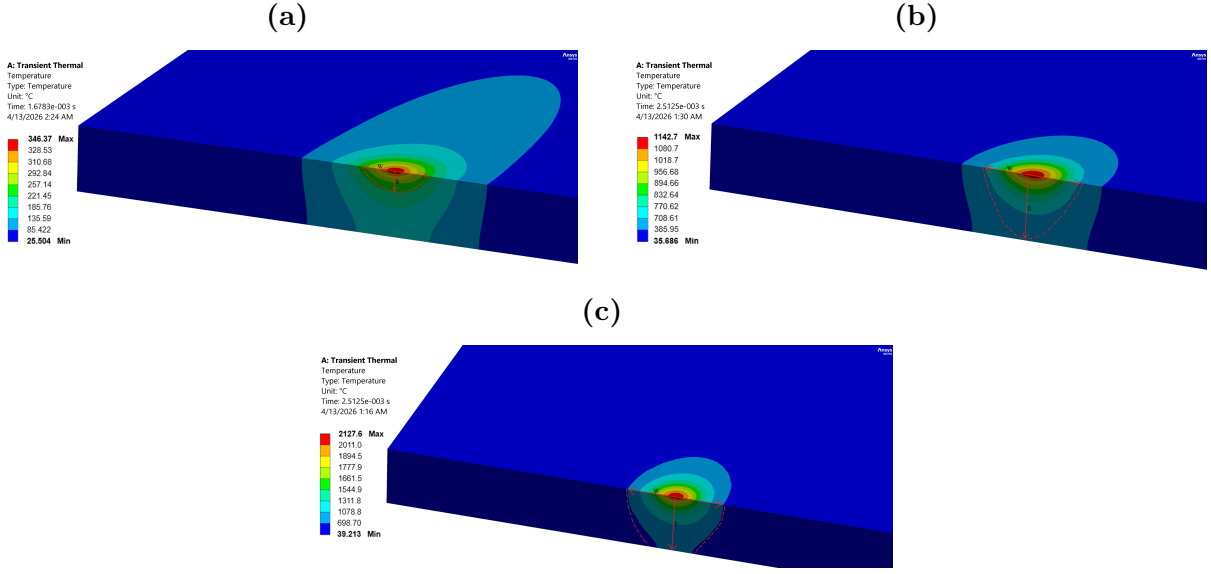


Figure 2: Representative FE temperature contours under different process conditions: (a) low-energy condition, $P = 100$ W, $v = 1200$ mm/s, $d = 0.10$ mm; (b) intermediate condition, $P = 150$ W, $v = 800$ mm/s, $d = 0.08$ mm; and (c) high-energy condition, $P = 200$ W, $v = 800$ mm/s, $d = 0.06$ mm.

contrast, the combination of $P = 200$ W, $v = 800$ mm/s, and $d = 0.06$ mm produced the highest predicted temperature of 2127.6 °C and an NPI of -1.18 . This temperature is well above the melting range of AlSi10Mg, indicating a highly energetic thermal condition with extensive melting. At such elevated temperatures, evaporation of relatively volatile alloy constituents may become relevant and may contribute to additional melt-pool phenomena such as recoil pressure. The negative NPI further indicates that the predicted melted volume exceeds the nominal track volume, corresponding to excessive melting under this processing condition. In comparison, the intermediate condition of $P = 150$ W, $v = 800$ mm/s, and $d = 0.08$ mm produced a maximum temperature of 1142.7 °C and an NPI of 0.0583 , indicating a more balanced melting condition with the predicted melted volume close to the nominal track volume.

3.2 Statistical effects of process parameters

Statistical analysis of the 27 FE results was performed using Minitab and Design-Expert. Minitab was used to evaluate the statistical significance of the process parameters and generate the Pareto and main-effects plots, whereas Design-Expert was used to develop the response surface models and perform the optimization.

