ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20231206200048

Original scientific paper
Received: 2023-12-06, Accepted: 2024-01-09

Influence of the LPBF Process Parameters on the Porosity of the AlSi10Mg Alloy

Sanja Šolić*, Iva Sakač, Vlado Tropša, Mario Šercer

Abstract: Laser powder bed fusion (LPBF) process has a great ability to produce complex AlSi10Mg 3D components with uncommon degrees of freedom for broad span of applications in different industries. Presence of the microstructural imperfections such as porosity, dependent on the parameters of the process can be detrimental to the printed products for different engineering applications. Parameters of the process and different post-processing heat and surface treatments are recognized for decrease of the occurrence of microstructural defects and for the improvement of the mechanical properties. The influence of laser power by applying four different laser speeds at one layer thickness with a constant hatch distance, on the microstructure and microhardness of the AlSi10Mg alloy was examined in this paper. The goal of the research was to determine whether increasing the laser speed will have a significant impact on the change in microstructure and the appearance of porosity in the tested samples.

Keywords: additive manufacturing; AlSi10Mg; microstructure; microhardness; porosity; process parameters

1 INTRODUCTION

The development of additive manufacturing technologies widened the possibilities for the production of complex geometry products directly from 3D models. Compared to conventional manufacturing technologies, additive technologies present certain advantages such as short production times of complex and personalized geometries, high resolution and accuracy with almost no material loss and are mostly used today for tooling and prototyping, in the automotive, space and aerospace industries and also in the production of personalized biomedical products [1, 2]. The selective laser melting (SLM) process is one of the most used additive manufacturing processes today, characterized by a very fast solidification process with high cooling rates of 106 - 108 °C/s, which promotes the cellular growth of crystal grains with uniform crystallization of metastable phases and hybrid crystals [2, 3]. Due to the possibility of complete structural and topological optimization of the product, this process enables the creation of monolithic complex geometries of optimal stiffness with a reduction in product mass of up to 50 %. Considering the significant growth in the use of these technologies, the standardization of the basic principles and terminology associated with additive technologies has been started, and since 2015, according to ISO/ASTM 52900:2021, the process of selective laser melting in powder bed is defined as the Laser Powder Bed Fusion process (LPBF) [2].

In addition to exceptional advantages, the LPBF process also has certain disadvantages such as very high internal stresses, enhanced anisotropy, microstructural porosity and other microstructural defects that can be reduced to a certain level by performing subsequent heat treatments or surface engineering treatments.

Due to their very good technical properties, such as low density, the best electrical and thermal conductivity in relation to density, good corrosion resistance, ductility, high strength and hardness, in combination with acceptable price range, aluminium alloys are widely used as engineering materials. Although many alloys are successfully used in the application of the LPBF process, aluminium-based alloys are still quite demanding for the production of parts with additive technologies, primarily due to the high reflection of the laser beam on the aluminium powder, which significantly affects the efficiency of the laser, the rapid formation of an oxide layer on the surface of the molten material, and a wide range of solidification of the high strength aluminium alloys [4, 5]. AlSi10Mg alloy is the most commonly used aluminium alloy in the LPBF additive manufacturing process due to its very good weldability of the layers, excellent casting properties and high conductivity, excellent strength-density ratio, good mechanical properties and low solidification shrinkage, and is used in a wide range of industries including automotive and aerospace.

The largest impact on the microstructure and properties of the LPBF additively manufactured products have the parameters of the process, of which the influence of laser power and speed, hatch distance, layer thickness and scanning strategy are investigated the most [3].

The laser power affects the amount of energy delivered into the substrate and affects the amount of melted powder in a given layer thickness which depends on the material in the process. Partial melting causes solidification defects due to not filling the entire volume in a given layer thickness. The speed of the laser affects the speed of melting and solidification. The hatch distance during melting determines the level of overlap of the melted layers in one-layer thickness, which enables better melting of the layers. The thickness of the layer determines the height of the powder that will be melted in each pass of the laser. Large layer thicknesses affect incomplete melting and the occurrence of microstructural defects such as balling [6].

