Direct Metal Laser Sintering Of Alsi10mg Alloy For Aerospace Application: A Review Of Current Literature

M. Madhuri

[1*]Assistant Professor, Department of Mechanical Engineering, AVN Institute of Engineering & Technology,
Hyderabad, Telangana, India.

***Corresponding Author:** M. Madhuri
*Email: madhuri.murala@gmail.com

Abstract

Additive Manufacturing (AM) has the main benefits of freedom of design, mass customization, waste minimization and the ability to manufacture complex shape. AM is the process of making 3D object from computer model data by depositing of material layer by layer. In this research mechanical properties are investigated on AlSi10Mg alloy made by Direct Metal Laser Sintering (DMLS) and also provides this paper layer-by-layer additive process simulation before the DMLSprinting process, which saves time, cost, and material. The quality and performance of the additive manufactured (AM) parts depends on the build orientation. A model based on an L9 orthogonal array of Taguchi design experiments was created to perform the mechanical properties such as tensile strength, metallurgical structure and hardness for AlSi10Mg alloy. The DMLS- AM high production cost associated with laser power, scan speed, hatching distance and layer thickness for process parameters optimization on mechanical properties.

Keywords: Additive Manufacturing (AM), Laser Powder Bed Fusion (LPBF), Direct Metal Laser Sintering (DMLS), AlSi10Mg Alloy, Tensile Strength, Microstructure, Hardness and Surface Roughness.

1. Introduction

At present, additive manufacturing (AM) is an invigorated technology in sectors like bio medical, dentistry, aerospace, automobile and manufacturing [1]. In this technique, there is an addition of material in a stacking manner to build a prototype or a functional part despite of subtracting material from stock as in the case of conventional machining as shown in Figure 1[2,3]. Beside of having limited availability of feasible materials and machines [4], it is emerging technology capable of producing small and medium lot size parts in relatively less time with more accuracy [5,6]. There is availability of more work space and flexibility of manufacturing due to no tooling. According to ASTM [7], the AM technologies are of two types namely Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) [8,9]. The laser additive manufacturing (LAM) process consists of four processes: wire feed, powder feed, powder bed, and other processes [10,11]. The four technologies are layered in an additive approach. The 3D CAD (computer aided design) geometry is layer by layer (such as sliced) into the thin layers and with slice files [12,13], each additive layer manufacturing (ALM) method creates physical AM parts in the SLM process based on the given process parameter [14,15]. In comparison to other ALM process pathways, manufacturing components using powder bed fusion (PBF) provides the most geometrical flexibility and accuracy, producing a full dense sample of 99.95 % [16,17]. Many factors affect the final AM part quality of an SLM printed sample based on material properties (such as morphology, powder size, and distribution) [18]. Another significant component is the laser heat input, which limits the degree of powder particle consolidation defect shape formation by causing turbulence in the melt pool, which can generate a keyhole defect [19,20]. This is particularly relevant in the space industry and automobile industry, where aluminium alloys are commonly used [21]. The specific applications for AlSi10Mg alloys used in different industries (aerospace, biomedical, and automobile manufacturing industries) are due to their light weight, recycling, high mechanical properties, and low thermal expansion [22,23]. The AlSi10Mg alloy parts are manufactured by LPBF-SLM (ASTM/ISO 52900). The mechanical tensile properties of samples are prepared in horizontal build orientation (X-direction) [24] because it is much stronger than vertical samples (Y direction) from the literature review [25].

