A Study of Process Optimization and Wear Behavior of Additive Manufacturing Process of ALSi10Mg

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ABSTRACT

Additive Manufacturing (AM), frequently referred to as 3D printing, has emerged as a transformative technology that possesses the capacity to revolutionize traditional manufacturing methodologies. Unlike subtractive manufacturing processes, which involve the removal of material from a solid substrate, additive manufacturing fabricates objects incrementally, layer by layer, directly from digital schematics. This approach offers a multitude of advantages, including the ability to produce complex geometries, reduce material waste, and customize products to meet specific individual specifications.

Additive manufacturing (AM) of aluminium alloys, particularly AlSi10Mg, has gained significant interest due to its applicability in aerospace, automotive, and tooling industries. This study investigates the effect of T6 heat treatment on the wear behavior and mechanical properties of AlSi10Mg parts produced by Selective Laser Melting (SLM). Post-processing included solution heat treatment followed by artificial aging. Vickers hardness testing and dry sliding wear tests were performed to analyze the changes in micro hardness and wear resistance. The results revealed a significant increase in hardness and improved wear resistance after heat treatment, indicating the effectiveness of T6 treatment in enhancing the performance of AM AlSi10Mg components.

Keywords: Additive Manufacturing, DMLS, ALSi10Mg, T6 Heat Treatment, Wear Resistance, Pin-on-Disc

INTRODUCTION

AlSi10Mg is a popular aluminium alloy known for its excellent combination of properties, including high strength, low density, and good corrosion resistance. This alloy is widely used in various industries, including aerospace, automotive, and manufacturing, due to its versatility and performance. In this exploration, we will delve into the properties, applications, manufacturing processes, advancements, and future perspectives of AlSi10Mg alloy.

AISI10Mg (a magnesium alloy) is valued for its Lightweight properties, High strength-to- weight ratio, Potential applications in aerospace, automotive, and biomedical sectors. But there are disadvantages associated with AISI10Mg namely Magnesium's flammability and oxidation sensitivity during printing, Lack of standardized process parameters for printing, limited data on mechanical properties post-manufacturing. Despite the benefits of Additive Manufacturing (AM), the use of AISI10Mg remains limited due to processing difficulties, lack of research, and insufficient knowledge about its behavior during and after additive manufacturing. There is a clear need to explore and optimize AM techniques for AISI10Mg to make it viable for widespread industrial use.

AlSi10Mg is an aluminum alloy commonly used in metal additive manufacturing due to its lightweight nature, good strength-to-weight ratio, and excellent thermal properties. The process is typically carried out

using Selective Laser Melting (SLM), where the alloy powder is melted layer by layer using a high-powered laser.

After fabrication, parts often undergo solution heat treatment (T6) heat treatment, which involves solution treatment, quenching, and artificial aging. This improves the alloy's mechanical properties by dissolving and redistributing alloying elements, enhancing strength and hardness.

Aluminium-silicon-magnesium (AlSi10Mg) alloy is widely used in additive manufacturing due to its excellent strength-to-weight ratio, good thermal conductivity, and corrosion resistance. Selective Laser Melting (SLM), a prominent powder bed fusion AM process, allows for the production of complex geometries with high dimensional accuracy. However, the as-built components often possess residual stresses, anisotropic microstructures, and relatively lower ductility. To mitigate these issues, post-processing techniques such as T6 heat treatment are employed. T6 heat treatment includes solution zing, quenching, and aging processes which refine the microstructure, relieve residual stresses, and enhance mechanical properties. This research aims to evaluate the effectiveness of T6 heat treatment on the wear and hardness behavior of SLM-processed AlSi10Mg specimens using Vickers hardness and wear testing techniques.

LITERATURE REVIEW

Several researchers have worked on ALSi10Mg using additive manufacturing methods. The previous research work is presented as follows

Vineesh Vishnu et. al., [2023] have conducted their research on Direct Metal Laser Sintering (DMLS).It is a novel manufacturing method for creating metallic parts from a 3D CAD model. Aluminum alloy (AlSi10Mg), known for its lightweight and strength, is pertinent to the aerospace and automotive sectors. This research investigates the dry sliding wear characteristics of DMLS AlSi10Mg, comparing it with chrome steel and alumina under varying loads (5 N, 10 N, 20 N). Wear morphology was analyzed using scanning electron microscopy with energy dispersive spectroscopy, 3D profilometer, and X-ray diffraction. Results show that friction values ranged from 0.62 to 0.35 for chrome steel and 0.8 to 0.45 for alumina. Wear rates increased with load, notably higher for alumina (74%, 20%, and 33% more than chrome steel at 5 N, 10 N, and 20 N). High wear resistance against chrome steel is due to stable oxide layer prevents direct metallic interaction. Alumina test showed wear mechanisms like adhesion, delamination, and oxidative wear, while chrome steel exhibited adhesion and delamination [1]

