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Process parameters effect on porosity rate of AlSi10Mg parts additively manufactured by Selective Laser Melting: challenges and research opportunities

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ABSTRACT

Purpose: The present study aims to conduct a literature review on the various methods explored to enhance the quality of AlSi10Mg parts manufactured via the Selective Laser Melting (SLM) process. Specifically, the research focuses on identifying strategies for reducing the porosity level in SLM-fabricated AlSi10Mg parts. Considering the highly competitive nature of the market in which SLM technology is employed, improving part quality is necessary to ensure business continuity and maintain a competitive edge.

Design/methodology/approach: The present study offers a comprehensive examination of the SLM process, particularly emphasising the diverse parameters that can influence the porosity rate in SLM-fabricated parts. By providing a detailed description of the SLM process, we highlight the intricacy of this technology and discuss the significance of various parameters. Furthermore, we present a literature review of prior research on SLM, summarising the studied parameters and their impact on porosity. This research aims to enhance our understanding of the SLM process and the parameters that affect the density of SLM-fabricated parts.

Findings: The present study aims to identify research opportunities in the field of SLM technology. One particularly promising area of investigation is exploring the correlation between scan direction and the porosity rate in SLM-fabricated parts. This research seeks to enhance our understanding of the relationship between these two parameters and their potential impact on the quality of SLM-fabricated parts.

Practical implications: By reducing porosity, industries such as aerospace and aeronautics can attain enhanced performance through mechanical system optimisation.

Originality/value: The present study summarises the various methods previously investigated for reducing the porosity rate in parts manufactured using the SLM process. Additionally, it proposes new avenues for achieving further parameter optimisation to attain higher levels of quality.

Keywords: Selective Laser Melting, Porosity reduction, AlSi10Mg, Laser powder bed fusion, Density improvement

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Additive Manufacturing, or AM, is an innovative manufacturing method with immense potential. According to Gartner's Hype Cycle for emerging technologies in 2015 [1], the adoption of AM in industries is projected to become widespread and reach maximum productivity within the next 2-5 years. This forecast is supported by the increasing number of manufacturers utilising AM for mass production. Statistical data indicates significant growth in the research sector associated with Additive Manufacturing, with a 40% increase from 2015 to 2019 [2], further affirming the expansion of this promising technology.

Additive Manufacturing, also known as 3D printing, is a manufacturing process that involves the layer-by-layer addition of material to build parts. It differs from subtractive processes like milling or turning, where the material is removed from a larger block to achieve the desired shape. Both methods have their advantages and disadvantages, and they are often used in combination to leverage the benefits of each. According to Vega et al. [3], Additive Manufacturing can be categorised into seven main categories: Material Extrusion, Directed Energy Deposition (DED), Vat Polymerization, Binder Jetting, Material Jetting, Sheet Lamination, and Powder Bed Fusion (PBF), which includes Electron Beam Melting (EBM), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM). Dobrzański et al. [4] identified four categories of technologies that utilise metal and ceramic powders, with one of these technologies being the focus of this review, namely Powder Bed Fusion.

Additive Manufacturing, particularly SLM, also called Laser Powder Bed Fusion (L-PBF), is an advanced technology belonging to the Additive Manufacturing (AM) family of processes. Developed by the Fraunhofer Institute for Laser Technology (ILT) [5], SLM technology has garnered considerable attention as an additive manufacturing method owing to its numerous advantages.

One of the primary advantages of SLM is its capability to manufacture parts with high mechanical properties and relatively good dimensional accuracy. Moreover, the process offers versatility by accommodating a wide range of materials. Additionally, SLM enables the production of near-net-shape parts, reducing the need for extensive post-processing. However, this technology has certain drawbacks, such as the requirement for significant support structures during production, which can be time-consuming and material-intensive. In summary, SLM is a powerful technology with the potential to revolutionize the manufacturing industry, but it is also important to consider its limitations.

According to the research conducted by A.Y. Al-Maharma et al. [6], the characterisation of porosity in AM reveals a functional dependence and can be categorised into two distinct types. The first type, engineered porosity, involves the intentional creation and precise control of pore structures to enhance performance and serve specific functions. The second type, referred to as porous defects, refers to unintentionally formed pores within the well-prepared structure of the additively manufactured material. Engineered porosity offers various advantages in certain manufacturing domains, including weight reduction while maintaining structural integrity, improved energy absorption, facilitation of fluid or gas flow, optimisation of thermal insulation, promotion of biocompatibility in medical implants, controlled drug release, and enhanced sound absorption.

