



A Review On Lightweight Materials For Metal Additive Manufacturing Process

Aaref Pathan¹, J.B. Shaikh², S.C. Borse³, K.B. Kolhapure⁴

1PG Student, Department of Mechanical Engineering DIEMS Chh. Sambhajinagar

2,3,4Asst. Professor, Department of Mechanical Engineering DIEMS Chh. Sambhajinagar

Abstract: Additive Manufacturing (AM) has rapidly evolved as a transformative technology, enabling the production of complex, high-performance materials that exhibit superior mechanical and tribological properties. Among the materials benefiting from this advancement is AlSi10Mg, an aluminium-silicon-magnesium alloy. AlSi10Mg has gained notable attention in industries like aerospace and automotive due to its excellent strength-to-weight ratio, high thermal conductivity, and robust wear resistance. These properties make it particularly suitable for lightweight, high-stress applications. This review consolidates state-of-the-art research on AlSi10Mg, specifically focusing on components produced through Direct metal laser sintering process (DMLS), a prominent AM technique. DMLS enables precise control over the materials microstructure and properties by melting and fusing powdered material layer-by-layer using a high-energy laser. The review delves into the influence of various DMLS processing parameters, play a crucial role in influencing the alloy's density, porosity, and internal stress, ultimately affecting its mechanical performance. Additionally, the review examines post-processing treatments enhancing AlSi10Mg's strength, ductility, and fatigue resistance. Furthermore, the impact of these treatments on the alloy's microstructure, particularly the distribution and morphology of silicon phases within the aluminium matrix, is critically discussed, as they influence wear resistance and hardness.

Keywords: DMLS, AlSi10mg, Additive Manufacturing

I. INTRODUCTION

1. Introduction

Recent advancements in manufacturing have been significantly influenced by additive manufacturing (AM) technologies, which enable the production of complex, customized, and lightweight parts. Among the various AM techniques, Direct Metal Laser Sintering (DMLS) stands out for its capability to fabricate high-performance metal components directly from CAD designs, bypassing the need for molds or tooling. This method utilizes a high-powered laser to selectively melt fine metal powders layer by layer, creating dense, functional parts with precise geometric accuracy. AlSi10Mg, a frequently used aluminum alloy in AM, is prized for its excellent strength-to-weight ratio, superior thermal conductivity, and corrosion resistance, making it suitable for critical applications in the aerospace, automotive, and tooling sectors. However, the mechanical properties of parts produced via DMLS are significantly affected by process parameters such as laser power, scan speed, hatch spacing, and build orientation. Incorrect parameter settings can lead to defects like porosity, poor surface finish, and mechanical anisotropy, which may undermine the performance and reliability of the printed components. This research aims to systematically investigate the impact of key process parameters on the mechanical properties of AlSi10Mg parts manufactured using DMLS. Through experimental analysis and statistical modeling, the study seeks to identify optimal parameter settings that enhance part quality and performance. Additionally, regression equations are developed to predict output

characteristics, thereby reducing the need for extensive trial-and-error experimentation. By addressing current gaps in parameter standardization and property predictability, this work advances the understanding and application of DMLS in high-demand industrial sectors.

Fatma Alamri Imad Barsoum [1] observed that among five machine learning algorithms evaluated for relative density, surface roughness, and hardness, ANN and SVR excelled in predicting relative density and hardness. However, for surface roughness, ANN and RF were superior to the other models. ANN demonstrated greater predictability for the three properties of AlSi10Mg fabricated parts based on process parameters. Kadir Aydin and Ibrahim Karaag [2] noted that additive manufacturing parts are subjected to various loads in their operational environments, but due to their rigid structure, they tend to break suddenly after bending. Nevertheless, these manufactured parts can encounter numerous different loads in their usage locations. To assess the resistance of AlSi10Mg materials produced by the SLM method to bending deformation and to study the impact of local heating on their deformation resistance, test samples were bent in dies at angles of 6, 7.5, 9, and 15 degrees after being locally heated to temperatures of RT, 300, 400, and 500 C. Yusuf Siyambaş Yakup Turgut [3] It has been revealed that laser power and scanning speed parameters are critical for product quality in the additive manufacturing of AlSi10Mg alloy. Hiren M. Gajeraa,b and Komal G. Dave [4] optimization of process parameter to improve the dimensional accuracy of DMLS parts. The results show that higher laser power, lower scan speed, higher layer thickness and lowest hatch distance to provide less shrinkage rate in DMLS parts. The effect of layer thickness and interaction effect layer thickness vs. layer thickness are very significant for shrinkage rate of CL50WS material in DMLS process. Shrinkage rate increase with increase of the scanning speed and the layer thickness in a certain range, but it decreases with the increasing of the laser power. Empirical model for all responses have been developed for predication of responses by manipulating value of the process parameter. After this study, the RSM provide optimal process parameter laser power 129.814-watt, scan speed 554.439 mm/sec, layer thickness 0.05 mm and hatch spacing 0.01 mm for optimized the shrinkage. The experimental value of delta H, delta W and delta L came out to be 0.014214, 0.01504 and 0.006945 respectively by using of RSM parameter setting, Actual value compared with the predicted value of the optimal parameter setting of RSM, which give an error of about 6.42%, 8.29 % and 10.72% respectively. R K SHAH1 and P P DEY [5] The most important process parameter affecting relative density was found to be Hatch Spacing, whereas for UTS it was Laser Power but Hatch Spacing also had an important influence. The optimum process parameter for both density and UTS was found to be the following process parameter of LP 330 W, SS 1200 mm/s and HS of 0.15 mm. The highest energy density of 93.43 J/mm³ which gave the least relative density value did not gave the least value for UTS rather it was energy density of 67.6 J/mm³ which provided the least UTS value, which suggests that the UTS values of the samples are not solely depended on the density of the components. Fracture surface analysis need to be carried out to understand the effect of density and energy density on the UTS.