The statistical behavior of $T_{\max}$ differed from that of NPI. For maximum temperature, laser power and spot diameter were statistically significant, whereas scanning speed was not significant within the investigated parameter range. The linear model was statistically significant ($p < 0.0001$) and explained 87.51% of the variation in maximum temperature ($R^2 = 0.8751$; $R^2_{\text{adj}} = 0.8435$). The fitted model in terms of the actual process parameters was

$$T_{\max} = 4363.94 + 19.979P - 0.368v - 52147.97d. \quad (11)$$

The positive coefficient of laser power indicates that increasing laser power increases the predicted maximum temperature because more energy is supplied to the material. In contrast,

the negative coefficient of spot diameter indicates that increasing the spot diameter reduces energy concentration and consequently lowers the predicted peak temperature. The relatively small coefficient and statistical insignificance of scanning speed indicate that its influence on $T_{\max}$ was comparatively limited within the investigated range. This phenomenon also stated on Figure 3.

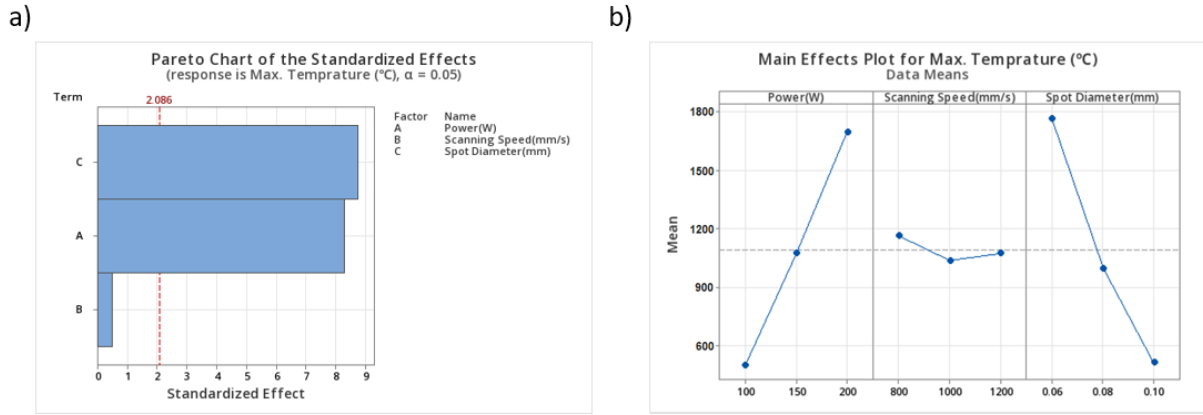


Figure 3: Statistical effects of process parameters on maximum temperature: (a) Pareto chart and (b) main-effects plot.

In contrast to the approximately linear behavior of maximum temperature, NPI exhibited a strongly nonlinear response. The quadratic response surface model was statistically significant ($p < 0.0001$), with $R^2 = 0.9944$, $R^2_{\text{adj}} = 0.9914$, and $R^2_{\text{pred}} = 0.9850$. All three linear terms and the power–speed, power–spot diameter, and speed–spot diameter interactions were significant as Figure 4(a) illustrated. The quadratic terms of laser power and scanning speed were also significant, indicating curvature in the NPI response.

The main-effects analysis in the Figure 4(b) showed that increasing laser power generally reduced NPI, whereas increasing scanning speed and spot diameter generally increased NPI within the investigated range. These trends indicate that NPI is governed by the combined effects of energy input and its spatial and temporal distribution. The significant interaction terms further demonstrate that the effect of one process parameter depends on the levels of the other parameters. Therefore, porosity tendency cannot be adequately characterized using a single energy-related parameter or by considering the process parameters independently.