In contrast, porous defects can significantly impact the mechanical properties, structural integrity, and overall functionality of additively manufactured components. These unintended voids can compromise the material's tensile and fatigue strengths as they serve as initiation sites for damage under tensile and cyclic loading [7-9]. Furthermore, the rough surface resulting from these defects can adversely affect the corrosion resistance of additively manufactured parts, especially those composed of metals, when exposed to highly aggressive corrosive environments [10,11].

SLM technology, an advanced form of 3D printing, utilises Computer-Aided Design (CAD) models to precisely and accurately build complex parts layer by layer using fine powders [12]. The selective fusion of specific areas within the layers using a high-energy laser beam results in the formation of complete parts [13-16]. This process offers several advantages, including manufacturing highly intricate parts such as waveguides, lightweight structures in the aerospace industry, assembly-free heat exchangers, and moulds with internal flow channels. Moreover, SLM technology is recognised as an eco-friendly manufacturing method as it reduces waste and helps conserve resources [17]. The capability to fabricate complex shapes provides designers with greater freedom as they can create previously unattainable parts using traditional manufacturing techniques [12]. Furthermore, the SLM process demonstrates high dimensional accuracy and excellent mechanical properties.

SLM technology can process a wide range of materials in powder form. Among the most commonly utilised alloys in SLM are Ti6Al4V, Inconel718, 316L, and AlSi10Mg. These alloys find diverse applications in aerospace, dental, aeronautics, automotive, robotics, and medical industries. Working with multiple materials enables the production of parts with specific properties, including high strength, corrosion resistance, and biocompatibility, which are crucial for various fields. Leveraging SLM technology to process these alloys has produced high-quality and highly precise parts that are well-suited for a wide array of applications.

To achieve high-quality final parts using SLM technology, a material alloy in powder form with specific characteristics and a granulation ranging from 10 to 60 µm [18] is utilised. The raw material for SLM can be obtained through various powder atomisation processes, such as water atomisation, inert gas atomisation, or plasma atomisation [19]. The different powder atomisation processes enable the production of powders with specific granulation and tailored properties, offering designers greater flexibility in selecting materials that meet the requirements of their intended applications.

In the layer-based approach of SLM technology, the construction of a part involves spreading fine powder in layers, typically with a thickness ranging from 20 µm to 150 µm [20]. Various types of powder spreading systems are employed in SLM machines, with flexible carbon fibre brush blades commonly used in EOS machines [20] and rigid rollers utilised in Addup machines [21]. These systems play a critical role in ensuring the consistent and precise thickness of each powder layer, which is vital for achieving the desired quality and accuracy of the final part [22]. Figure 1 illustrates the layering mechanics employed in SLM machines. Complex geometries and shapes can be fabricated with high precision and accuracy through this layering process.

In their research, Nesma T. Aboulkhair et al. pointed out a specific challenge associated with utilising SLM technology for processing the AlSi10Mg alloy [17]. They noted that, compared to other powder alloys, the AlSi10Mg powder exhibits a lower flowability rate, as demonstrated in Table 1. This lower flowability rate presents difficulty in achieving uniform layering of the alloy and necessitates meticulous attention to avoid any irregularities in the layering process.

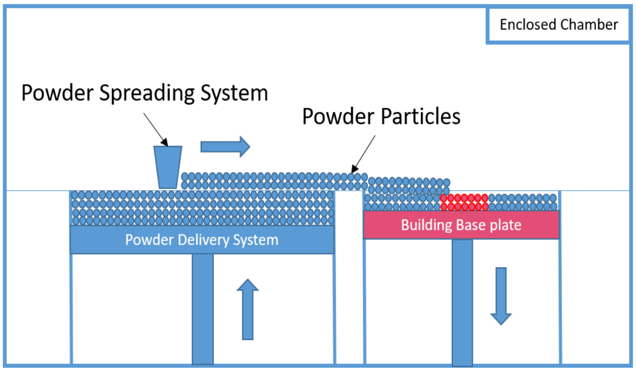

Fig. 1. Example of layering cinematics in SLM machines [21]

Table 1.
Comparing the flowability of different SLM candidate materials [17]

Powder Material	Flowability, s/50 gm
Ti64	47
Stainless Steel 316	14.6
Al6061	77
AlSi10Mg	No flow

Following the deposition of thin powder layers, a CAD model guides the selective melting process using one or multiple high-energy laser beams.

These laser beams are precisely directed using a scanner head comprising multiple mirrors, as depicted in Figure 2. The scanner head's intricate configuration allows for the accurate and controlled melting of the powder layers during the additive manufacturing.