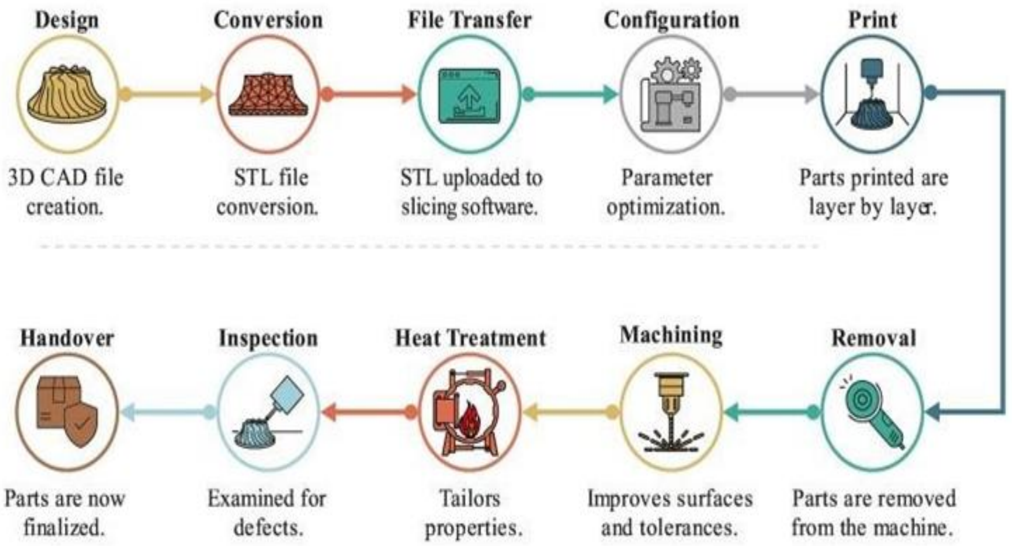

Figure 1: Part geometry manufacturing using conventional method (machining) and additive manufacturing sequence.

1.1 Classification of Additive Manufacturing

Additive Manufacturing (AM) system is categorized according to material state- solid based system; Powder based system, and liquid Based system as shown in Figure 2. Solid based AM system is meant to encompass all forms of material in the solid state. The solid form can be including the shape or size in the form of a wire, a roll, laminates and pellets. Powder is cured by layer in the solid state. However, it is intentionally created as a category outside the solid based AM system i.e., powder in grain like form. Liquid based AM system has the initial form of its material in liquid state. Through a process commonly known as currying the liquid, the liquid is converted into the solid state.