To evaluate the influence of the combination of the above parameters, the amount of heat input or the energy density of the laser, E, J/mm^3, is used, which is described by the equation:

$$E = \frac{P}{v \cdot h \cdot t}, \tag{1}$$

where P, W, is the laser power, v, mm/s, the laser speed, h, mm, hatch distance and t, mm, the thickness of the melting layer [3].

The scanning strategy refers to the raster that the laser will pass through when building the product. It is possible to change it between layers based on the requirements for microstructure or geometry in a certain part of the product itself. This parameter has a very large role in determining the final properties of the product because microstructures, mechanical properties and the amount and type of residual stresses are a direct consequence of the scanning strategy [7].

The most significant influence on the mechanical properties of products obtained by the LPBF process is the degree of porosity, that is, the relative density of the workpiece in relation to the theoretical density of the material. Alloys with an almost theoretical density obtained by the LPBF process generally have better properties under tensile load, higher values of the impact toughness and better dynamic properties, therefore it is very important to know the influence of the process parameters on the occurrence and amount of porosity in the material [8, 9]. Given that the LPBF process is a relatively slow process that requires significant amount of time compared to the conventional technologies, especially for products of larger dimensions, in practice there is a tendency to increase the laser speed, with the aim of shortening the building time, which can affect the amount of porosity and reduce the mechanical properties of the product.

In this paper, the influence of laser power by applying four different laser speeds with one thickness of the melted layer with a constant hatch distance, on the microstructure and microhardness of the AlSi10Mg alloy was examined. The purpose of the research was to determine whether increasing the laser speed will have a significant impact on the change in microstructure and the appearance of porosity in the tested samples along with the influence on the microhardness of the samples.

2 MATERIALS AND METHODES

For the purposes of this research, eight test samples of the AlSi10Mg alloy in the shape of a prism with dimensions of 20 × 20 × 10 mm were printed by the laser powder bed fusion additive process on the EOS M270 3D printing machine. Metal powder of the AlSi10Mg alloy produced by EOS, with the chemical composition shown in Tab. 1, was used.

Table 1 Chemical composition (% wt) of the AlSi10Mg powder

Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb	Sn	Ti	Al
9,0 – 11,0	≤0,55	≤0,05	≤0,45	0,2 – 0,45	≤0,05	≤0,1	≤0,05	≤0,05	≤0,15	rest

The parameters of the LPBF process with sample markings are shown in Tab. 2. In the building process, the thickness of the melted layer was 0,06 mm with a constant hatch distance of 0,2 mm.

Fig. 1 shows the test samples in powder bed during the cleaning process.

After separation from the plate, the test samples were prepared for further analysis by means of the standard metallographic procedure. The microstructural analysis of the samples was performed on the samples that were in the polished condition and after etching. For etching, Keller solution (2,5 mL HNO_3; 1,5 mL HCl; 1,0 mL HF and 95 mL deionized water) was prepared.

Figure 1 Test samples in powder bed during the cleaning process

Table 2 LPBF process parameters with sample markings

Sample	Laser speed, mm/s	Laser Power, W	Energy density, J/mm^3
1	1100	370	28,03
2	1200	370	25,69
3	1300	370	23,72
4	1400	370	22,02
5	1100	300	22,73
6	1200	300	20,83
7	1300	300	19,23
8	1400	300	17,86

The microstructure was analysed by means of the Olympus GX53F-5 light microscope equipped with a DP23-CU micro digital camera. The amount of porosity in the microstructure was determined with the image analysis software Image J. For the analysis of the porosity five images of every sample in polished condition at the magnification of 100 x were analysed and the presented results represent the mean value of five obtained results.

The Vickers hardness HV 1, HV 0,2 and HV 0,1, was measured on a KB 30 S microhardness tester (KB Prüftechnik GmbH). The presented results represent the mean value of five indentations with each applied load. Microstructural analysis and hardness measurement were performed at the Laboratory for material testing at University North.