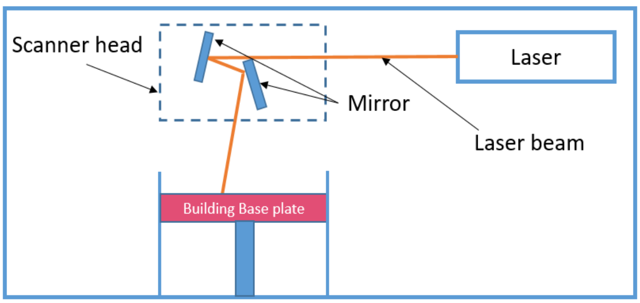

Fig. 2. Laser beam direction by mirrors [21]

Table 2.
Comparing thermal conductivity and reflectivity of different SLM candidate materials [17]

Powder material	Thermal conductivity, W/(m K)	Reflectivity, %
Ti64	6.7	53–59
Stainless Steel 316	21.4	60
Al6061	172	91
AlSi10Mg	146	91

As mentioned by Nesma T. Aboulkhair et al. [17], AlSi10Mg powder exhibits a high reflectivity and thermal conductivity compared to other powder alloys, as indicated in Table 2. This characteristic necessitates higher laser power to compensate for these effects during the melting process and ensure proper and effective melting of the powder material. The higher laser power helps overcome the challenges associated with the high reflectivity and thermal conductivity of AlSi10Mg, allowing for successful melting and desired consolidation of the powder layers.

The use of AlSi10Mg alloy is widespread in the aeronautic and aerospace industries due to its advantageous properties, including lightweight characteristics and high corrosion resistance [23]. However, it is important to note that this alloy exhibits high reactivity to oxygen and hydrogen under high-temperature conditions. To mitigate this reactivity, parts manufactured from AlSi10Mg are typically produced within a controlled environment using an inert gas, such as argon. The inert gas is circulated within the build chamber at a controlled flow rate, serving three main functions, as depicted in Figure 3. Firstly, it prevents oxidation during the part construction process. Secondly, it safeguards the optical system from fumes generated during the process. Lastly, it shields the powder bed from spattering. Both inert gas flows, labelled as inert gas flow 1 and inert gas flow 2, are utilised to accomplish these objectives effectively.

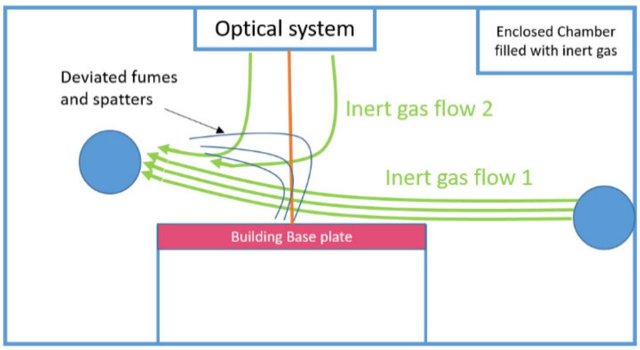

Fig. 3. Inert gas flow circulation in the SLM printing chamber [21]

Upon the completion of each manufacturing process, the residual powder that has changed its properties, particularly the particle size distribution due to the thermal impact of the laser, is recovered and restored to its original characteristics. This is achieved by implementing a sieving mechanism, which separates the used powder from any debris or unwanted particles, allowing for the recycling and reutilization of the powder in subsequent manufacturing cycles. The sieving process helps maintain the quality and consistency of the powder, ensuring that it retains its original properties and can be effectively reused in future additive manufacturing processes.

Based on the various factors discussed, it is evident that controlling the SLM process can be challenging, which may result in various deficiencies, including porosity.

Based on the studies previously cited and the analysis of the functioning of the SLM process, it is possible to identify some important but non-exhaustive list of challenges that pose difficulties in achieving mastery of the process for AlSi10Mg production using SLM technology:

- The low flowability of AlSi10Mg powder poses challenges to the layering process and can lead to variations that impact the overall stability of the process, especially in terms of porosity generation.
- The high reflectivity and conductivity of AlSi10Mg can make the process unstable and difficult to control.
- The requirement for inert gas circulation to protect the powder bed from the spatters effect can make the mastery of the process more intricate, especially for large-scale machines where achieving laminar flow becomes challenging in the fusion chamber.
- The recycling step, aimed at restoring the initial properties of the powder, also contributes to the difficulty of mastering the process.

The remaining portion of the document consists of three main sections. The first section entails a comprehensive literature review examining previous research to mitigate the porosity rate in parts manufactured using SLM technology. This section aims to comprehensively understand the existing knowledge and strategies employed in reducing porosity.