Harsh Sonia, Nandita Limbasiya said that [6] AlSi10Mg samples were printed by the Direct Metal Laser Sintering process (DMLS) and examined with mechanical and surface properties. Mechanical and surface property include tensile strength, hardness, density, and surface roughness of as built additively manufactured AlSi10Mg. The energy density of 56J/mm³ is used for fabrication of DMLS AlSi10Mg. The build sample density is observed around 96% at specific energy density. Hulusi Bugra Bagci, Binnur Sagbas [7] Laser power, scanning speed, beam offset and sample angle parameters effects dimensional accuracy of DMLS produced AlSi10Mg parts. Scanning speed is a important parameter for linear dimensions. While manufacturing DMLS parts, it is possible to reduce dimensional errors with scanning speed. Teeth geometry have been mostly affected by beam offset parameter. Moreover, samples produced with 0.04 mm offset gave the best dimensional results. Mr. K. R. Rathod1, Mrs. M.C. Karia [8] conclude that – Laser Power (64.73%) is influencing parameter for dimensional accuracy, Layer Thickness is influencing parameter for Roughness Value (83.47%) and Hardness (92.19%). To fulfill the specified condition (Higher dimensional accuracy, Lower surface roughness and higher hardness) can be fulfilled by using parameter Laser Power 370W, Layer Thickness 20µm, Scan Speed 1500mm/s. P. Fathia,M.Rafieazada [9] The large melt pools of Surface 1 sample exhibited a finer and more uniformly distributed grains having a weaker texture, ascribed to the faster cooling and higher solidification rate of the melt pools in this sample, resulted from the increased overlapping between its melt pools.

1.1 Classification of additive manufacturing

[10] Additive manufacturing is an emerging technology in the current scenario. The initial stage of additive manufacturing is the stereolithography process where only polymer material can use to develop a three-dimensional prototype. Nowadays with the advancement of technology and material, two different AM processes are capable to develop a prototype from the various materials as well as from different metals which behave same as a final product (the components with all required properties). Recently, the highest reach of AM technology is manufacturing of bio-components for the human being. The classifications of AM technology based on the material used are as follows. From the beginning of stereolithography, nowadays AM have reached to make bio components of the human. One of the wide ways of classifying AM systems is by the initial form of their material. Generally, the AM is classified in the following main three categories.

1. Liquid-based processes
 - a. Stereolithography
 - b. Solid ground curing
2. Solid-based processes
 - a. Laminated object molding
 - b. Fused deposition mold
3. Powder-based processes
 - a. Selective laser sintering
 - b. Three-dimensional printer

Additive manufacturing technologies was started with the plastic and paper material after that with time, laser-based AM had risen with the commercialization of selective laser sintering in 1987. Then, AM shifted to a metallic product, and rapid prototyping tooling (RPT) word had come in the market. Pattern, mold, and cavities are commonly used in tooling industries. Permanents and consumable pattern have been made by the craftsman or sand casting with metal or wood. These conventional processes were taken too much time, which increases the lead time of the product. With RPT technology, these patterns can be made in a short time, which decreases the product lead time. Processes such as selective laser sintering (SLS) can produce metal and ceramic tools. In the case of the SLS, a binder was used to make components and temperature of the laser intensity is up to the 80-90% of the melt temperature of the powder material. After SLS, Direct metal laser sintering (DMLS) process was innovated and commercialized. In Direct metal laser sintering powder material are fully melted, make molten pool and make the desired shape of the components. DMLS melts fully powder material in order to achieve, the less porosity. DMLS made parts can be used directly as an end functional part, die or mold and pattern in respective industries. Thus, generally, metallic AM process has been used for the tooling industries as well as aerospace industries and automobile industries where complex component which not possible in the conventional process.

Classification of metallic powder additive manufacturing processes

Categories	Technologies	Printed “ink”	Power Sources
Material extrusion	Fused deposition modeling (FDM)	Thermoplastics, ceramic slurries, metal pastes	Thermal energy
Powder bed fusion	Selective laser sintering (SLS)	Polymides/polymer	A high powered laser beam
	Selective laser Melting	Atomized metal, ceramic powder	
	Direct metal laser Sintering		
	Electron beam Melting		Electron beam
Vat photo polymerization	stereo lithography	Photopolymer, ceramic	Ultraviolet laser
Material jetting	Polyjet/inkjet printing	Photopolymer, wax	Thermal energy/ photocuring
Binder jetting	Indirect inkjet printing (Binder 3DP)	Polymer powder, ceramic powder, metal powder	Thermal energy
Sheet lamination	Laminated object manufacturing	Plastic film, metallic sheet, ceramic tape	Laser beam
Directed energy Deposition	Laser engineered net shaping (LENS) Electronic beam welding (EBW)	Molten metal powder	Laser beam

2. Direct metal laser sintering (DMLS)

Among the AM techniques available, Direct metal laser sintering (DMLS) has become the primary method for producing AlSi10Mg components due to its high precision and flexibility in customizing material properties. [11] Each layer is selectively melted based on a digital model, allowing intricate shapes and designs to be manufactured without the need for molds or dies.

DMLS offers a unique advantage over traditional casting by enabling precise adjustments in processing parameters. These parameters influence key aspects of the alloy's final properties, such as microstructure, mechanical strength, tensile strength, hardness, and wear resistance. For instance, adjusting laser power and scanning speed can impact the cooling rate, thereby controlling the size of the cellular structure formed within the alloy. [12] A rapid cooling rate tends to result in a fine microstructure, enhancing the materials strength and wear resistance compared to cast counterparts. DMLS-produced AlSi10Mg components generally exhibit bettered mechanical properties, such as higher tensile strength and hardness, due to their refined microstructures. The enhanced control over the microstructure also contributes to the alloy's superior tribological performance, making it well-suited for applications requiring high resistance to wear and friction. By tailoring processing parameters, manufacturers can achieve a balance of strength, flexibility, and wear

resistance that meets specific performance requirements. This customization is a distinct advantage of DMLS over traditional methods, where controlling such properties is often more challenging.