3 RESULTS AND DISCUSSION

Fig. 2 presents the microstructure of the test samples in a polished condition. On almost all samples, melting lines are clearly visible indicating the building pattern of the samples. A certain proportion of porosity is visible on all samples, and the porosity is more pronounced on samples built with lower laser power, with a significant increase in porosity in the samples printed with the lowest laser energy density (samples 6, 7 and 8).

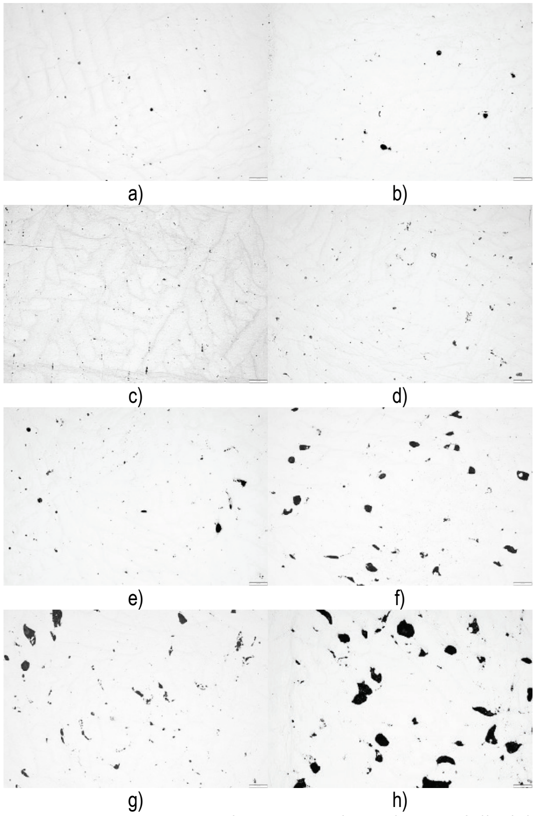

Figure 2 Polished microstructures of the samples (magnification 50:1): a) 1, b) 2, c) 3, d) 4, e) 5, f) 6, g) 7 and h) 8

The amount of the measured porosity is presented in Tab. 3. The results show that the amount of the measured porosity rises almost four times with the increase of the laser speed of 100 mm/s for lower laser power, resulting with the decrease of laser energy density from 22,73 to 20,83 J/mm^3. Further increase in laser speed resulted in further increase of the porosity of the samples with the increase in porosity for more than seven times for the total of 300 mm/s increase in laser speed. Fig. 3 shows the influence of the energy density on the obtained porosity of the samples.

Table 3 Porosity of the samples

Sample	Porosity, %
1	0,19
2	0,33
3	0,33
4	0,46
5	0,54
6	2,11
7	2,09
8	3,86

The obtained results show that the proper selection of the process parameters is very important for obtaining the required properties with minimum microstructural defects and that the increase in laser speed for the purpose of reduction in building time can have significant impact on the density of the products which is in accordance with the literature; Limbasiya et al. [3] and Sabzi et al. [9] state that complete melting of the metal powder cannot be achieved with the low laser energy density which result in partial melting which leads to the increase of the porosity which reduces the relative density of the printed parts.

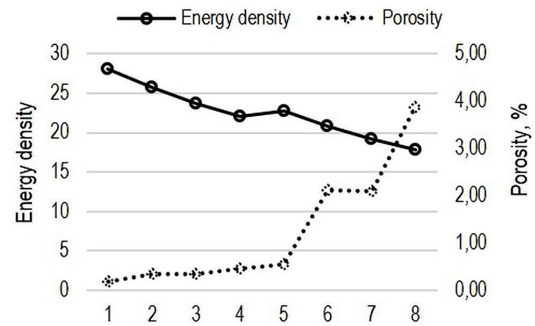

Figure 3 Influence of the energy density on the porosity of the samples

Fig. 4 shows the microstructure of the samples after etching with the Keller solution. The microstructure of the test samples was analysed in the transverse direction in relation to the printing direction (perpendicular to the Z axis). On all test samples after etching, a banded morphology with clearly defined melting lines is observed, and the laser melting area in the direction of the X and Y axes is clearly visible.