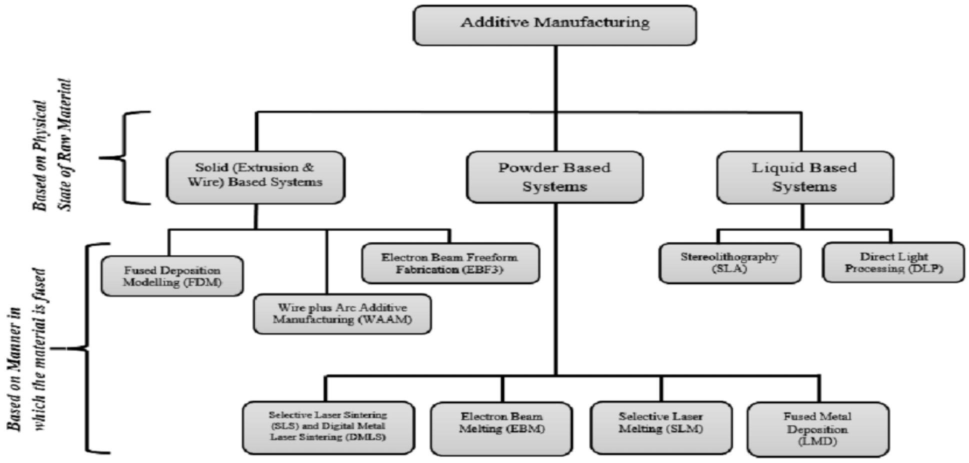

Figure 2: Classifications of Additive Manufacturing

1.2 Additive manufacturing process

All AM technique adopts the same basic approach which has five steps in the process chain i.e., part modelling, data conversion and transmission, checking and preparing, building and post processing as shown in Fig. 1, the very first step to part model print from CAD file using the modelling software. The CAD model object describes the geometrical properties of the object. The CAD model file is then converted to STL file format. This file format defines the external closed surface of the original CAD model. The Standard Triangular Language (STL) file sent to the AM for build-up process. The AM process build parameter (builds direction, layer powder, layer thickness, scan speed. etc.) the part is then printed by an automated process without any monitor. When a printing is done, the printed part is removed and sent for post processing after that, the object is ready for application. The 3D printing has revolutionized every aspect of Industrial (Production and Manufacturing) market as well as automotive, aerospace, medical/dental, robotics, and domestic appliances. AM has been generally applied in different industries, including construction (building), prototyping and biomechanical.

1.3 Materials used in additive manufacturing

Like any manufacturing process, 3D printing needs high quality materials that meet consistent specifications to build consistent high-quality devices. To ensure this, procedures, requirements, and agreements of material controls are established between the suppliers, purchasers, and end- users of the material. 3D printing technology is capable to produce fully functional parts in a widerange of materials including ceramic, metallic, polymers and their combinations in form of hybrid, composites or functionally graded materials as shown in the Figure 3.

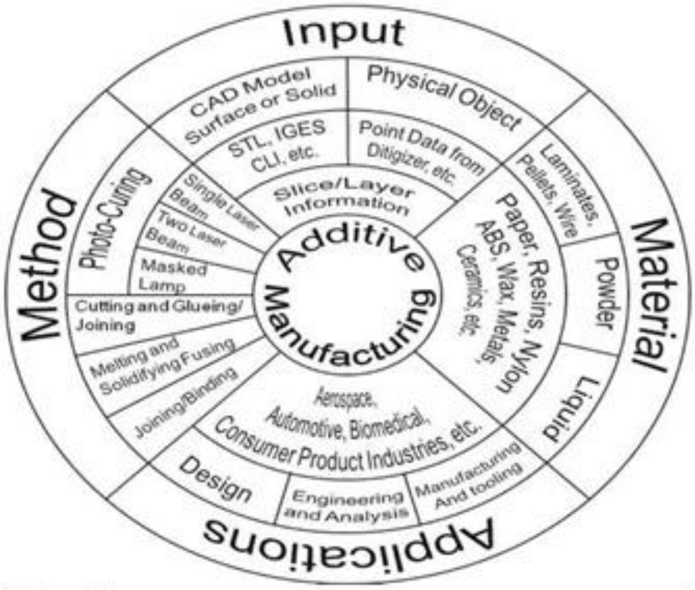

Figure 3: Material of Additive Manufacturing

The specific applications for AlSi10Mg alloys used in different industries (aerospace, biomedical, and automobile manufacturing industries) are due to their light weight, recycling, high mechanical properties, and low thermal expansion. The AlSi10Mg alloy parts are manufactured by LPBF-SLM (ASTM/ISO 52900). The mechanical tensile properties of samples are prepared in horizontal build orientation (X-direction) because it is much stronger than vertical samples (Y direction) from the literature review. The tensile test yields high properties (as built and preheated at 2000C) when compared to Al6061 casting material. The material's ductility was improved bya stress-relieving heat treatment at 2000C for 2 hours, which resulted in the alteration of Si-rich cellular borders. It is known that structural evolution during heat treatment has an impact on mechanical properties measured at high temperatures, particularly tests like fatigue and mechanical properties, which are improved. The strength of an AM part is primarily determinedby process parameter variation and post-processing. Previous studies on mechanical properties have used high laser power in watts, scan speed in mm/s, and hatching distance in m. The AM strength depended on the process parameters and build orientation. Previous work of mine investigated optimised process parameters with a fully dense and defect-free component. The mechanical properties of tensile tests with different conditions of AlSi10Mg alloy were conductedusing the optimal process parameter [5].