Nesma T. Aboul khair et. al., [2019] worked on Metal Additive Manufacturing (AM) processes, such as selective laser melting (SLM), enable the fabrication of arbitrary 3D- structures with unprecedented degrees of freedom. Research is rapidly progressing in this field, with promising results opening up a range of possible applications across both scientific and industrial sectors. Many sectors are now benefiting from fabricating complex structures using AM technologies to achieve the objectives of light-weighting, increased functionality, and part number reduction, among others. AM also lends potential in fulfilling demands for reducing the cost and design-to- manufacture time. Aluminium alloys are of the main material systems receiving attention in SLM research, being favoured in many high value applications. However, processing them is challenging due to the difficulties associated with laser-melting aluminium where parts suffer various defects.[2]

B. Rozegari ghashghay et. al., [2014] conducted studies on AlSi10Mg alloy and its grain refinement capabilities. On the capability of grain refinement during selective laser melting of AlSi10Mg alloy. he origin and capability of grain refinement in the microstructure of selective laser melted AlSi10Mg alloy. The fraction of the refined equiaxed grains by the size of less than 10μm is considered (-40%) and were classified in to two categories 1) Those having high amount of GOS which originated during solidification due to the low amount of thermal gradient ratio.2) Those fine grains that held GOS <1degree revealing that they were fresh grains developed through dynamic recrystallization. Refined equiaxed grains have been differentiated through plotting grain orientation spread maps. The high fraction of the low angle boundaries indicated the high potential for the substructure development, sub grain formation, and activation of continuous dynamic recrystallization as the main restoration mechanism. Besides the extensive substructure

development and sub grain formation are the main proof for governing of continuous mechanisms of recrystallization Mechanisms. Required stored energy for dynamic recrystallization was provided during the process and the imposed micro-plastic strains were estimated considering the length and width of the melt pools. The critical strain of recrystallization was measured to be 0.18 using compression testing method at 450-degree Celsius which was lower than that calculated during selective laser melting. The calculated micro –plastic strain has been compared with a critical strain of dynamic recrystallization obtained from the hot compression testing mechanism [3]

Y. Du et. al., [2022] conducted studies on fatigue life of printed parts though AM processSmooth surfaces in the printed parts are essential for long fatigue life and high dimensional accuracy. They are currently achieved by post-process machining and grinding of external surfaces that add extra costs. Mitigating the surface roughness of internal channels remains a challenge. Here we use a high-throughput screening approach that analyzes the value of a dimensionless index for many experiments and provides a pathway for reducing the surface roughness without the need for postprocessing. The index is derived by dimensional analysis of causative variables that affect the roughness of the surface such as heat input, powder diameter, layer thickness, pool aspect ratio, Marangoni force, contact angle, and enthalpy of melting of alloys. Using the results of high-throughput screening, we develop easy-to-use process maps that are consistent with the experimental observations.[4]

Noriko Read et. al., [2014] have conducted studies on AlSi10Mg alloy In this paper, the influence of selective laser melting (SLM) process parameters (laser power, scan speed, scan spacing, and island size using a Concept Laser M2 system) on the porosity development in AlSi10Mg alloy builds has been investigated, using statistical design of experimental approach, correlated with the energy density model. A two-factor interaction model showed that the laser power, scan speed, and the interaction between the scan speed and scan spacing have the major influence on the porosity development in the builds. By driving the statistical method to minimize the porosity fraction, optimum process parameters were obtained.[5]

B. Chen et. al., [2017] reported that a selective laser melted (SLM) AlSi10Mg alloy has unique hierarchical microstructures. There are micro-sized Al grains and trans granular ultrafine cellular structures around primary Al, and the cell boundary is made up of alternate eutectic Si and eutectic Al phases. The SLM AlSi10Mg alloy has both high tensile strength and high strain- hardening capability, which are superior to Al-Si alloys fabricated by conventional powder metallurgy and cast methods. Post-tensile highresolution microscopy analyses provide further evidence supporting Orowan looping as a strengthening mechanism of the SLM.[6]