The second section presents novel approaches and potential improvements to decrease the porosity rate in SLM-fabricated parts further. This section will explore new techniques, process parameters, and material considerations that have the potential to enhance the quality and reduce the porosity in the final parts.

Lastly, the document summarises the key findings from the literature review and the proposed improvement methods. It will also outline the next steps and future directions for further research in reducing porosity in SLM-produced parts. The conclusion section will provide a comprehensive study overview and highlight potential avenues for future exploration and experimentation.

2. Porosity improvement challenges of SLM parts: literature review

This study aims to conduct a comprehensive literature review of previous research studies focused on reducing the porosity level in parts fabricated using SLM technology. SLM has emerged as a prominent additive manufacturing technique that offers numerous advantages and has found application in various industries, including aerospace, medicine, and aeronautics.

The utilisation of SLM technology in these industries has demonstrated its potential in delivering high-quality products that effectively meet the stringent requirements and specifications of end-users. With its ability to produce complex and intricate parts precisely, SLM has become a valuable tool in achieving optimal results in industries with essential advanced manufacturing techniques.

Reducing porosity in SLM-fabricated parts is a critical aspect as it directly influences the mechanical properties, structural integrity, and overall performance of the final products. By conducting a thorough literature review of existing studies, this research aims to identify and analyse the strategies, methodologies, and advancements proposed and explored to mitigate porosity issues in SLM manufacturing.

The findings of this study will contribute to the existing body of knowledge, provide insights into the current state of research, and uncover new opportunities for further improvement in reducing porosity levels in SLM-fabricated parts.

The quality of parts manufactured through SLM can be assessed based on several important characteristics, including porosity or density, mechanical properties, surface roughness, hardness, and dimensional accuracy. Achieving a high level of quality in the SLM industry is a significant challenge, as it must be balanced with cost considerations and production time. Research efforts in the field of SLM are focused on optimising these characteristics to ensure the production of parts that meet the specific requirements of industries such as aerospace, medicine, and aeronautics.

Porosity is a common occurrence observed in parts manufactured using SLM technology. While porosity can be advantageous in certain applications, such as the medical biology field, where it enables the production of biocompatible scaffolds with internal and external pores for improved bone tissue integration, it is considered a defect in industries such as aeronautics, aerospace, and automotive, where high mechanical properties are crucial.

Extensive research conducted by E. Yasa et al. [25] has demonstrated that porosity significantly impacts the mechanical properties of SLM parts. The presence of pores in SLM-produced parts affects their density, resulting in altered mechanical characteristics and potentially compromising the functionality of mechanical systems. Current research in SLM aims to explore methods to minimise porosity and produce parts with superior mechanical properties that meet the rigorous requirements of diverse industries.

Porosity in a material refers to the percentage of voids present compared to its total volume. Quantification of porosity can be achieved using two methods: a volume-based approach that relies on tomography measurement and a surface-based approach that calculates the surface area of accessible pores. Figure 4 provides an example of porosity observed in SLM parts, where the surface-based approach was utilised to measure the porosity. The pores are depicted in black, while the solid material is represented in white. Extensive research in the field of SLM is dedicated to comprehending the factors influencing porosity and devising strategies to minimise it.

Fig. 4. Example of porosities encountered in parts produced in SLM

In their study on Al-Si-Mg alloys fabricated by SLM, Kun V. Yang et al. [26] identified three distinct types of porosity found in these alloys. The first type is large irregular-shaped porosities, also known as lack-of-fusion porosities, resulting from insufficient energy density during fabrication. The second type is large round porosities, referred to as keyhole porosities, which are caused by the use of excessive energy density. The third type is gas porosities with a size below 5 µm, arising from the presence of hydrogen on the surface of powder grains. The morphology of the porosity provides valuable insights into its formation mechanism. This understanding can greatly assist industrial manufacturers in identifying the root causes of porosity-related defects and resolving quality issues more efficiently. It enables the assessment of energy density used for powder melting, distinguishing between low and high energy settings, and provides insights into powder quality and the influence of hydrogen in the process.

Ferrar et al. [25] have highlighted the extensive number of parameters that can potentially impact the SLM process, with more than 130 parameters identified. Among these parameters, approximately 13 have been identified as critical factors that significantly influence the quality characteristics of the final manufactured parts. These vital parameters are crucial in determining the porosity level, mechanical properties, surface finish, dimensional accuracy, and other important aspects of the fabricated parts. Understanding and optimising these key parameters is essential for achieving high-quality SLM parts that meet the stringent requirements of various industries.