2. Material and Methodology

2.1 Aim and Scope of study

The aim of the research was to compare chosen mechanical properties as well as character of microstructure of AlSi10Mg alloy obtained by DMLS method. The investigations involved all the specimens were fabricated for optimization of process parameters using L9 orthogonal array(OA) by producing a DMLS-AlSi10Mg alloy.

2.2 AlSi10Mg Material

The laser power melted AlSi10Mg aluminium alloy printed specimens for tensile tests were fabricated by the DMLS process. The Table 1 shows the chemical composition of AlSi10Mg.

Table 1: Chemical composition of AlSi10Mg alloy (www.slm-solutions.com).

Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn	Other total
Bal.	9.00-11.00	0.55	0.05	0.45	0.20-0.45	0.10	0.15	0.05	0.05	0.05	0.15

2.3 DMLS Printing Process

The DMLS is a common 3D printing or additive manufacturing technique that is also referredto as selective laser melting (SLM) as shown in the Figure 4. In this process, each layer of a part is created by aiming alaserat the powder bed in specific points in space, guided by a digitally produced CAD (computer- aided design) file. Once a layer is printed, the machine spreads more powder over the part and repeats the process. The process is ideal for printing precise, high-resolution parts with complexgeometries. DMLS machines use a laser to heat the particulate matter to its melting point in a digital process that eliminates the need for physical molds. The resultingparts are accurate, have excellent surface quality and near-wrought mechanical properties. DMLS printers are recommended when you want to print a limited number of industrial items that are otherwise difficult or impossible to fabricate because of hollow spaces, undercuts, challenging angles, andother complexities. DMLS is ideal for low-volume parts and when you want to avoid the time and expense of creating a tooling. DMLS parts can be stored digitally and printed on demand, which reduces inventory costs and increases design flexibility. In this process, powdered metal free of binder or fluxing agent is sintered by the scanning of a high-power laser beam at 20 or 40 μm layers, with the option of bronze, steel, stainless-steel 316L, titanium, or Al-30% Si. Next, the recoater arm then sweeps over a new layer of powder, allowing a new layer to be sintered on the already built layer. The DLMS process does not require any subsequent sintering of the produced parts because of the fact that parts are produced with 95% density. Though layers are sintered, support structures are required. Parts may require a variety of post processes, including heat treating, support removal, shot peening, and more. DMLS has the ability to produce fine features and thin walls, with good accuracy, resolution, and mechanical properties of the finished parts. The DMLS process is being considered for producing complex, fully functional metal parts and inserts mostly used for production of small geometrically complex parts that would be difficult to produce by classic methods. As shown in Figure 3, a pressure die-cast tool is fabricated using the DMLS process. Although direct tool is best known for plastic injection molding, it is also used for other tooling types including blow molding, extrusion, die casting,and sheet metal forming. These molds can even be used in metal injection molding with low melting point in a series of about a thousand pieces.

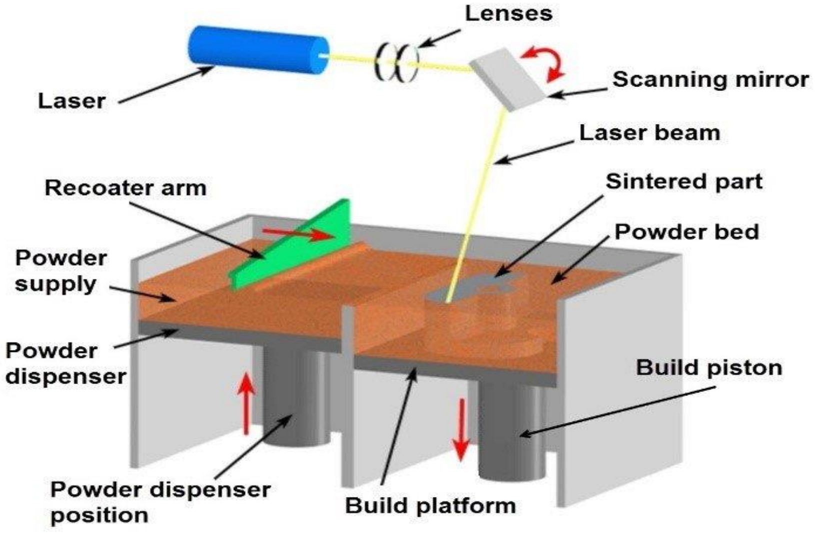

Figure 4: Schematic diagram of the DMLS process [15].