Laura Cordova Monica Campos et.al.,[2013] have worked on SLM and AM methods And try to Reveal the Effects of Powder Reuse for Selective Laser Melting by Powder Characterization. The paper investigates the impact of reusing powders in the (SLM) process for four commonly used AM powders, namely Inconel 718, Ti6Al4V, AlSi10Mg, and Scalmalloy, by characterizing changes in morphology, composition, and flowability. Reusing AlSi10Mg powder in the (SLM) process can lead to changes in particle size distribution, morphology, and an increase in oxygen content. These changes are associated with remelting, variations in composition, and potential contamination during the process. The characterization techniques used in the procedure include sieve analysis to determine particle size distribution, scanning electron microscopy (SEM) with an energy-dispersive X-ray spectroscopy (EDS) detector to analyze chemical composition, and quantitative morphological analysis to assess particle features. The analysis of powder composition and microstructure helps validate the hypothesis that changes occur due to the melting process and possible contamination of the build chamber.5.46%. Overall, the study concludes that the differences between powders from different manufacturers are small, leading to a recommendation for the most economical powder. [7]

Nandita Limbasiya et. al., [2022] worked on AlSi10Mg material through Selective Laser Melting (SLM) process has a great potential to create unique 3D components of AlSi10Mg with exceptional degrees of freedom for wide range of applications in industries. However, the presence of porosity and other defects influenced by process parameters can be harmful to fabricated components in some applications. Process parameters and post-processing treatments helps in minimizing the metallurgical defects and enhance the mechanical properties. This review aims to provide a detailed description of the recent research done on the

SLM- AlSi10Mg including the effect of SLM process parameters on the mechanical properties of the alloy. The effect of different heat treatments on the microstructure and overall mechanical properties of SLM fabricated AlSi10Mg alloy parts also discussed.[8]

David Riegraf et.al.,[2013] conducted Experimental analysis of parameters for AlSi10Mg powders from different manufacturers in selective laser melting. The paper provides an analysis of AlSi10Mg powders from different manufacturers for selective laser melting, focusing on various parameters such as moisture content, morphology, size distribution, flowability, and porosity. The study distinguishes itself from other researchers by using six powders of the same specification but from different manufacturers. It investigates the moisture content of the powders, finding that it ranges from 5% to 15% and can be reduced by using dry bags. The morphology and size distribution of the powders are examined using scanning electron microscopy, revealing the presence of partially round, misshapen, and adhesive particles. Flowability is determined using a calibrated Hall flow meter, and it is found that a lower proportion of fine particles in the powder leads to a more uniform flowability. Porosity analysis is conducted on test cubes, and the results show porosity ranging from 0.12[9]

Evangelia Georgantzia et. al., [2021] worked on aluminium alloys through 3D printing route.Over the last few decades aluminum alloys have been increasingly used in the construction sector due to their favorable properties. Thereafter, many research projects have been carried out with the aim to obtain a more comprehensive understanding of their structural performance and develop accurate and reliable design formulae. The scope of this paper is to provide a comprehensive review of research by discussing the reported experimental, numerical and analytical work on structural aluminum alloys. The paper presents an overview of research studies on the mechanical properties of aluminum alloys under monotonic, cyclic and thermal loading conditions. Moreover, a considerable amount of experimental and numerical investigations focusing on the structural performance and design of aluminum columns, beams and beam-columns is reviewed. The performance of connections and composite aluminum- concrete members is also discussed. [10]

AlSi10Mg

AlSi10Mg is a popular aluminium alloy known for its excellent combination of properties, including high strength, low density, and good corrosion resistance. This alloy is widely used in various industries, including aerospace, automotive, and manufacturing, due to its versatility and performance. In this exploration, we will delve into the properties, applications, manufacturing processes, advancements, and future perspectives of AlSi10Mg alloy.

Properties of AlSi10Mg Alloy

- AlSi10Mg alloy exhibits several key properties that make it suitable for a wide range of applications:
- Lightweight: AlSi10Mg alloy has a low density, approximately one-third that of steel, making it ideal for applications where weight reduction is critical, such as aerospace and automotive components.
- High Strength: AlSi10Mg alloy can be heat-treated to achieve high strength and stiffness, comparable to some steel alloys, while maintaining a lightweight design.
- Corrosion Resistance: AlSi10Mg alloy forms a protective oxide layer on its surface, providing excellent resistance to corrosion in various environments, including marine and aerospace applications.
- Thermal Conductivity: AlSi10Mg alloy exhibits good thermal conductivity, making it suitable for heat exchangers, cooling systems, and electronic components.
- Machinability: AlSi10Mg alloy can be easily machined, fabricated, and welded using conventional manufacturing processes, allowing for the production of complex shapes and structures.