Several researchers, including those referenced in studies [18, 26-29], have extensively studied the impact of various process parameters on the final parts manufactured using SLM technology. These parameters encompass a range of factors, such as laser power, scan speed, hatching strategy, layer thickness, and more. In the study conducted by Gibson I et al. [16], the process parameters influencing the porosity level in AlSi10Mg SLM parts have been categorised into four main categories: Laser-related parameters, Scan-related parameters, Powder-related parameters, and Temperature-related parameters. Table 3 provides a comprehensive overview of these categories and the specific parameters within each category, shedding light on their influence on porosity formation during the SLM process. Such research is crucial in optimising the process parameters to minimise porosity and enhance the quality of SLM parts.

Most research in the field has focused on investigating and optimising four key process parameters: laser power, scan speed, hatching strategy, and layer thickness. These parameters are crucial in determining the quality, porosity level, and mechanical properties of parts produced using SLM technology. Researchers have conducted numerous studies to understand the influence of these parameters on the final characteristics of the manufactured parts and to develop guidelines for their optimal selection in order to achieve the desired outcomes.

Additionally, volumetric energy density (VED) has been studied as a combination of these four parameters. VED is quantified as [J/mm^3] and is calculated as the combination of the four aforementioned parameters:

$$VED = \frac{P}{v * h * t} \quad (1)$$

where P [W] is the laser power, v [mm/s] is the scan speed, h [mm] is the hatch spacing, and t [mm] is the layer thickness.

A.H. Maamoun et al. [30] conducted a design of experiment to examine the impact of SLM process parameters on the porosity of AlSi10Mg alloy parts. They analysed four parameters: laser beam power (P), laser scan speed (v), hatch spacing (h), and volumetric energy density (VED). Their findings indicated that employing an energy density within the 50 to 60 J/mm^3 range resulted in a high relative density of up to 99.7%.

A similar study conducted by Jing Chen et al. [27] determined that achieving a VED of approximately 44.53 J/mm^3 is suitable for producing a dense AlSi10Mg alloy.

Moreover, N. Read et al. [31] employed a design of experiment approach to optimise the SLM process, focusing on four parameters: laser power (P), scan speed (v), hatch spacing (h), and island size. Their findings indicated that utilising an optimal VED value of 60 J/mm^3 resulted in minimised porosity.

Table 3.
Classification of SLM influencing parameters [16]

Process parameters			
Laser-related	Scan-related	Powder-related	Temperature-related
Laser power	Scan speed	Particle size	Powder bed temperature
Spot size	Scan spacing	Particle shape & distribution	Powder feeder temperature
Pulse duration	Scan pattern	Powder bed density	Temperature uniformity
Pulse frequency		Layer thickness	
		Material properties	

Furthermore, Rao et al. [32] observed that the porosity level remains consistent whether a VED of 50 J/mm or 100 J/mm^3 is employed. These findings support the conclusions drawn by Giovagnoli et al. [28] and Pal et al. [18] that the volumetric energy density-based approach has certain limitations in accurately estimating porosity.

Based on the studies mentioned above, it can be inferred that there is a variation in the optimal value of VED, which aligns with the findings of Giovagnoli et al. [28], who concluded that relying solely on this parameter is inadequate for optimising the porosity rate.

Additionally, Cha et al. [33] conducted a study to investigate the influence of the built atmosphere on the porosity level of AlSi10Mg parts manufactured using SLM. They discovered that regardless of the built atmosphere employed, the resulting parts exhibited consistent porosity levels. This indicates that the built atmosphere has a negligible effect on the porosity level of AlSi10Mg parts produced through SLM.

Moreover, Liu et al. [29] determined that laser power significantly impacts porosity in SLM of AlSi10Mg powder, contributing to 49.43% of the porosity variation. Scan speed was the second most influential factor, contributing to 33.74% of the porosity variation. These conclusions were drawn using factor analysis of SLM process parameters with normalised quantities and the Taguchi method.

Numerous studies [18, 26-29] have focused on optimising the five key parameters to minimise porosity. These investigations have demonstrated that adjusting these parameters can lead to a reduction in porosity rates.

Another approach to reducing porosity involves examining the influence of powder storage conditions and characteristics. Weingarten et al. [34] explored different drying methods for the aluminium powder to mitigate the adherence of hydrogen to the surface of powder grains, which can contribute to porosity. The study investigated drying powder within the machine using low laser power and high scan speed, as well as drying powder at temperatures of 90°C and 200°C in an oven. The results indicated that drying powder at 90°C reduced hydrogen content by 35%, while drying at 200°C reduced it by 50%. The study also revealed that drying powder outside the machine was more effective in reducing porosity.