2.1 Process Parameters

2.1.1 Laser Power

Laser power is the total energy output delivered by the laser onto the powder bed. This energy input directly affects the melt pool's temperature and depth, influencing how effectively particles fuse together. Higher laser power Optimal combinations of process parameters, [11-14] such as a laser power of 390 W, a speed of 1500 mm/sec, and a hatch distance of 0.21 mm, led to the best mechanical performance, with run 16 achieving the highest grey relation grade (GRG) of 5.685. [13]

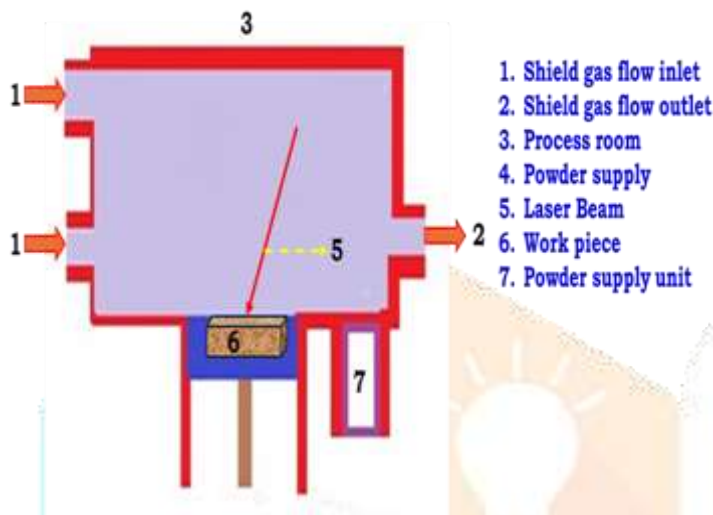


Figure 1. Schematic of DMLS process.

promotes deeper penetration and better fusion between particles, enhancing part density and strength. However, excessive power can cause overheating, leading to defects like keyhole porosity and vaporization, both of which can degrade the parts quality. For AlSi10Mg, achieving an optimal laser power level is crucial to balancing penetration depth with stable fusion and avoiding defects [14].

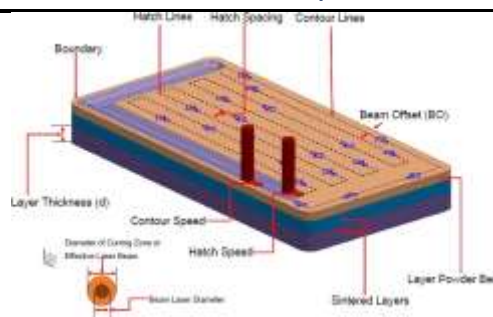
2.1.2 Scanning Speed

This parameter affects the exposure time of the laser on each area, impacting the heat input and, consequently, the melt pool dynamics. A high scanning speed reduces energy absorption, which can prevent excessive heat buildup but may lead to inadequate melting and weaker bonding.

[15] Conversely, a slower scanning speed allows for deeper fusion, reducing porosity but increasing the risk of overheating. The optimal scanning speed for AlSi10Mg balances full melting with stability, ensuring sufficient bonding between layers without introducing excessive heat.

2.1.3 Hatch Spacing

Hatch spacing refers to the distance between successive laser passes across the powder bed. This spacing is critical for ensuring overlapping of melted tracks, creating a continuous structure without gaps. If hatch spacing is too large, un-melted areas may remain, leading to porosity and weak bonding. [16] On the other hand, a narrow hatch spacing increases the heat input per area, potentially causing residual stress or warping. For AlSi10Mg, optimizing hatch spacing supports a consistent, dense microstructure, contributing to uniform mechanical properties across the part



2.1.4 Laser Energy Density

Laser energy density combines laser power, scanning speed, and hatch spacing to describe the energy delivered per unit area. This parameter is essential to achieving complete melting and bonding between particles. [17] Low energy density can lead to insufficient melting and high porosity, compromising mechanical strength. However, high energy density may cause keyhole porosity or other thermal defects. For AlSi10Mg, optimal energy density helps achieve a high-density, strong structure with minimal porosity, maximizing mechanical performance in applications demanding durability.

2.1.5 Scanning Strategy

Scanning strategy refers to the laser path across the powder bed. Different strategies, such as unidirectional, bidirectional (zigzag), and checkerboard or island scanning, influence heat distribution and residual stresses. Unidirectional Scanning moves the laser in a single direction and can lead to residual stress due to thermal gradients. [18] Bidirectional (Zigzag) Scanning involves alternating scan directions, distributing heat more evenly and reducing residual stresses. Checker board or Island Scanning breaks the layer into sections, distributing heat in a controlled sequence, which minimizes residual stress build up, especially useful for larger parts. These strategies affect grain structure and isotropy. Unidirectional scanning often creates columnar grains, whereas island scanning promotes equiaxed grains, resulting in more isotropic properties.

2.1.6 Powder Layer Thickness

Powder layer thickness impacts resolution, surface finish, and build time. Thicker layers reduce build time but may require higher power or slower speed to achieve full melting, risking defects like porosity. [19] Thinner layers offer better surface finish and higher resolution, as the laser can more effectively melt each layer, creating a dense microstructure. However, thin layers increase build time. For AlSi10Mg, choosing the right layer thickness is essential to balance between production efficiency and mechanical quality.

2.1.7 Preheat Temperature

Preheat temperature refers to the temperature applied to the powder bed before the laser melts each layer. Preheating reduces thermal gradients between layers, decreasing residual stress and potential warping. It also lowers the energy needed to melt the powder, which can improve part quality by reducing the chances of thermal cracking and distortion. [20] For materials prone to residual stress, like AlSi10Mg, preheating is particularly beneficial in maintaining dimensional accuracy and reducing post-processing needs.

2.1.8 Beam Spot Size

Beam spot size is the diameter of the laser beam on the powder bed. It affects the concentration of energy applied and the width of the melt track. [21] A smaller spot size provides higher precision and can improve detail in intricate parts but may increase build time as more passes are required. Larger spot sizes, while faster, can decrease resolution and lead to a coarser surface finish. [22] For AlSi10Mg, choosing an appropriate beam spot size based on part complexity is essential for achieving a balance between precision and efficiency.

2.2 Post-Processing Techniques

Post-processing techniques are essential for optimizing the properties of Additively Manufactured (AM) AlSi10Mg parts, as they address residual stresses, improve mechanical performance, and enhance surface finish.

Heat treatment is widely used to relieve residual stresses that develop during the AM process due to rapid heating and cooling cycles. [23] For AlSi10Mg, solution heat treatment followed by aging is common. This approach involves heating the part to a temperature that allows for phase transformation, followed by

1. Heat treatment
 - a) Reduces stress
 - b) Improves density
2. Hot isostatic pressing
 - a) Closes voids
 - b) Increases the density
3. Surface finishing
 - a) Smoothen surface
 - b) Enhance the wear resistance

controlled cooling to improve ductility and reduce brittleness. Aging further promotes the precipitation of strengthening phases, which can increase hardness and yield strength. Overall, heat treatment enhances the alloy's ductility and toughness. Hot Isostatic Pressing (HIP) is a post-processing method involving AM part to high temperatures and isostatic pressure within a pressurized chamber. [24] HIP effectively closes internal voids and porosities that may form during the powder bed fusion process, enhancing the part's density and strength. Also, by applying surface finishing techniques, manufacturers can achieve smoother surfaces, enhancing the component's performance in applications where surface interaction is critical, such as in sliding or rotating components.