The interaction effects among the process parameters are illustrated in Figure 5. The non-parallel trends indicate that the effect of one process parameter on NPI depends on the level of another parameter. The most pronounced interaction is observed between laser power and scanning speed, where the slope changes substantially with laser power. A noticeable interaction is also observed between laser power and spot diameter, as the effect of spot diameter varies with laser power. In comparison, the scanning speed–spot diameter lines are closer to parallel, indicating a comparatively weaker interaction. These trends are consistent with the statistical analysis, which identified the corresponding interaction terms as significant. Overall, the interaction behavior demonstrates that NPI is governed by the combined effects of laser power, scanning speed, and spot diameter rather than by any single process parameter.

The combined thermal and NPI results indicate two undesirable processing regimes. Low laser power, high scanning speed, and large spot diameter reduce the energy delivered to the material and produce positive NPI values associated with insufficient melting. Conversely, high

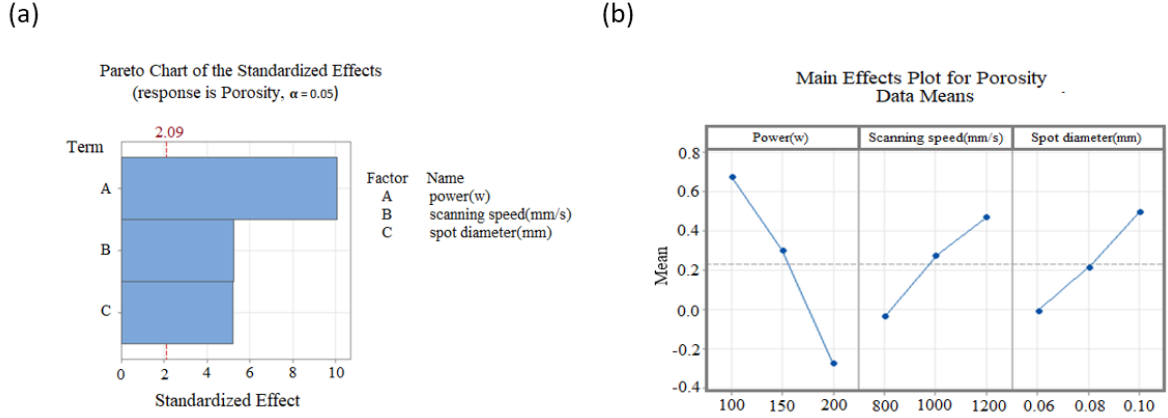


Figure 4: Statistical effects of process parameters on NPI: (a) Pareto chart and (b) main-effects plot.

laser power, low scanning speed, and small spot diameter increase energy concentration and produce negative NPI values associated with excessive melting. A suitable processing condition therefore requires a balance between these regimes, with NPI approaching zero rather than simply maximizing or minimizing the applied energy.

3.3 Response surface modeling and process optimization

The optimization was performed in Design-Expert using the developed response surface models, with the objective of minimizing the NPI toward zero. Several solutions with similar desirability were obtained. As shown in Table 2, the optimized solutions spanned approximately 151–164 W in laser power, 804–866 mm/s in scanning speed, and 0.079–0.084 mm in spot diameter. The corresponding VED values ranged from approximately 32.2 to 33.8 J/mm³, while the predicted NPI values were extremely close to zero.

Among the representative solutions, the combination of 150.804 W, 806.014 mm/s, and 0.079 mm produced a predicted NPI of -3.35×10^{-7} and a predicted maximum temperature of approximately 1055.37 °C. The other representative solutions also yielded NPI values very close to zero, ranging from -6.66×10^{-8} to 3.91×10^{-7} . The close agreement among these solutions indicates that minimizing NPI does not require a single unique parameter combination and supports the identification of a narrow optimized processing window within the investigated parameter space.

Table 2: Representative optimized process parameters obtained from RSM optimization.