In a separate study by Fiegl et al. [35], it was observed that the oxygen and hydrogen content in AlSi10Mg0.4 powder used in SLM significantly increased during recirculation. The researchers compared the oxygen and hydrogen levels of virgin powder and used powder over 30 months. They found that the oxygen content rose from 0.05% to 0.12%, while the hydrogen content increased from 80 ppm to 150 ppm. The study concluded that this powder degradation led to a decrease in density, resulting in specimens made from reused powder exhibiting four times higher porosity than those made from virgin powder.

The study conducted by Bin Anwar et al. [36] employed image processing and optical microscopy to assess the distribution of spatter on a powder bed of AlSi10Mg. The researchers utilised contrast for spatter detection and size determination, allowing them to quantify the distribution in terms of mass and size. The findings revealed that most spatter particles were concentrated along the scan direction, with a gradual reduction in both mass and size as the distance from the scanned regions increased. Additionally, minor distributions orthogonal to the scan direction were also observed. Figure 5 illustrates the distribution of spatter as observed in the study.

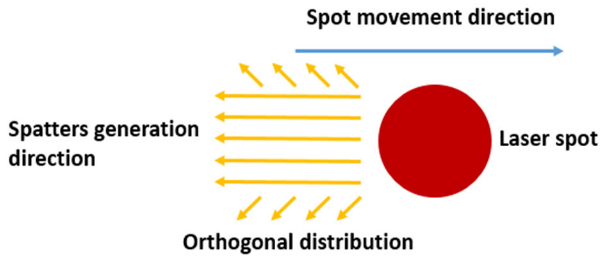

Fig. 5. Spatters distribution during the SLM process

In a separate study by Bin Anwar et al. [37], the effects of laser scan direction, part placement, and inert gas flow velocity on the tensile strength of AlSi10Mg parts fabricated using SLM were quantified. The researchers specifically investigated the influence of scan direction on tensile strength by considering two configurations, as illustrated in Figure 6: scanning in the same direction as the gas flow and scanning against the direction of the flow. The study demonstrated that scanning against the direction of the gas flow improved tensile strength compared to scanning in the same direction.

Regarding this conclusion, it can be important to study the effect of these two configurations on porosity formation.

S. Patel et al. [38] studied the influence of laser spot defocusing during the SLM process of the AlSi10Mg aluminium alloy on the density of the produced parts.

The primary objective of their research is to investigate the impact of laser beam defocusing on the production of low porosity parts using stable conduction mode and steady-state transition mode SLM process parameters for AlSi10Mg. The researchers aim to gain a deeper understanding of how variations in the focus of the laser beam can affect the SLM process and ultimately contribute to manufacturing high-quality parts with minimal porosity.

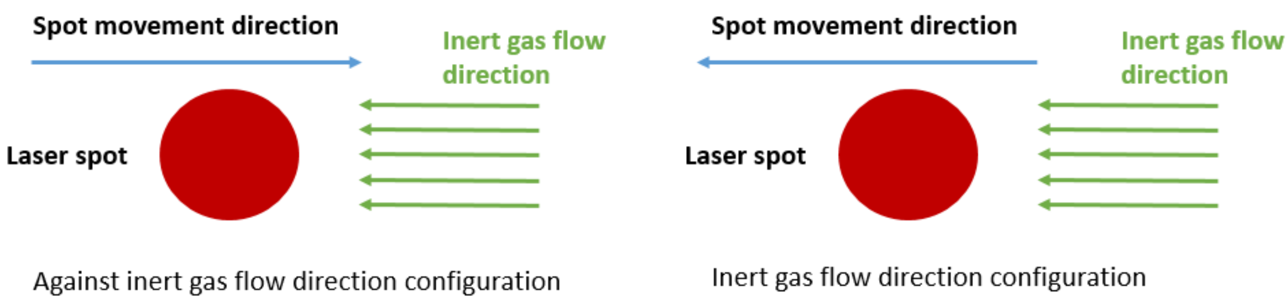

Fig. 6. Laser spot movement in or against the inert gas flow direction

To achieve this, the beam defocusing was deliberately positioned above the build plate, creating a divergent beam effect at the interaction point between the laser and the material, in contrast to a convergent beam effect that would have been obtained by defocusing below the build plate.

They demonstrated the relationship between the laser spot defocusing and the obtained result in terms of porosity.

Most of the previously cited studies did not consider the effect of the machine type, particularly the effect of the layering system. The definition of VED for a machine with a roller-based layering system and a machine with a flexible blade or fibre-based layering system may differ. It cannot be directly compared due to the powder compression effect applied by the roller, which is not present in machines with a flexible system. Compressing the powder increases its density and, consequently the volume of material within the same volume.