3. Mechanical properties

3.1 Tensile strength

The tensile strength of Additively Manufactured (AM) AlSi10Mg alloy, particularly when produced through Direct metal laser sintering (DMLS), is notably higher than that of conventionally cast versions. This enhanced tensile strength is largely attributed to the rapid cooling and solidification inherent in the DMLS process. [25] During DMLS, a high-energy laser selectively melts regions of AlSi10Mg powder in a layer-by-layer manner, and the rapid cooling that follows creates a unique fine cellular microstructure within the alloy. This microstructure, characterized by small and densely packed grains, leads to increased grain boundary density, which serves as a barrier to dislocation motion. Since dislocation movement within a material generally weakens its structure, the refined grain boundaries in DMLS-processed AlSi10Mg significantly increase its tensile strength, making it an attractive option for applications in industries such as aerospace and automotive, where materials are regularly subjected to high stress. However, DMLS-processed AlSi10Mg often has limitations in ductility due to residual stresses that accumulate during rapid cooling. These internal stresses can make the material more brittle, increasing fracture risk under certain loads, despite high tensile strength. Additionally, porosity can impact ductility and tensile strength, as incomplete powder melting, or gas entrapment creates voids within the structure that concentrate stress. [26] To balance these effects and improve ductility, post-processing techniques like stress-relief heat treatment and Hot Isostatic Pressing (HIP) are often applied, which effectively reduce internal stresses and porosity, improving both tensile strength and ductility.

3.2 Fatigue Resistance

Fatigue resistance is a vital property for AlSi10Mg components, particularly those used in industries such as aerospace and automotive, where materials are subjected to repeated cyclic loading. Fatigue failure occurs when a material gradually weakens under fluctuating stress, ultimately leading to fracture. The fatigue performance of Additively Manufactured (AM) AlSi10Mg has been studied extensively, with results showing that it is comparable to, and in some cases superior to, conventionally cast AlSi10Mg. This favourable performance in AM AlSi10Mg is attributed to the refined microstructure achieved during the Direct metal laser sintering (DMLS) process, which typically includes smaller grains and increased grain boundary density, factors that help to resist crack initiation and propagation under cyclic loading. Surface treatments like shot peening and polishing are often applied to improve fatigue resistance, reducing stress concentrators and extending the materials service life under cyclic loads. Despite this, there are factors unique to AM that can negatively affect the fatigue life of AlSi10Mg, most notably surface roughness and internal defects like porosity. During the DMLS process, the laser selectively melts layers of AlSi10Mg powder to create a part, but this process often leaves a relatively rough surface. This roughness, composed of partially melted particles, re-solidified splashes, and microscopic peaks and valleys, can act as stress concentrators under cyclic loads. [27] These surface irregularities can initiate microcracks when subjected to fatigue loading, making the material more susceptible to fatigue failure. Comparatively, cast AlSi10Mg generally has a smoother surface finish when freshly manufactured, making it initially less vulnerable to fatigue-induced cracking. Porosity is another critical factor influencing fatigue resistance in AM AlSi10Mg.

Porosity can form when the laser does not fully melt all powder particles, leaving small voids or defects within the material.[29] These pores become weak points, acting as crack initiation sites when the material is under fatigue loading. Pores within the bulk of the material, particularly larger or clustered pores, concentrate stress locally and thus reduce the overall fatigue resistance. In summary, the fatigue endurance of AM AlSi10Mg is comparable to that of conventionally cast material, but it is highly dependent on minimizing surface roughness and internal porosity. Surface treatments like shot peening and polishing play substantial role in enhancing fatigue resistance by reducing surface defects and adding compressive stress.

4. Tribological properties

a. Wear resistance

Wear resistance is a crucial property for materials used in tribological applications, where components experience frequent friction and potential material degradation over time. Additively Manufactured (AM) AlSi10Mg, especially when processed through Direct metal laser sintering (DMLS), exhibits significant improvements in wear resistance due to its refined microstructure and enhanced hardness. This wear resistance makes AM AlSi10Mg suitable for high- performance applications in industries like automotive, aerospace, and manufacturing, where parts are regularly exposed to abrasive or sliding contact. The primary reason for the improved wear resistance in DMLS- processed AlSi10Mg lies in the unique microstructure produced by the rapid solidification. During DMLS, the laser melts each layer of AlSi10Mg powder and allows it to cool and solidify almost instantaneously. [30] This rapid cooling produces a fine cellular structure with evenly distributed silicon particles, which are naturally hard and resistant to abrasion. In AM AlSi10Mg, the silicon particles are finely dispersed within the aluminum matrix, creating a composite-like structure where the hard silicon particles bear a significant portion of the frictional load. This structure contrasts with the coarse, less uniform distribution of silicon particles seen in conventionally cast AlSi10Mg, where larger grains reduce wear resistance. As a result, the microstructural refinement in DMLS-processed AlSi10Mg contributes to higher wear resistance, making it ideal for tribological applications. Moreover, the hardness of DMLS-processed AlSi10Mg is an important factor contributing to its wear resistance. Hardness plays a direct role in reducing wear. Higher hardness means that the material is less likely to deform under frictional forces, helping it maintain structural integrity even under abrasive conditions. These conditions make the surface more resistant to crack initiation and propagation, which helps prevent wear-related

degradation. [31] When combined with heat treatment, shot peening can significantly improve the materials surface properties, providing both enhanced hardness and resilience under frictional conditions. Fine-tuning these parameters affects the density and homogeneity of the final microstructure. For instance, higher laser power and optimized scanning strategies promote better fusion of powder particles, resulting in a denser material with fewer pores. In summary, the wear resistance of additively manufactured AlSi10Mg is a result of its fine microstructure, enhanced hardness, and These properties make it a valuable material choice for advanced engineering applications where reliable wear performance is critical.

These properties make it a valuable material choice for advanced engineering applications where reliable wear performance is critical.