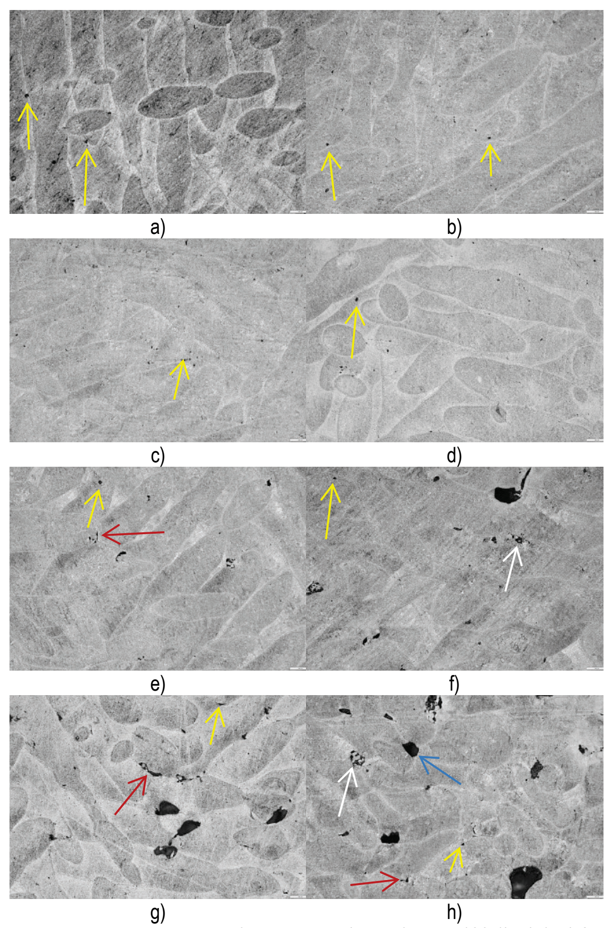

Figure 4 Etched microstructures of the samples (magnification 100:1): a) 1, b) 2, c) 3, d) 4, e) 5, f) 6, g) 7 and h) 8

Microstructural analysis shows that the porosity (marked with yellow arrows) is present in all samples with the increase in the samples with lowest energy density (samples 6, 7 and 8). In addition to porosity, incomplete melting is also observed on the samples, which is indicated by red arrows in the figures. If a sufficient amount of energy is not introduced into the substrate, there is not a sufficient amount of energy to dissolve the metal powder, so the metal powder does not melt evenly, and even during solidification, the entire volume is not filled, which is why areas of incomplete melting are created [10]. The blue arrow shows other microstructural defects, cavities of larger dimensions that arise due to an insufficient amount of melt that should fill the space between the melting layers. All these defects are caused by improperly adjusted parameters. The lower the energy density of the laser, the weaker the power for melting of the powder, and if there is not enough energy to melt the powder, the formation of layers without porosity and other defects in the microstructure cannot occur. Most cavities of larger dimensions are present at samples 6, 7 and 8. Balling [6] was also observed and is indicated by white arrows on samples 6 and 8. Presence of multiple microstructural defects and increased porosity confirms that the proper selection of process parameters is very important for achieving desired properties of the additively manufactured products with less defects [11]. Low energy density will result in partial melting of the powder particles which will result in more porosity and reduction of the relative density of the built AM product. On the other hand, formation of the keyhole defects is caused due to the spatter and the turbulence in molten pools that occur at the high energy density. Choosing the optimum energy density is crucial for production of additively manufactured parts with high relative density [11].