3. Technique used in methodology

In our study three levels of laser power, scanning speed, hatch spacing was chosen. The levels ofthe process parameter are shown in Table 2. L9 orthogonal array design of experiment (DoE) wasdeveloped demonstrated in Table 3.

Table 2: Levels and their Factors for DMLS of AlSi10Mg alloy.

Parameters	Level 1	Level 2	Level 3
Laser power in Watts	250	300	350
Scan speed in mm/s	1000	1200	1400
Hatching distance in μm	120	140	160

Table 3: Used L9 orthogonal array as per DoE (Minitab)

Laser power (Watt)	Scan speed (mm/sec)	Hatching distance (μm)
250	1000	120
250	1200	140
250	1400	160
300	1000	140
300	1200	160
300	1400	120
350	1000	160
350	1200	120
350	1400	140

3.1 Specimen Design

The SLM-AlSi10Mg specimens are prepared for tensile testing as per ASTM standard E8/E8M. The circular-bar rod specimen dimensions are; total diameter of 10 mm with a length of 100 mm; gauge diameter of 6 mm with a length of 25 mm and a fillet radius of 6 mm as shown in Figure 5.

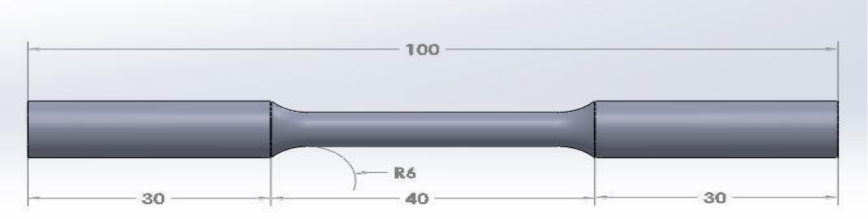

Figure 5: Test specimen size and its dimension considered tensile testing CAD model diagram.

All the specimens were fabricated for the optimization of process parameters using the Taguchi L9 orthogonal array (OA) by producing a DMLS-AlSi10Mg alloy. The process parameters thatvaried were laser power is 250, 300, and 350 Watts; scan speed is 1000, 1200 & 1400 mm/s and hatch spacing is 120, 140 & 160 µm. The remaining process parameters are constant i.e., laser spot diameter is 75 µm, layer thicknesses is 30 µm, the build platform temperature is 150^0C/2hr, and a scanning pattern and build orientation is 0^0. The maintain atmosphere in the SLM printingprocess at a maximum oxygen content level of 0.12%.

3.2 Analysis of variance (ANOVA)

ANOVA was first introduced by Sir Ronald A, Fisher, and the British biologist. ANOVA is a method of partitioning total variation into accountable sources of variation in an experiment. It is a statistical method used to interpret experimented data and make decisions about the parameters under study. ANOVA is a statistical method used to test differences between two or more means.

3.3 Signal to Ratio (S/N Ratio)

Taguchi method stresses the necessity of studying the response variable using the signal- to-noise ratio, resulting to decrease the effect of quality characteristic variation due to the uncontrollable parameters. The S/N ratio can be used in three types:

Larger the better:

$$\frac{S}{N} = -10\ \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \ldots\ldots\ldots(1) \qquad [20]$$

Smaller the better:

$$\frac{S}{N} = -10\ \log\left(\frac{1}{n}\sum_{i=1}^{n}{y_i}^2\right) \quad \ldots\ldots\ldots(2) \qquad [20]$$

Nominal the best:

$$\frac{S}{N} = -10\ \log\left(\sum_{i=1}^{n}{y_i}^{-2}/s^2\right) \ldots\ldots\ldots(1) \qquad [20]$$

Where, n is the total number of experiments, yi^2 is the density value for i^{th} experiment.