4.2 Friction Coefficient

The friction coefficient of Additively Manufactured (AM) AlSi10Mg is a critical factor influencing its performance in applications involving sliding wear and frequent material contact, such as in aerospace, automotive, and industrial components. [32] The friction coefficient is a measure of the resistance encountered when two surfaces slide against each other, directly affecting the wear rate, energy efficiency, and operational longevity of parts. In AM AlSi10Mg, this property is largely determined by the surface roughness and the distribution of hard silicon particles within the aluminum matrix. DMLS technique for AlSi10Mg, produces a unique microstructure with a fine Si-particles finely dispersed within the aluminum matrix, contributing to a lower friction coefficient compared to conventionally cast AlSi10Mg. These silicon particles are naturally hard and act as microscopic load-bearing elements within the matrix. [33] Their homogeneous distribution means that they reduce localized frictional forces by offering a smooth, consistent interaction between sliding surfaces, which in turn minimizes material deformation under load. This reduction in friction allows AM AlSi10Mg to perform well in tribological applications, where maintaining low friction is essential for efficiency and part longevity. However, surface roughness also plays a key part in determining the friction coefficient. [36] In AM processes like DMLS, the layered structure can leave the surface of AlSi10Mg with some roughness, especially if no post-processing is applied. Rough surfaces increase friction because microscopic peaks and valleys create additional resistance as they meet a counterpart surface.

5. Microstructure

5.1 As-Built Microstructure

Fine microstructure, which results from the rapid cooling and solidification rates intrinsic to the DMLS process, sets it apart from the coarser structure observed in conventionally manufactured AlSi10Mg. In DMLS, a high-energy laser selectively melts a powder layer of AlSi10Mg in a highly controlled manner. [37] Each layer of melted powder solidifies almost instantaneously as the laser moves along the build surface. This rapid solidification creates a unique microstructure marked by a cellular network of aluminum and silicon phases. Specifically, where grains are significantly smaller are found in conventionally cast AlSi10Mg alloy where fine grain structure provides a more robust and homogenous distribution of properties, contributing to the alloy's strength and durability. In DMLS-processed AlSi10Mg, silicon remains in a supersaturated state. This super saturation occurs because the rapid cooling does not allow silicon to fully separate out or coalesce into larger particles, as it would in slower cooling processes. As a result, DMLS AlSi10Mg exhibits a microstructure with finely dispersed silicon particles distributed evenly throughout the aluminum matrix. These particles strengthen the material by acting as barriers to dislocation movement, thus improving alloy's confrontation to distortion and wear. This homogenous distribution of silicon particles also aids in improving tribological properties, such as wear resistance, by providing a uniform, hard phase throughout the matrix. The fine cellular network observed in DMLS AlSi10Mg contributes not only to increased hardness but also to better fatigue resistance. The cellular structure, with its many grain boundaries, hinders the propagation of microcracks under cyclic loading, making it more difficult for cracks to grow and ultimately increasing fatigue life. In conventionally cast

AlSi10Mg, enhanced fatigue resistance can be largely attributed to its refined cellular structure, which is a direct outcome of the rapid cooling rates in DMLS. Another advantage of the as-built microstructure of AM AlSi10Mg is its improved wear resistance. The dense and fine-grained microstructure, coupled with the presence of hard silicon particles, reduces material loss during sliding or abrasive contact. [38] In conventional manufacturing, AlSi10Mg is prone to coarser silicon particle formations, which do not provide the same level of wear protection as the finely dispersed silicon particles in DMLS-processed AlSi10Mg. This micro structural refinement allows AM AlSi10Mg to retain its shape and function even under conditions of high friction or sliding wear, a property highly valued in automotive and aerospace components that experience continuous wear over time. While the as-built microstructure offers considerable benefits, it also presents some challenges, primarily due to the high residual stresses introduced by rapid cooling. These stresses arise because diverse zones of the material cool at slightly altered rates, creating internal strains. In some cases, these residual stresses can affect the materials overall performance by making it more susceptible to cracking or warping. To address this, post-processing treatments are often employed to relieve these stresses, thereby stabilizing the microstructure without significantly altering its favorable properties. [39] This refined microstructure provides a set of enhanced mechanicals and tribological properties, including improved hardness, wear resistance, and fatigue life, which distinguish it from conventionally cast AlSi10Mg. These attributes make AlSi10Mg particularly suitable for high-stress applications in industries that demand materials with durability, and wear endurance. Also, manufacturers can optimize this microstructure to meet specific performance requirements, making it a valuable material choice in advanced engineering applications.

5.2 Effect of Heat Treatment

It is a critical post-treating phase for tailoring microstructure and enhancing the mechanical properties of AlSi10Mg, particularly via DMLS owing to quick solidifying rates. AlSi10Mg generally has a fine cellular structure with a super saturated aluminum matrix containing dispersed silicon particles. While this as-built microstructure offers considerable advantages, it can also harbour residual stresses and minor defects. Heat treatment provides a means to stabilize and further refine this microstructure, enabling control over properties such as hardness, ductility, and wear resistance. A common heat treatment process for AlSi10Mg involves solutionizing and aging. Solutionizing typically occurs at high temperatures, allowing the silicon and magnesium within the alloy to dissolve into the aluminum matrix. During this stage, the alloy is held at a solutionizing temperature that facilitates the redistribution of silicon and magnesium atoms within the matrix. This step helps to homogenize the microstructure, eliminate residual stresses, and create a more uniform distribution of alloying elements. Solutionizing also provides a clean slate for the aging process, allowing the desired precipitates to form more evenly³⁷. During aging, silicon and magnesium precipitate out of the supersaturated matrix, forming fine, dispersed particles within the aluminum. The presence of finely distributed precipitates increases alloy by preventing the easy faction of dislocations, which in turn enhances resistance to deformation. The refined microstructure resulting from this process is particularly beneficial³⁸. However, while aging generally improves hardness and strength, there is a delicate balance in the aging process known as over-aging. Over-aging occurs when the aging process is prolonged beyond the optimal duration, or if the temperature is higher than ideal. During over-aging, the precipitates, instead of remaining fine and evenly dispersed, begin to grow larger and coarser. Coarse precipitates provide fewer obstacles to dislocation movement and can thus diminish the materials hardness and wear resistance. In essence, over-aging reduces the materials mechanical performance by allowing a less favorable microstructure to develop. In AM AlSi10Mg, this reduction in hardness and wear resistance is undesirable for applications that require robust material integrity over time. The precise control of heat treatment parameters is essential to maximize the mechanical benefits of AlSi10Mg. For example, a shorter aging time or a lower aging temperature may be applied to achieve a fine, stable distribution of precipitates without risking over-aging. This control is particularly beneficial in DMLS-processed AlSi10Mg, where the rapid cooling has already imparted a degree of refinement to the