P (W)	v (mm/s)	d (mm)	VED (J/mm ³)	NPI
163.922	865.630	0.084	32.20	-6.66×10^{-8}
154.065	804.410	0.083	32.96	9.80×10^{-8}
150.804	806.014	0.079	33.83	-3.35×10^{-7}
160.010	838.743	0.084	32.44	3.91×10^{-7}

The optimized VED range of approximately 32–34 J/mm³ falls within reported processing ranges for AlSi10Mg and provides an additional indication of the physical plausibility of the optimized processing region [23,24]. However, VED is used only as a supplementary comparison;

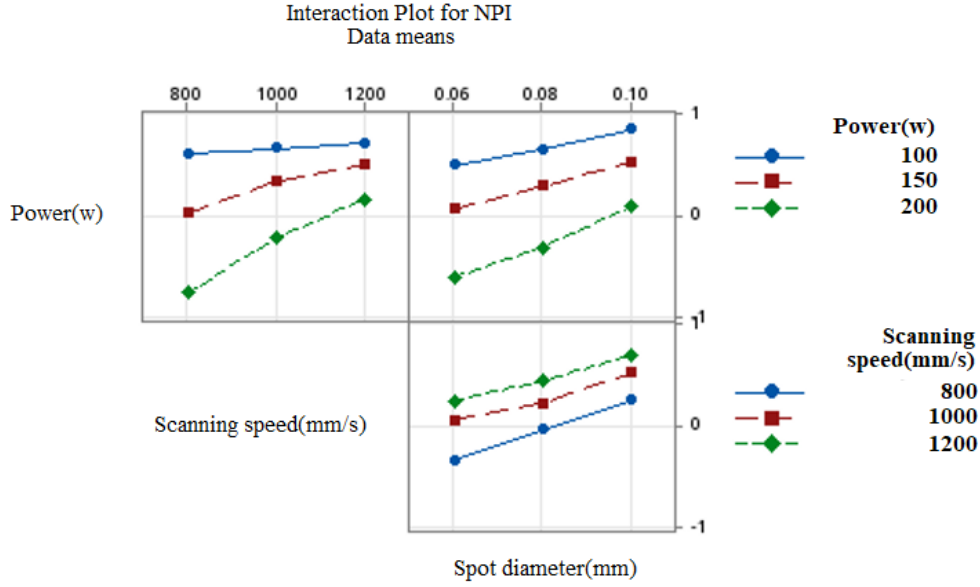


Figure 5: Interaction effects of laser power, scanning speed, and spot diameter on the NPI.

the optimization itself is based on the FE-derived NPI and maximum-temperature response. This distinction is important because VED does not explicitly account for the spatial distribution of laser energy associated with different spot diameters.

3.4 Validation

The FE model was quantitatively assessed by comparing predicted melt-pool dimensions with experimental measurements reported in the literature. For the condition of 195 W and 800 mm/s, the predicted melt-pool width and depth were 169.8 and 72 μm , respectively, compared with experimental values of 144 and 65.4 μm . The corresponding errors were 15.19% and 12.04%. The complete comparison is summarized in Table 3.

Table 3: Comparison of FE-predicted and experimental melt-pool dimensions.

Process parameters	Width (μm)			Depth (μm)		
	Exp. Ref.	Predicted FE	Error (%)	Exp. Ref.	Predicted FE	Error (%)
195 W, 800 mm/s [25]	144	169.8	15.19	65.4	72.0	12.04

To further evaluate the model with the trend of melt pool width and melt pool depth with scanning speed was compared with published experimental observations, as shown in Figure 6.

Although the published experimental data were obtained using a laser power of 250 W while the present study employed 200 W, both studies exhibit the same trend. Increasing the scanning speed decreases both melt pool width and melt pool depth due to the reduction in energy input per unit length. This agreement demonstrates that the developed finite element model successfully captures the thermal behaviour of the selective laser melting process.

The differences between the numerical and experimental melt-pool dimensions can be attributed to the simplifying assumptions of the thermal model. In particular, the present model

does not explicitly account for melt-pool fluid flow, Marangoni convection, recoil pressure, evaporation, or detailed keyhole dynamics. In addition, the validation data were obtained from published experimental studies and may therefore involve differences in material condition, powder characteristics, equipment, and processing conditions.