4. Conclusion

In this study the manufacturing of AlSi10Mg component was carried out by DMLS process by varying the process parameters primarily laser power, scan speed and hatch distance and they were optimized to get the best result for ultimate tensile strength, microstructure and hardness byusing ANOVA and Taguchi analysis.

- Taking into consideration production parameters of DMLS material, metallographic observationas well as references knowledge, optimization of conditions of sintering through decrease of scanspeed and hatch spacing will have an impact on favourable microstructure and on decrease of number of key-hole pores.
- The most important process parameter affecting tensile strength it was laser power in watts, but hatching distance in µm also had an important influence.

5. Summary

Summarizing all the results of the research and observations, it should be noted that the DMLS technology gives wide range of possibilities to manufacture complex-shape structures and components. However, to achieve high mechanical properties and favorable microstructure, the parameters should be selected properly, to avoid high porosity, which is mainly responsible for the poor properties of tested material.

References

1. Frazier, W. E., Metal Additive Manufacturing, A Review, Journal of Materials Engineering and Performance, vol .23(6), 2014, pp. 1917–28.
2. An Overview on 3D Printing Technology: Technological, Materials, and Applications.
3. Mudda Nirish and R.Rajendra, "Optimization Process Parameter on Wear Characterization of Al6061 and AlSi10Mg Alloy Manufactured by Selective Laser Melting", *International Journal of 3D Printing and Additive Manufacturing*, vol.2, no.1, ISSN: 2833-5430, pp.1-10, 2022.
4. Mudda Nirish and R.Rajendra, "Heat Treatment Effect on the Mechanical Properties of AlSi10Mg Produced by Selective Laser Melting", *Journal of Mechanical Engineering Research and Development*, vol.45, no.2, ISSN: 1024-1752, pp.19-28, 2022.
5. Mudda Nirish and R.Rajendra, "Suitability of metal additive manufacturing processes for part topology optimization-A comparative study", *Materials Today: Proceedings*, vol.27, pp.1601-1607, 2020.
6. Li B, Wang H, Jie J, Wei Z. Effects of yttrium and heat treatment on the microstructure and tensile properties of Al–7.5 Si–0.5 Mg alloy. Materials & design. 2011 Mar 1; 32(3):1617-22.
7. Mudda Nirish and R.Rajendra, "Additive Layer by Layer Simulation and Taguchi Loss of Function for AlSi10Mg Alloy Samples Manufactured by Selective Laser Melting", *International Journal of Mechanical Engineering*, vol.7, no.5, ISSN: 0974-5823, pp.765-770, 2022.
8. Mudda Nirish and R.Rajendra, "Selective Laser Melting process parameter simulation and Topology optimisation by aerospace component of AlSi10Mg alloy", *American Institute of Physics*, vol. 2648, no. 1, pp. 020019 (1-7), 2022.
9. Mudda Nirish and R.Rajendra, "Effect of Heat Treatment on Wear Characterization of AlSi10Mg Alloy Manufactured by Selective Laser Melting", *Journal of Mechanical Engineering Research and Development*,vol.45, no.2, ISSN: 1024-1752, pp.10-18, 2022.
10. Calignano F, Manfredi D, Ambrosio EP, Iuliano L, Fino P. Influence of process parameterson surface roughness of aluminum parts produced by DMLS. The International Journal ofAdvanced Manufacturing Technology. 2013 Aug; 67:2743- 51.