microstructure. Properly calibrated heat treatment can enhance this fine structure, creating a balance between high tensile strength and sufficient ductility. [40] Heat treatment also contributes to improved wear resistance in AM AlSi10Mg. The presence of fine precipitates distributed throughout the aluminum matrix during optimal aging serves to harden the material, making it more resistant to surface degradation under wear conditions. Applications that expose components to continuous friction or abrasive wear particularly benefit from heat-treated AlSi10Mg. For instance, automotive and aerospace parts that must withstand repeated contact and surface wear can maintain their performance over time due to the hardened, wear-resistant surface created by effective heat treatment. Overall, heat treatment is a valuable tool for optimizing the properties of additively manufactured AlSi10Mg. Through solutionizing and controlled aging, manufacturers can promote the formation of fine precipitates within the aluminum matrix, enhancing hardness, strength, and wear resistance. However, precise control over heat treatment parameters is essential, as over-aging can lead to coarser precipitates, diminishing the mechanical advantages. By tailoring the microstructure through heat treatment, AM AlSi10Mg can be optimized for high-performance applications requiring a sequence of strength, durability, and wear resistance.

5.3 Porosity and Defects

Porosity is a prevalent issue in Additively Manufactured (AM) materials, and AlSi10Mg is particularly susceptible to it by DMLS process. Porosity refers to small voids or air pockets within the material that form during fabrication. In AlSi10Mg, these pores typically arise from two primary sources: incomplete melting of powder particles and gas entrapment during the DMLS process. These voids act as weak points within the structure, making it more vulnerable to crack initiation and propagation under stress. [42] During DMLS, the laser selectively melts metal powder particles to form each layer of the AlSi10Mg component. However, if the laser power, scanning speed, or other parameters are not optimized, incomplete melting can occur. In this case, powder particles may only partially fuse, leaving gaps or pores in the material. This is particularly common when laser energy is insufficient to fully melt the particles or when scanning speeds are too high. In some instances, excess heat can also cause vaporization, leading to the formation of small gas bubbles that are trapped as pores in the solidified metal. These issues result in a porous structure that degrades the materials overall strength and durability. Gas entrapment is another factor contributing to porosity in DMLS-processed AlSi10Mg. When the laser melts the powder, any gases within the powder particles or the surrounding environment can become trapped in the molten pool. As the pool solidifies quickly, there may not be enough time for the gas to escape, leading to the formation of gas porosity. [43] Entrapped gases are particularly problematic because they create spherical voids that are more challenging to eliminate. These gas-induced pores, like those caused by incomplete melting, can compromise the material's mechanical performance by serving as focal points for stress concentration. The impact of porosity on mechanical properties is significant. Pores act as stress concentrators, where stress tends to accumulate under loading conditions. For example, under cyclic loading, a porous structure may fail at much lower stress levels compared to a denser, pore-free structure. This makes minimizing porosity essential for applications requiring high structural integrity, especially in fields like aerospace and automotive, where components are regularly exposed to high and variable loads. To address porosity and enhance the density and mechanical performance of AlSi10Mg, post-processing methods are often employed. HIP is a process that applies both high temperature and high pressure to the part in a pressurized chamber, typically filled with an inert gas. Under these conditions, the material is heated just below its melting point, and the applied pressure compresses any voids within the structure. [44] The combined effects of heat and pressure cause the material to plastically deform around the pores, closing them and eliminating internal voids. This process significantly reduces porosity, leading to a denser and mechanically stronger material. In conclusion, porosity is a common but manageable issue in additively manufactured AlSi10Mg. The presence of pores, due to incomplete melting or gas entrapment, can compromise the materials mechanical properties by serving as sites for stress concentration and crack initiation. However, post-processing techniques like hot isostatic pressing offer an effective solution for reducing porosity and improving overall material strength and density. By employing HIP or optimizing AM

processing parameters, manufacturers can achieve a more reliable, durable AlSi10Mg component suitable for demanding applications.

6. Applications of Additively Manufactured AlSi10Mg

Additively Manufactured (AM) AlSi10Mg is rapidly gaining traction in various high-performance industries, including aerospace, automotive, and electronics makes AlSi10Mg an attractive material for components that must perform reliably under stress while minimizing overall weight. DMLS process used in AM enables precise control over the alloy's microstructure and properties, a level of customization difficult to achieve through traditional manufacturing methods. [45] This capability to tailor properties opens a wide range of applications and provides industries with innovative solutions to traditional challenges.

6.1 Aerospace Applications

Additively manufactured AlSi10Mg is well-suited for aerospace due to its lightweight, high strength, and thermal stability. It enables the production of complex geometries like lattice structures, improving material efficiency and reducing weight—key for enhancing fuel economy and lowering emissions. [46] Components such as brackets, actuator housings, and landing gear parts benefit from its wear resistance and durability, while its heat dissipation makes it ideal for engine-related parts.

6.2 Automotive Applications

In the automotive area, additively manufactured AlSi10Mg has become a material of choice for several applications, including engine parts, transmission components, and structural elements. AlSi10Mg's strength-to-weight ratio is particularly beneficial for automotive applications where lightweight materials are essential for increasing fuel efficiency and improving vehicle performance. Reducing the weight of engine and transmission components translates to less energy required for acceleration, allowing for better fuel economy and reduced emissions. Additionally, AM AlSi10Mg enables the integration of complex shapes and thin-walled structures, which are useful for manufacturing lightweight, high-performance components with intricate geometries. Engine parts, in particular, benefit from AM AlSi10Mg's thermal conductivity and wear resistance. For instance, cylinder heads, piston heads, and intake manifolds, which are continuously exposed to high temperatures and mechanical stress, require materials that can handle intense operating conditions without degrading [48].

6.3 General Advantages of AM AlSi10Mg

One of the key advantages of using additively manufactured AlSi10Mg across these industries is the ability to fine-tune the microstructure to achieve desired properties. Traditional manufacturing techniques, such as casting, have limited control over the microstructure and are subject to constraints such as mold design and cooling rates. In contrast, the DMLS process used in AM enables the rapid cooling and solidification necessary to produce a refined microstructure with enhanced mechanical properties. Furthermore, AM allows for reduced lead times and cost savings in prototype development and production. [49] In applications where design customization is essential, AM enables manufacturers to produce parts directly from digital models, which reduces the need for tooling and molds. This level of flexibility is particularly valuable for industries that prioritize rapid prototyping and iterative design processes, such as aerospace and automotive sectors. AlSi10Mg also exhibits excellent mechanical properties, with superior strength, good thermal conductivity, augmented wear resistance, good thermal stability and fatigue resistance, which are critical for components exposed to variable loads and high temperatures. As a lightweight alloy, AlSi10Mg offers high strength while owning component weight low—a critical reason for industries that prioritize fuel efficacy, such as aerospace and automotive. The rapid melting and solidification during the AM process enhance the alloy's microstructure, resulting in refined grains and an improved distribution of silicon, which can boost mechanical properties and resistance to crack propagation [50].