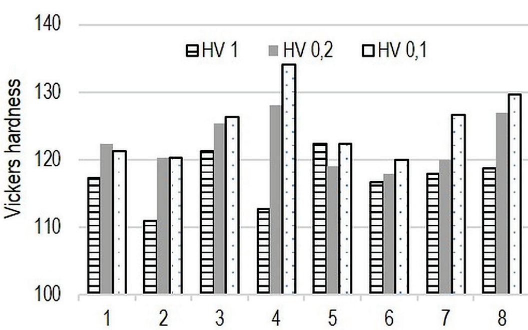

Figure 5 Measured Vickers hardness of the samples

The results of the microhardness measurement are presented in the Fig. 5. The results show that the range of the process parameters used within this research did not affect significantly the results of the hardness measurement. Generally, the LPBF products exhibits higher average hardness results compared to conventionally produced parts [12, 13]. However different LPBF process parameters affects differently the hardness values of the AlSi10Mg parts. Several research [13, 14] studied the influence of the LPBF process parameters on the hardness of the AlSi10Mg alloys. The results showed that increase in laser power decreases the microhardness of the samples produced, with the same trend accomplished with the energy density increase. The cause was accredited to the reduction in grain size. Also it has been noticed that the increase in scanning speeds results with the high microhardness values due to increase in cooling rate [15].

4 CONCLUSION

Laser powder bed fusion process is one of the most widely used additive manufacturing processes today, which enables complete structural and topological optimization of the product, which makes possible to create the monolithic complex geometries with optimal stiffness while reducing product mass by up to 50 %.

In this paper, the influence of two values of laser power with the combination of four laser speeds with the constant thickness of the melted powder and the constant hatch distance on the microstructure and microhardness of the AlSi10Mg alloy was examined. The obtained results showed that the amount of laser energy density used in the melting process have a significant effect on the increase of the microstructural porosity. The primary influence has the laser speed, where each increase in the laser speed by 100 mm/s for every laser power caused the increase in porosity of the built samples which leads to conclusion that the selection of the optimal parameters of the process is the key for production of additively manufactured parts with high relative density. The laser energy density range studied in this paper and the increase in porosity did not significantly affect the changes in the hardness of the tested samples.

The wide application of the LPBF additive process is justified by the good properties of the workpieces and processing with minimal material loss. However, in order to realize the possibility of using such products in concrete exploitation conditions of mechanical load, it is necessary to achieve full density of the material with minimal porosity and microstructural defects, for which it is necessary to take care of the selection of optimal parameters of the LPBF additive process.

5 REFERENCES

[1] Viderščak, D., Schauperl, Z., Šolić, S., Ćatić, A., Godec, M., Kocijan, A., Paulin, I., & Donik, Č. (2021). Additively Manufactured Commercial Co-Cr Dental Alloys: Comparison of Microstructure and Mechanical Properties. *Materials, 14*(23), 7350. https://doi.org/10.3390/ma14237350

[2] Alghamdi, F., Song, X., Hadadzadeh, A., Shalchi-Amirkhiz, B., Mohammadi, M., & Haghshenas, M. (2020). Post heat treatment of additive manufactured AlSi10Mg: On silicon morphology, texture and small-scale properties. *Materials Science & Engineering A, 783*, 139296. https://doi.org/10.1016/j.msea.2020.139296

[3] Limbasiya, N., Jain, A., Soni, H. et al. (2022). A comprehensive review on the effect of process parameters and post-process treatments on microstructure and mechanical properties of selective laser melting of AlSi10Mg. *Journal of Material Research and Technology, 21*, 1141-1176. https://doi.org/10.1016/j.jmrt.2022.09.092

[4] Clement, C. D., Masson, J., & Kabir, A. S. (2022). Effects of Heat Treatment on Microstructure and Mechanical Properties of AlSi10Mg Fabricated by Selective Laser Melting Process. *Journal of Manufacturing and Materials Processing, 6*(3), 52. https://doi.org/10.3390/jmmp6030052

[5] Šolić, S., Dolić, N., & Tropša, V. (2021). Influence of the Annealing Termperature on the Microstructure and Hardness of SLM AlSi10Mg Parts. *Conference Proceedings International Conference on Materials - Corrosion, Heat Treatment, Testing and Tribology, 2021* / Stojanović, Ivan - Zagreb: Hrvatsko društvo za zaštitu materijala, Zagreb, 369-375