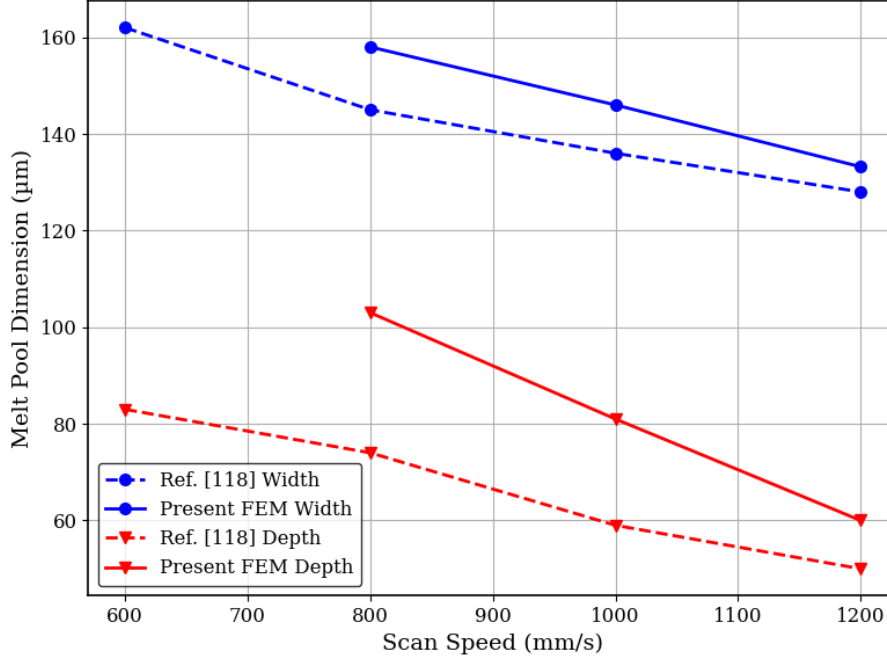


Figure 6: Comparison of melt pool dimensions between the present numerical results and published experimental data [26].

The numerical results were also consistent with the reported reduction in melt-pool dimensions at higher scanning speed. Although the available experimental comparisons involved slightly different laser powers, the predicted dimensions followed the same overall tendency reported in the literature. Therefore, the comparison provides supporting evidence that the FE model captures the principal thermal response of the process within the investigated parameter range.

3.5 Microstructural characterization

Experimental SEM micrographs were examined to provide qualitative microstructural verification of the numerical predictions. Representative micrographs are presented in Figures 7 and 8. The images reveal different defect morphologies, including approximately spherical pores, irregular discontinuities, lack-of-fusion regions, and partially unmelted powder particles. These features provide qualitative evidence of the defect tendencies predicted by the FE-derived NPI under different process conditions.

The experimentally observed defects can be related to the two principal regimes identified from the numerical analysis. At high energy input, keyhole-related defects and spherical gas pores were observed in Figures 8(c) and 8(g), corresponding to (200 W, 1200 mm/s, 0.06 mm) and (200 W, 800 mm/s, 0.06 mm), respectively. The combination of high laser power and a small spot diameter produced concentrated thermal input, while the lower scanning speed in the latter condition increased the interaction time. These conditions promoted elevated melt-pool