7.0 Conclusion

AlSi10Mg has emerged as a highly promising material for use in the Direct Metal Laser Sintering (DMLS) process, particularly in the context of automotive applications where weight reduction, complex geometries, and high mechanical performance are critical. Its excellent strength-to-weight ratio, thermal conductivity, and wear resistance make it ideal for components such as brackets, housings, and engine parts. The ability of DMLS to fabricate intricate and lightweight structures directly from digital models supports material efficiency, improved fuel economy, and reduced emissions—key targets for the modern automotive industry. However, to fully harness the potential of AlSi10Mg in DMLS, several areas require further exploration. These include the optimization of process parameters to improve part quality and reduce defects, the application of advanced post-processing techniques such as heat treatment and hot isostatic pressing to enhance mechanical properties, and the development of modified alloys with tailored performance characteristics. Additionally, future work should focus on redesigning components specifically for additive manufacturing to exploit the design freedom offered by DMLS. Real-world validation of AlSi10Mg parts under actual automotive service conditions, as well as comprehensive cost-effectiveness and sustainability assessments, will also be crucial for the widespread industrial adoption of this technology.

8.0 References

1. F. Alamri, I. Barsoum, S. Bojanampati, and M. Naelouf, "Prediction of porosity, hardness and surface roughness in additive manufactured AlSi10Mg samples," 2025.
2. K. Aydin, İ. Karagöz, M. O. Kıbtach, and S. Bayram, "Increasing of Deformation Strength: Evaluating of Local Heating on Selective Laser-Melted AlSi10Mg," 2024.
3. Y. Siyanbajl and Y. Turgut2, "Experimental investigation and optimization of the effects of manufacturing parameters on geometric tolerances in additive manufacturing of AlSi10Mg alloy," 2024.
4. H. M. Gajera, "Experimental Investigation and Analysis of Direct Metal Laser Sintering Process for CL50WS Material," 2023.
5. R. K. Shah and P. P. Dey, "Process parameter optimization of cl50ws process to produce AlSi10Mg components," 2022.A
6. H. Soni and N. Limbeoya, "Investigation of mechanical and surface properties of additively manufactured AlSi10Mg part produced through direct metal laser sintering," 2022.
7. H. B. Bağcı, B. Sagdic, and M. N. Durakbasa, "Effect of direct metal laser sintering process parameters on dimensional accuracy of additively manufactured parts," 2020.
8. M. R. Rathod and M. C. Karli, "Experimental Study for Effects of Process Parameters of Selective Laser Sintering for AlSi10Mg," 2020.
9. P. Fathi, M. Rafsouzafa, and X. Duan, "On microstructure and corrosion behaviour of AlSi10Mg alloy with low surface roughness fabricated by direct metal laser sintering," *Additive Manufacturing*, vol. 29, pp. 126–145, 2019.
10. M. Mohammadi and H. Asgari, "Achieving low surface roughness AlSi10Mg 20oC parts using direct metal laser sintering," 2019.
11. J. Nandy and N. Yedla, "Sintering of AlSi10Mg particles in direct metal laser sintering process: A molecular dynamics simulation study," *Materials Today: Proceedings*, vol. 18, pp. 121803–121810, 2019.
12. S. A. Fatemi, F. Zamani Ashary, A. Jalali Asadabadi, and A. Aleshamsi, "Experimental investigation of process parameters for layer thickness and density in direct metal laser sintering: A response surface methodology approach," 2017.
13. R. K. Shah and P. P. Dey, "Process parameter optimization of DMLS process to produce AlSi10Mg components," *International Journal of Mechanical Engineering and Technology*, vol. 10, no. 6, pp. 112–118, 2019.
14. P. Kumawat and B. S. Prasad, "A detailed study on optimizing DMLS process parameters to enhance AlSi10Mg metal component properties," 2024.
15. R. E. Chite and V. D. Wakchaure, "A review on process parameters, microstructure and mechanical