It is also interesting to note that most of the samples used to measure the porosity rate are of simple shape, typically cubes, which do not contain any up facing or downfacing areas. These areas may exhibit behaviour that is significantly different from the middle facing areas studied in these samples. Given that the produced parts are typically composed of different types of areas, the parameters proposed as optimal may result in porosities in these areas.

It would be interesting to replace the parameter number of powder recycling with a number of production cycles it has undergone, as two scenarios can be envisioned: (i) using non-recycled powder to produce a platform containing a very small part, and (ii) using non-recycled powder to produce a platform loaded with parts. It is evident that at the end of production, the condition of the two powders after recycling is not comparable, as in the second scenario, a larger portion of the powder has been thermally affected, which may lead to oxidation and alteration of its characteristics.

If we aim to synthesise the various challenges, conducted studies, and observations discussed in this section, it can be stated that:

- There are over 130 parameters that can influence porosity [24].
- 13 of these parameters are the most influential [24].
- Four parameters, namely laser power, scanning speed, hatch spacing, and layer thickness, have received the most extensive research attention in the literature.
- The parameter with the greatest influence on porosity is laser power, followed by scanning speed [29].
- Studying these four parameters yields highly promising results in terms of porosity rate [18, 26-29].
- A combination of these four parameters, such as Volumetric Energy Density, has been extensively studied and has demonstrated that this parameter alone is not sufficient to optimise the porosity rate [27-28, 30-32].
- The low flowability of AlSi10Mg powder may result in irregularities in the powder bed, which can affect the layer thickness, one of the key parameters, and consequently impact the porosity rate [17].
- The high conductivity and reflectivity of AlSi10Mg make the process challenging to master [17].
- The requirement for inert gas recycling to mitigate the impact of spatters and the difficulty in achieving laminar flow make the process challenging to master [24].
- The nature of the inert gas used does not affect the porosity rate of the produced parts [33].
- The effect of powder porosity on the porosity rate of the parts is not permanent, and preheating the powder helps restore its characteristics [34].
- The number of cycles the powder undergoes increases the oxygen content and the porosity rate in the produced parts [35].

3. Research opportunities

Several studies [12-14, 17,18, 25-29, 32,34] have focused on finding ways to increase the density of AlSi10Mg parts produced using SLM technology by investigating the effect of varying the standard parameters. To achieve a high-density rate, the effect of some other parameters should be explored in detail.

This section comprises four categories of research opportunities, each about a specific aspect that might contribute to porosity reduction.

3.1. Related to the cooling rate

The study conducted by Rao et al. [32] examined the impact of preheating the build plate on the formation of porosity in SLM. They tested two temperatures, 35°C and 200°C, and found that variations in cooling rate can affect the presence of pores in the melt pool. Another factor that may affect the cooling rate and porosity formation is the amount of the build plate covered by parts; a larger fused volume within the same base plate will produce more heat and alter the cooling rate. This presents an intriguing research opportunity that can be approached in various ways:

1. The first approach is a macroscopic one and consists of finding a correlation between the build plate filling rate BPFR defined as equation (2) and the porosity level of built parts:

$$BPFR = \frac{PV}{BPV} \tag{2}$$

where PV is the total volume of different parts present on the baseplate and BPV is the build plate's total volume.
2. The second approach consists of studying the correlation between the surface average of total fused sections by layer and the porosity level.
3. In another approach, we can explore the possibility of finding a correlation between the fused surface within a layer and the porosity level within the same layer.
4. The last approach, and the most complete one, can consist of taking into consideration all the precedent approaches and also taking into consideration fused surface variation during layer construction.

Due to the demonstrated effect of cooling rate on porosity level in part produced using SLM technology, another promising research opportunity consists of studying the correlation between the four following parameters and their effect on porosity level:

A. Artificial cooling time, which represents the time allowed for the precedent layer to cool before fusing the current one,
B. The height of the layer, which represents the distance between the current layer and the baseplate,
C. The position of the part in the baseplate.

This approach may permit defining a minimum artificial cooling time allowing the manufacturing of parts with the desired porosity level independently of layer height or part position with high productivity.

Cha. et al. [32] studied the effect of change in chamber gas from argon to nitrogen on porosity level and demonstrated no significant difference between the two gases. But an important research opportunity may be to study the effect of injected inert gas temperature on porosity level. This temperature may affect the heat dissipation behaviour and, therefore, the cooling rate of parts during manufacturing.