[6] Aboulkhair, N. T., Maskery, I., Tuck, C., Ashcroft, I., Everitt, N. M. (2016). On the formation of AlSi10Mg single tracks and layers in selective laser melting: microstructure and nanomechanical properties. *Journal of Materials Processing Technology, 230*, 88-98. https://doi.org/10.1016/j.jmatprotec.2015.11.016

[7] Shipley, H., McDonnell, D., Culleton, M., Coull, R., Lupoi, R., O'Donnell, G., & Trimble, D. (2018). Optimization of process parameters to address fundamental challenges during selective laser melting of Ti-6Al-4V: A review. *International Journal of Machine Tools and Manufacture, 128*, 1-20. https://doi.org/10.1016/j.ijmachtools.2018.01.003

[8] Gor, M., Dobriyal, A., Wankhede, V., Sahlot, P., Grzelak, K., Kluczynski, J., et al. (2022). Density prediction in powder bed fusion additive manufacturing: machine learning-based techniques. *Appl Sci, 12*, 7271. https://doi.org/10.3390/app12147271

[9] Sabzi, H. E. & Rivera-Díaz-del-Castillo, P. E. J. (2019). Defect prevention in selective laser melting components: compositional and process effects. *Materials, 12*(22), 3791. https://doi.org/10.3390/ma12223791

[10] Sufiiarov, V. S., Popovich, A. A., Borisov, E. V., Polozov, I. A., Masaylo, D. V., & Orlov, A. V. (2017). The effect of layer thickness at selective laser melting. *Procedia Engineering, 174*, 126-134. https://doi.org/10.1016/j.proeng.2017.01.179

[11] Gor, M., Soni, H., Wankhede, V., Sahlot, P., Grzela, K., Szachgluchowicz, I., et al. (2021). A critical review on effect of process parameters on mechanical and microstructural properties of powder-bed fusion additive manufacturing of SS316L. *Materials, 14*(21), 6527. https://doi.org/10.3390/ma14216527

[12] Read, N., Wang, W., Essa, K., & Attallah, M. M. (2015). Selective laser melting of AlSi10Mg alloy: process optimization and mechanical properties development. *Materials & Design, 65*, 417-424. https://doi.org/10.1016/j.matdes.2014.09.044

[13] Maamoun, A. H., Xue, Y. F., Elbestawi, M. A., & Veldhuis, S. C. (2018). The effect of selective laser melting process parameters on the microstructure and mechanical properties of Al6061 and AlSi10Mg alloys. *Materials, 12*(1), 12. https://doi.org/10.3390/ma12010012

[14] Mathe, N. R. & Tshabalala, L. C. (2019). The validation of the microstructural evolution of selective laser-melted AlSi10Mg on the in-house built machine: energy density studies. *Progress in Additive Manufacturing, 4*(3), 431-442. https://doi.org/10.1007/s40964-019-00086-6

[15] Chen, B., Yao, Y., Song. X., Tan, C., Cao, L., & Feng, J. (2018). Microstructure and mechanical properties of additive manufacturing AlSi10Mg alloy using direct metal deposition. *Ferroelectrics, 523*(1), 153-166. https://doi.org/10.1080/00150193.2018.1392147

Authors' contacts:

Sanja Šolić, Associate Professor Dr.
University North, Department of Mechanical Engineering
Jurja Križanića 31b, 42000 Varaždin, Croatia
E-mail: ssolic@unin.hr

Iva Sakač, mag. ing. mech.
University North, Department of Mechanical Engineering
Jurja Križanića 31b, 42000 Varaždin, Croatia
E-mail: ivsakac@unin.hr

Vlado Tropša, Associate Professor Dr.
University North, Department of Mechanical Engineering
Jurja Križanića 31b, 42000 Varaždin, Croatia
E-mail: vtropsa@unin.hr

Mario Šercer, Dr., director
Development and Training Centre for Metal Industry Metal Centre in Čakovec,
Bana Josipa Jelačića 22D, 40 000 Čakovec, Croatia
E-mail: ravnatelj@metalskajezgra.hr