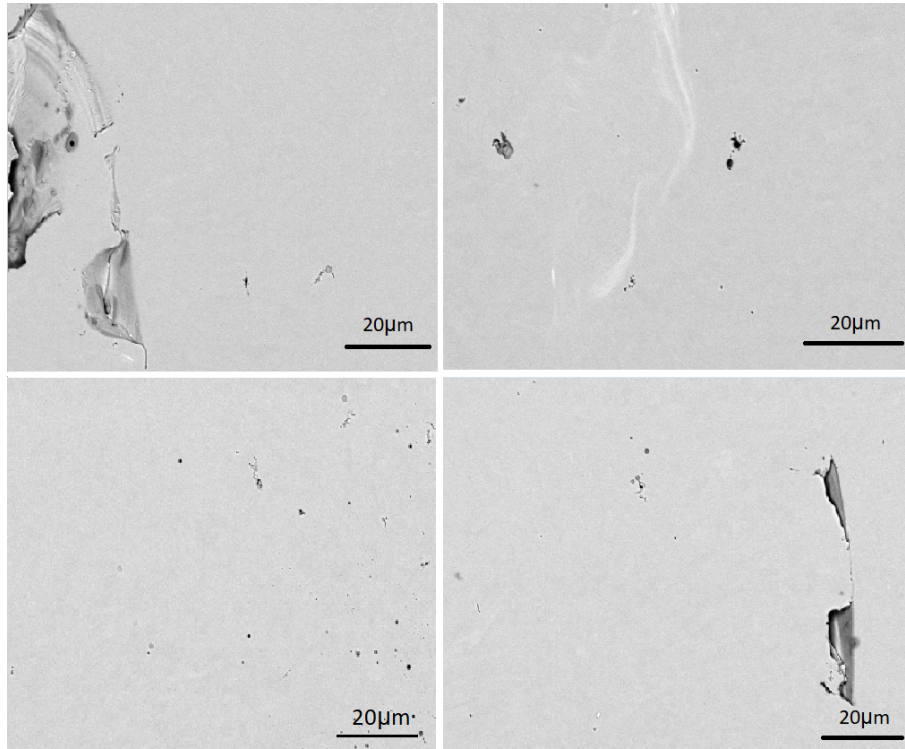


Figure 7: Representative SEM micrographs showing variations in defect morphology and distribution observed in the fabricated AlSi10Mg specimens.

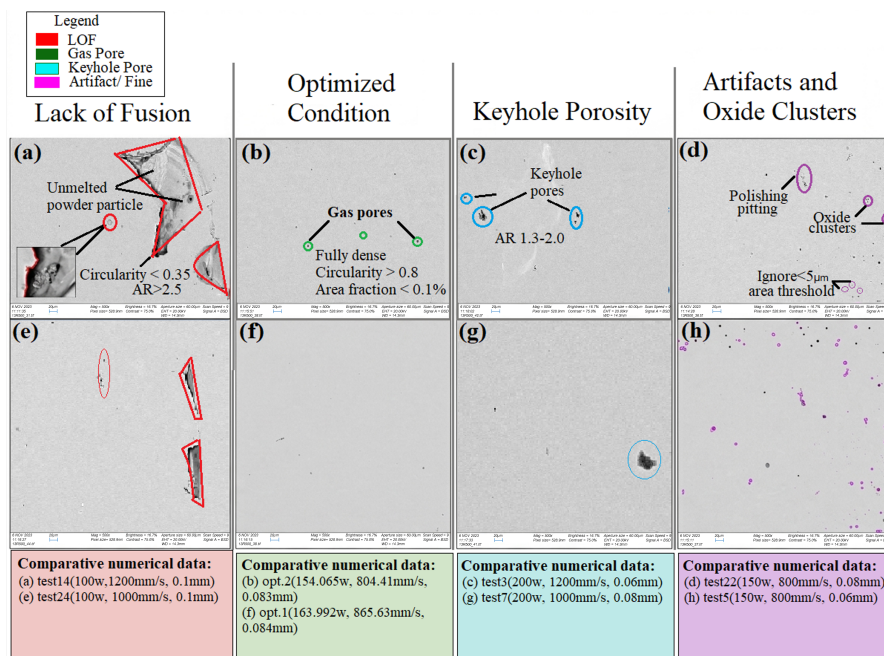


Figure 8: Representative SEM micrographs illustrating the microstructural features observed under selected experimental processing conditions.

temperatures and unstable vapor cavities, resulting in keyhole formation and pore generation, consistent with the negative NPI values and elevated temperatures predicted by the numerical model.