- properties of additively manufactured AlSi10Mg alloy,” 2023.
16. Li P, Warner D, Fatemi A, Phan N. Critical assessment of the fatigue performance of additively manufactured metallic materials. *Int J Fatigue*. Elsevier. 2016; 93:257- 271.
 17. Attar H, Calin M, Zhang LC, Scudino S, Eckert J. Manufacture by Direct metal laser sintering and mechanical behavior of commercially pure titanium. *Mater Sci Eng A*. 2014; 593:170-177. <https://doi.org/10.1016/j.msea.2013.11.038>
 18. Sun SH, Kuo C, Hsu KY. Applications of AlSi10Mg alloy produced by selective laser melting. *Addit Manuf*. 2019; 28:434-446.
 19. Kumar S, Rahman Z. Properties and applications of additively manufactured AlSi10Mg alloy in automotive industry. *J Mater Process Technol*. 2020; 293:117-124.
 20. Supriya B, Thimmaiah MB, et al. Wear behavior of AA2219-B4C composite fabricated via stir casting followed by age hardening. *J Inst Eng India Ser D*. 2024. <https://doi.org/10.1007/s40033-024-00736-2>
 21. Louvis E, Fox P, Sutcliffe CJ. Direct metal laser sintering of aluminium components. *J Mater Process Technol*. 2011; 211(2):275-284. <https://doi.org/10.1016/j.jmatprotec.2010.09.019>
 22. Li Y, Zhang X, Chen Z. Controlling microstructure in AM of AlSi10Mg through parameter optimization. *Mater Des*. 2021; 194:108-116.
 23. Sercombe TB, Li X. Direct metal laser sintering of aluminium and aluminium metal matrix composites- Review. *Mater Technol*. Taylor and Francis. 2016; 31(2):77-85. <https://doi.org/10.1179/1753555715Y.0000000078>
 24. Thijs L, Verhaeghe F, Craeghs T, Humbeeck JV, Kruth JP. A study of the microstructural evolution during Direct metal laser sintering of Ti-6Al-4V. *Acta Mater*. 2010; 58(9):3303-3312. <https://doi.org/10.1016/j.actamat.2010.02.004>
 25. Suard M, Ebel T, Friedrich B. Direct metal laser sintering of AlSi10Mg alloy. *Mater Des*. 2014; 61:140-150.
 26. Amato KN, Gaytan SM, Murr LE, Martinez E, Shindo PW, Hernandez J, et al. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. *Acta Mater*. 2012; 60(5):2229-2239. <https://doi.org/10.1016/j.actamat.2011.12.032>
 27. Murr LE, Gaytan SM, Medina F, et al. Next-generation biomedical implants using additive manufacturing of complex, cellular, and functional mesh arrays. *Philos Trans R Soc A Math Phys Eng Sci*. 2010; 368(1917):1999- 2032. <https://doi.org/10.1098/rsta.2010.0010>
 28. Li P, Warner DH, Fatemi A, Phan N. Critical assessment of the fatigue performance of additively manufactured metallic materials. *Int J Fatigue*. Elsevier. 2016; 93:257- 271.
 29. Attar H, Calin M, Zhang LC, Scudino S, Eckert J. Direct metal laser sintering and mechanical behavior of Al-Si alloys. *Mater Sci Eng A*. 2014; 640:280-289.
 30. Rangappa R, Patel GCM, Chate GR, et al. Coaxiality error analysis and optimization of cylindrical parts of CNC turning process. *Int J Adv Manuf Technol*. 2022; <https://doi.org/10.1007/s00170-022-09184-2>
 31. Liu C, Wang Y, Wu J. Effects of laser parameters on microstructure and properties of AlSi10Mg. *Mater Sci Eng A*. 2019; 737:270-278.
 32. Zhang Y, Xu Z. Impact of scan speed on AlSi10Mg in selective laser melting. *Mater Process J*. 2020; 2:42-55.
 33. Read N, Wang W, Essa K, Attallah MM. Direct metal laser sintering of AlSi10Mg alloy: Process optimization and mechanical properties development. *Mater Des*. 2015; 65:417-424. <https://doi.org/10.1016/j.matdes.2014.09.044>
 34. Shankar VK, Lakshmikanthan A, Selvan CP, et al. Prediction of transient temperature at bit-rock interface using numerical modelling approach and optimization. *Int J Interact Des Manuf*. 2024; 18:6109-6121. <https://doi.org/10.1007/s12008-023-01543-x>
 35. Casati R, Vedani M. Metal matrix composites reinforced by nano-particles- A review. *Metals*. 2014; 4(1):65-83. <https://doi.org/10.3390/met4010065>
 36. Qiu C, Panwisawas C, Ward M, Basoalto HC, Brooks JW, Attallah MM. On the role of melt flow into the surface structure and porosity development during selective laser melting. *Acta Mater*. 2015; 96:72-79. <https://doi.org/10.1016/j.actamat.2015.06.004>
 37. Kumaraswamy S, Malik V, Devaraj S, Jain VK, Lakshmikanthan A. A study of shear friction factor in friction stir welding for developing a finite element model and its importance in the context of formation

- of defect-free and defective weld. *Mater Today Proc.* 2021; 45(Part):299-303. <https://doi.org/10.1016/j.matpr.2020.10.651>
38. Hooreweder BV, Moens D, Boonen R, et al. Analysis of fracture toughness and crack propagation of Ti6Al4V produced by selective laser melting. *Adv Eng Mater.* 2012; 14(1-2):92-97. <https://doi.org/10.1002/adem.201100233>
39. Qian M, Das S. Direct metal laser sintering and its effects on microstructure and properties of alloys. *J Mater Process Technol.* 2015; 1(7):389-403.
40. Tang M, Pistorius PC. Oxides, porosity, and fatigue performance of AlSi10Mg parts produced by selective laser melting. *Int J Fatigue.* 2017; 94:192-201. <https://doi.org/10.1016/j.ijfatigue.2016.06.002>
41. Sheshadri R, Nagaraj M, Lakshmikanthan A, et al. Experimental investigation of Direct metal laser sintering parameters for higher surface quality and microhardness properties: Taguchi and super ranking concept approaches. *J Mater Res Technol.* 2021; 14:2586-2600. <https://doi.org/10.1016/j.jmrt.2021.07.144>
42. Liu W, Ma J, Luo J, Zhang Z. Effects of surface finishing on microstructure and mechanical properties of AlSi10Mg produced by DMLS. *Mater Des.* 2018; 140:153-162.
43. Weng F, Zhang H, Brochu M. A review of additive manufacturing of aluminum alloys and aluminum matrix composites. *J Mater Sci Technol.* 2017; 33(4):407-422.
44. Sahadevan P, Selvan CP, Bhaumik A, Lakshmikanthan. Direct metal laser sintering parametric optimization for microhardness of 17-4 PH stainless steel. *J Mines Metals Fuels.* 2023; 71(12):2512-2519. <https://doi.org/10.18311/jmmf/2023/35128>
45. Sun SH, Kuo C, Hsu KY. Applications of AlSi10Mg alloy produced by selective laser melting. *Addit Manuf.* 2019; 28:434-446.
46. Murr LE, Amato KN, Gaytan SM, et al. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. *Acta Mater.* 2010; 60(5):2229-2239. <https://doi.org/10.1016/j.actamat.2011.12.032>
47. Sahadevan P, Selvan CP, Bhaumik A, Lakshmikanthan. Surface roughness optimization of Direct metal laser sintering printed 17-4 PH stainless steel parts. *J Mines Metals Fuels.* 2023; 71(12):2405-2413. <https://doi.org/10.18311/jmmf/2023/35123>
48. Ning Y, Cong W, Qi H. Review of additive manufacturing of high-performance materials: Alloys, ceramics, and composites. *J Mater Process Technol.* 2018; 257:48-72.
49. Hooreweder BV, David M, Rene B, Jean-Pierre K, Paul S. Analysis of fracture toughness and crack propagation of Ti6Al4V produced by selective laser melting. *Adv Eng Mater.* 2012; 14(1-2):92-97
50. Liu W, Ma J, Luo J, Zhang Z. Effects of surface finishing on microstructure and mechanical properties of AlSi10Mg produced by DMLS. *Mater Des.* 2018; 140:153-162.
51. Qian M, Das S. Direct metal laser sintering and its effects on microstructure and properties of alloys. *J Mater Process Technol.* 2015; 1(7):389-403