Applications of AlSi10Mg Alloy

- AlSi10Mg alloy finds applications across various industries due to its unique combination of properties:

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- Aerospace: AlSi10Mg alloy is used in aerospace applications, including aircraft components, engine parts, and structural components, due to its lightweight, high strength, and corrosion resistance.
- Automotive: AlSi10Mg alloy is utilized in automotive components such as engine blocks, cylinder heads, and suspension components to reduce vehicle weight, improve fuel efficiency, and enhance performance.
- Manufacturing: AlSi10Mg alloy is used in additive manufacturing processes, such as selective laser melting (SLM) and powder bed fusion (PBF), to produce complex parts with optimized designs and properties.
- Electronics: AlSi10Mg alloy is used in electronic components, including heat sinks, housings, and chassis, due to its thermal conductivity, lightweight, and corrosion resistance.
- Consumer Goods: AlSi10Mg alloy is used in consumer goods such as sporting equipment, furniture, and recreational vehicles due to its lightweight, durability, and aesthetic appeal.
- These are just a few examples of the diverse range of applications enabled by AlSi10Mg alloy across industries.

Manufacturing Processes of AlSi10Mg Alloy

AlSi10Mg alloy can be produced using various manufacturing processes, including casting, additive manufacturing, and machining:

Casting: AlSi10Mg alloy can be cast into Molds to produce components with complex shapes and near-net dimensions. Casting processes include sand casting, die casting, and investment casting

- Additive Manufacturing: AlSi10Mg alloy can be produced using additive manufacturing techniques such as selective laser melting (SLM) and powder bed
- Fusion (PBF), which enable the production of complex parts with optimized designs and properties.
- Machining: AlSi10Mg alloy can be machined using conventional machining processes such as milling, drilling, and turning to achieve tight tolerances and surface finishes.
- These manufacturing processes allow us to produce a wide range of AlSi10Mg alloy components with diverse shapes, sizes, and properties.

TESTING OF MATERIAL

AlSi10Mg is an aluminium alloy commonly used in metal additive manufacturing due to its lightweight nature, good strength-to-weight ratio, and excellent thermal properties. The process is typically carried out using Selective Laser Melting (SLM), where the alloy powder is melted layer by layer using a high-powered laser.

After fabrication, parts often undergo T6 heat treatment, which involves solution treatment, quenching, and artificial aging. This improves the alloy's mechanical properties by dissolving and redistributing alloying elements, enhancing strength and hardness.

Solution Heat Treatment (T6)

The printed samples underwent **T6 heat treatment**, which involves:

- **Solutionising** at elevated temperature to dissolve soluble phases.
- **Quenching** to retain a supersaturated solid solution.
- **Artificial aging** to precipitate strengthening phases.

This treatment significantly improves the **mechanical strength** and **wear resistance** of AlSi10Mg by refining the microstructure and precipitating Mg2Si phases.

Vickers Hardness Testing

Vickers hardness tests were performed before and after T6 treatment. The results showed a noticeable **increase in hardness** after heat treatment, indicating enhanced material strength and improved resistance to

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plastic deformation.

Wear Testing

Wear behavior was analyzed under controlled conditions. The T6-treated samples demonstrated **lower wear rates** and better resistance due to the hardened surface and more uniform microstructure. The wear mechanism was predominantly **abrasive and adhesive**, but post-treatment reduced material loss.

PROBLEM STATEMENT

The problem statement related to additive manufacturing of AlSi10Mg alloy involves addressing challenges and optimizing the process for producing high-quality components.

One of the most significant limitations in LPBF-manufactured AlSi10Mg parts is the poor as- built surface quality. Due to the nature of layer-wise deposition and powder spreading, the resulting surface roughness is considerably higher compared to conventionally machined or cast components. Surface irregularities can lead to stress concentration points, which negatively impact fatigue life, especially in dynamic loading environments.

Additionally, mechanical properties such as hardness and wear resistance are not uniform throughout the part. Variability in laser energy absorption, scan strategy, and heat dissipation leads to inconsistent microstructure formation and the presence of defects such as porosity, unmelted particles, and microcracks. These issues necessitate extensive post- processing (e.g., heat treatment, hot isostatic pressing, or surface finishing) to bring the components up to industrial standards, thus increasing manufacturing lead time and cost.