In contrast, insufficient-energy conditions produced lack-of-fusion defects and partially unmelted material. Figures 8(a) and 8(e), corresponding to (100 W, 1200 mm/s, 0.10 mm) and (100 W, 1000 mm/s, 0.10 mm), respectively, show irregular discontinuities, partially unmelted powder particles, and pore clusters. The combination of low laser power, relatively high scanning speed, and large spot diameter reduced the energy delivered to the material, limiting melt-pool penetration and interlayer bonding. This behavior is consistent with the positive NPI values predicted under low-energy conditions.

The specimens produced within the optimized process region, shown in Figures 8(b) and 8(f), exhibited comparatively fewer visible defects and a more uniform microstructure. Only a small number of isolated pores and minor defect features were observed. This qualitative observation is consistent with the RSM optimization, where NPI values approached zero, indicating a more balanced melting condition between insufficient and excessive energy input. Overall, the microstructural observations support the numerical prediction that process parameters strongly influence defect formation and that the optimized region provides improved melting conditions.

4 Conclusions

A finite element-based response surface methodology was developed to investigate and optimize the effects of laser power, scanning speed, and spot diameter on the thermal behavior and porosity tendency of AlSi10Mg during selective laser melting. A 3D transient thermal finite element model was combined with a full factorial design of 27 simulations and response surface modeling.

The results showed that laser power and spot diameter were the dominant parameters affecting maximum temperature, while scanning speed had a statistically insignificant effect within the investigated range. In contrast, laser power, scanning speed, and spot diameter all significantly affected the NPI, with significant interaction and curvature effects. Low energy input promoted insufficient melting and lack-of-fusion tendency, whereas excessive energy input resulted in very high temperatures and negative NPI values associated with over-melting and a tendency toward thermal instability.

RSM optimization identified a feasible processing window of approximately 151–164 W laser power, 804–866 mm/s scanning speed, and 0.079–0.084 mm spot diameter. The corresponding VED ranged from approximately 32 to 34 J/mm³, with NPI values close to zero. These results demonstrate that minimum porosity tendency is achieved through a balance between sufficient melting and thermal stability rather than by maximizing energy input.

The optimized processing window was further supported by comparison with published melt-pool dimensions and experimental SEM micrographs. The numerical model reproduced the general trends in melt-pool dimensions, while the experimental observations showed lack-of-fusion defects under low-energy conditions and keyhole-related defects under excessive-energy conditions. Overall, the combined FE-DOE-RSM framework provides an efficient approach for identifying a feasible processing window for porosity reduction in AlSi10Mg SLM.

5 Limitations and future work

The present study was limited to a single-track, single-layer thermal model and therefore did not account for multilayer thermal accumulation or track-to-track interactions. The FE model also involved several simplifying assumptions, including the use of a moving Gaussian heat source

and the exclusion of melt-pool fluid flow, Marangoni convection, recoil pressure, and evaporation. These simplifications limit the ability of the model to reproduce the detailed multiphysics behavior of the melt pool and associated defect-formation mechanisms. In addition, the optimization considered only laser power, scanning speed, and spot diameter, while other influential process parameters, including hatch spacing, layer thickness, powder characteristics, and scanning strategy, were not investigated. The experimental investigation using the XM200G was conducted for selected processing conditions and was used primarily for qualitative comparison of microstructural and defect features, rather than for comprehensive quantitative measurement of porosity or NPI. Quantitative assessment of the FE model was limited to comparison of selected melt-pool dimensions with experimentally reported values from the literature.

Future work should therefore extend the model to multiple tracks and layers and incorporate additional thermophysical phenomena to improve the prediction of melt-pool behavior and defect formation. The effects of hatch spacing, layer thickness, powder characteristics, and scanning strategy should also be incorporated into a broader optimization framework. Coupled thermo-mechanical and multiphysics simulations could further be employed to investigate residual stress, distortion, and microstructural evolution. Finally, more extensive experimental measurements of melt-pool dimensions and porosity should be conducted to provide quantitative validation of the optimized processing window.

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