11. Mudda Nirish and R.Rajendra, "Additive Simulation and Process Parameter Optimization for Wear Characterization Development by Selective Laser Melting of AlSi10Mg Alloy", *Journal of Characterization*, vol.2, no.2, ISSN: 2757-9166, pp.103-116, 2022.
12. Fulcher BA, Leigh DK, Watt TJ. Comparison of AlSi10Mg and Al 6061 processed through DMLS. In2014 International Solid Freeform Fabrication Symposium 2014. University ofTexas at Austin.
13. Mudda Nirish and R.Rajendra, "Fatigue Performance Improvement of AlSi10Mg Manufactured by Selective Laser Melting through Heat Treatment", *Journal of Mechanical Engineering Research and Development*, vol.45, no.3, ISSN: 1024-1752, pp.01-13, 2022.
14. Yan C, Hao L, Hussein A, Young P, Huang J, Zhu W. Microstructure and mechanical properties of aluminium alloy cellular lattice structures manufactured by direct metal lasersintering. Materials Science and Engineering: A. 2015 Mar 25; 628:238-46.
15. Li Z, Li C, Liu Y, Yu L, Guo Q, Li H. Effect of heat treatment on microstructure and mechanical property of Al–10% Mg2Si alloy. Journal of Alloys and Compounds.2016 Apr 5; 663:16-9.
16. Mower TM, Long MJ. Mechanical behavior of additive manufactured, powder-bed laser-fused materials. Materials Science and Engineering: A. 2016 Jan 10;651:198- 213.
17. Girelli L, Tocci M, Montesano L, Gelfi M, Pola A. Optimization of heat treatment parameters for additive manufacturing and gravity casting AlSi10Mg alloy. InIOP Conference Series: Materials Science and Engineering 2017 Nov 1 (Vol. 264, No. 1,p. 012016). IOP Publishing.
18. Trevisan F, Calignano F, Lorusso M, Pakkanen J, Aversa A, Ambrosio EP, Lombardi M,Fino P, Manfredi D. On the selective laser melting (SLM) of the AlSi10Mg alloy: process,microstructure, and mechanical properties. Materials. 2017 Jan 18; 10(1):76.
19. Palumbo B, Del Re F, Martorelli M, Lanzotti A, Corrado P. Tensile properties characterization of AlSi10Mg parts produced by direct metal laser sintering via nested effects modeling. Materials. 2017 Feb 8; 10(2):144.
20. Araujo LC, Lopes E. Mechanical properties of as built and heat treated AlSi10Mg specimens fabricated in different orientations using Direct Metal Laser Sintering (DMLS).2017.
21. Ghani SA, Zakaria MH, Harun WS, Zaulkafilai Z. Dimensional accuracy of internal cooling channel made by selective laser melting (SLM) and direct metal laser sintering (DMLS) processes in fabrication of internally cooled cutting tools. InMATEC Web of Conferences 2017 (Vol. 90, p. 01058). EDP Sciences.
22. Lorusso M, Aversa A, Manfredi D, Calignano F, Ambrosio EP, Ugues D, Pavese M. Tribological behavior of aluminum alloy AlSi10Mg-TiB 2 composites produced by directmetal laser sintering (DMLS). Journal of Materials Engineering and Performance. 2016 Aug; 25:3152-60.
23. Hadadzadeh A, Amirkhiz BS, Odeshi A, Mohammadi M. Dynamic loading of direct metallaser sintered AlSi10Mg alloy: Strengthening behavior in different building directions. Materials & Design. 2018 Dec 5; 159:201-11.
24. Hadadzadeh A, Baxter C, Amirkhiz BS, Mohammadi M. Strengthening mechanisms in direct metal laser sintered

AlSi10Mg: Comparison between virgin and recycled powders. Additive Manufacturing. 2018 Oct 1; 23:108-20.

25. Dvorak K, Dvorakova J, Zarybnicka L, Horak Z. Influence of 3D Printing Topology by DMLS Method on Crack Propagation. Materials. 2021 Dec 6; 14(23):7483.