3.2. Related to powder reuse count

The research conducted by Fiegl et al. [35] employed a qualitative experimental approach to investigate the influence of powder reuse on the density of manufactured parts. Specifically, the study examined the correlation between the recycling cycle count applied to the powder and the level of density achieved. Based on these findings, developing a systematic model that establishes a connection between the recycling cycle count, the powder's life cycle history, and the porosity level observed in produced parts would be advantageous. This is because the life cycle history of the powder, including its prior usage in production, can have a significant impact on the oxygen content of the powder, which, in turn, may influence the resulting porosity level in the manufactured parts.

3.3. Related to the scan direction

Based on the findings from the studies conducted by Bin Anwar et al. [36,37], it is important to investigate the influence of scan direction on the occurrence of porosity in the fabricated parts. The presence of spatter and its impact on the laser spot can reduce the energy input, leading to lack of fusion porosity. To gain a more comprehensive understanding of the effect of scan direction in relation to the direction of the inert gas flow on porosity formation, it would be beneficial to explore multiple angles (A) as depicted in the diagram shown in Figure 7. This approach will provide insights into how different orientations of the scan direction and gas flow can influence porosity formation and help optimise the SLM process parameters to mitigate porosity-related defects.

The angle (A) can be varied from 0° to 180° in increments of 10° to encompass a comprehensive range of configurations. Specifically, the angle of 0° represents the configuration where the scan direction is against the inert gas flow. In comparison, the angle of 180° represents the configuration where the scan direction is in the same direction as the inert gas flow. By considering multiple angles within this range, a thorough exploration of the effect of different orientations of the scan direction relative to the gas flow can be achieved, providing valuable insights into porosity formation and its mitigation strategies in the SLM process.

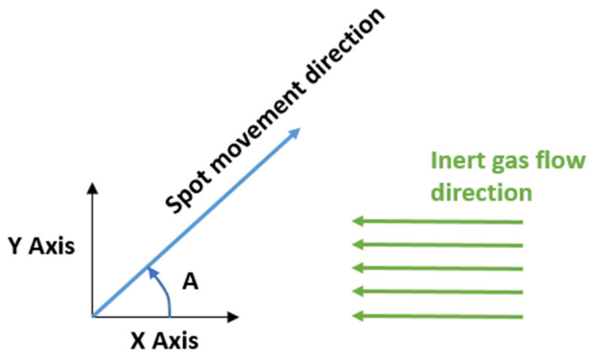

Fig. 7. Laser spot movement direction configuration

3.4. Related to part position

Given the machine architecture used in the SLM process, it is observed that the laser spot undergoes varying levels of defocusing across the build platform, with the centre and edges experiencing different effects, as depicted in Figure 8.

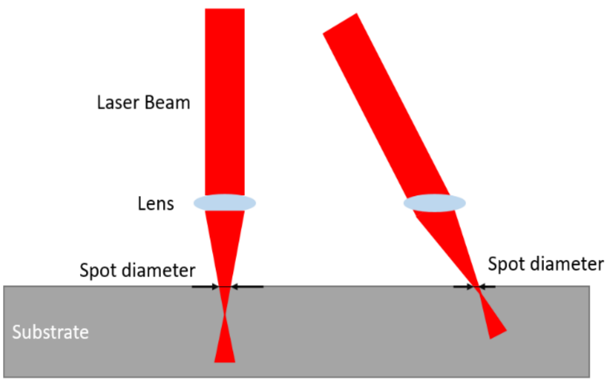

Fig. 8. Laser spot defocusing depending on melting position

The size of the laser spot changes in form and diameter when the melting position is at the edges of the baseplate.

Following the study by S. Patel et al. [36], it would be interesting to investigate the impact of the position of the piece on the manufacturing platform on the porosity rate.

An experiment can be imagined in which several test specimens are produced to measure porosity and are distributed throughout the entire build platform, which will allow for multiple levels of laser spot defocusing to be obtained and thus study the effect of part position.

The different samples can be measured using the surface-based approach to determine the porosity level.

4. Conclusion and outlook

In conclusion, the findings of this study can be summarised as follows:

- The effect of standard parameters, such as laser power, scan speed, hatching, layer thickness, and powder characteristics, on the porosity level of parts manufactured using SLM technology has been studied by multiple authors.
- A significant reduction in porosity can be achieved by manipulating these key parameters.
- Further research is needed to investigate the impact of cooling rate on the percentage of porosity.
- The concept of powder recycling count should be replaced with powder utilisation in relation to the building charging, and its examination is warranted to reduce the porosity rate.
- The scanning direction can be an important parameter influencing the porosity rate.
- The defocusing of the laser spot due to the part position, particularly in large machines, and its effect on the porosity rate should be investigated.

As an important way of optimisation, as a first step, it would be interesting to start by exploring the effect of parameters related to laser spot direction in relation to the inert gas flow direction. The experiment in section 3.3 can be performed.

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