METHODOLOGY

In principle, the SLM process appears relatively straightforward. However, there are many aspects which require attention in order to manufacture parts of sufficient structural integrity to enable industrial adoption. These aspects, namely: (i) process-, (ii) design-, and (iii) material-related. The present project work was carried out according to a sequence of steps and a methodology as mentioned in the figure.1

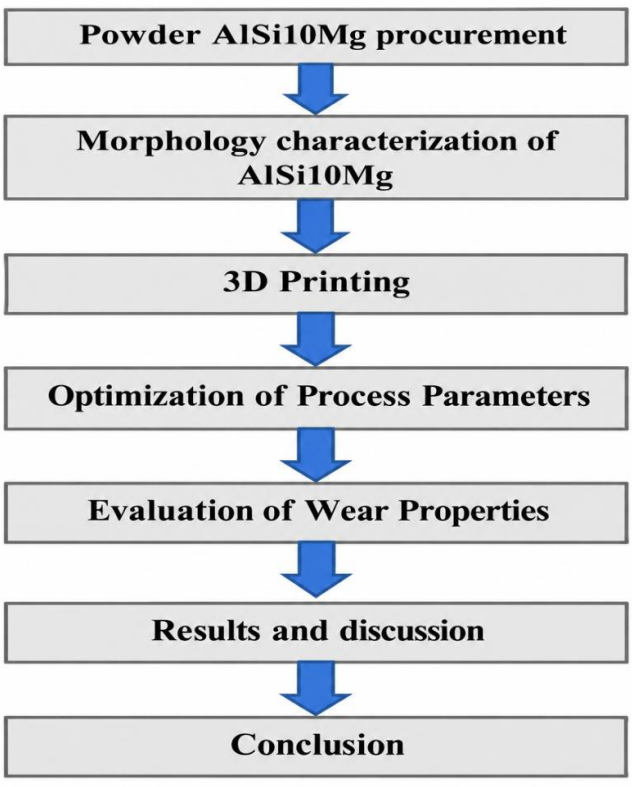


Figure 1. Methodology Flow chart

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EXPERIMENTAL PROCEDURE

Sample Preparation

Preparing the sample optimizing the various parameters like laser power, laser scan speed. The first step in SLM begins with slicing a computer aided design (CAD) file into a set of layers and then the modified data will be transferred to SLM machine where a high-power focused laser melts the contour of each layer until the part is finally materialized according to the contour. SLM sinters the powder with high temperature gradient and solidification velocity, which results in epitaxial to columnar grain morphology along the direction of building. Moreover, the morphology, the crystallographic texture along building direction and average grain size depends on the process parameters set, the scanning strategy and the laser energy.

A chessboard hatching style will be utilized for the bulk volume, with each layer divided into 3x3 mm2 square blocks, each of which will be labeled either black or white as per a real chessboard. Blocks labeled black will be melted first, followed by those labeled white, after which the laser beam contoured the layer along its perimeter twice. Each PHASE 2: To investigate the mechanical & tribological properties of AlSi10Mg alloy processed by SLM. block will be scanned with parallel tracks in order to obtain a low temperature gradient in the bulk volume; each layer (n+1) will be rotated by 30° with respect to the previous layer (n). Samples for microstructural characterization, density measurements and mechanical tests will be produced by varying Power, scan speed, Hatch pace, building direction and fluence. Then will study the micro hardness of the sample and conduct the tensile and wear test of the SLM sample



Figure 2: Selective laser melting process

Steps followed in preparation of samples of ALSi10Mg

The material known as AlSi10Mg alloy comprises spherical powder particles formed through a gas atomization technique, with the chemical composition of AlSi10Mg detailed in Table 1

Step 1: Design the specimens: Prepare the specimen geometry in CAD according to the planned tests. Specimens for hardness, wear and tensile testing may require different dimensions.

Step 2: Print the specimens: Print the AlSi10Mg specimens using the SLM/LPBF machine. Record the important process parameters, including laser power, scanning speed, layer thickness, hatch spacing, build orientation and powder condition.

Step 3: Remove the specimens from the build plate: After printing and cooling, remove the specimens using an appropriate cutting method, such as wire EDM or a suitable precision saw. Avoid excessive heating and mechanical deformation during removal.

Step 4: Clean and inspect the specimens: Remove loose powder and clean the surfaces. Inspect for visible cracks, distortion and other defects. Record the specimen identification number and build orientation.

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Step 5: Divide the specimens into groups

For a meaningful comparison, use at least two groups:

Group A — As-built: No T6 heat treatment; retain the original printed microstructure.

Group B — T6-treated: Subject the specimens to solution treatment, quenching and artificial aging.

Additional groups can be prepared if different heat-treatment schedules are being compared.

Table 1: The chemical composition of AlSi10Mg alloy.

Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn	Others total
Balance	9.00	0.55	0.05	0.45	0.25- 0.45	0.10	0.15	0.05	0.05	0.05	0.15

Heat Treatment T6 (Solution heat treatment) process parameters followed during the study of AlSi10Mg by selective laser melting by powder bed method as per the AMS 2770, AMS 2771, and ASTM B918.

Table 2: T6 Solution Heat treatment of AlSi10Mg alloy process parameters.

Stage	Temperature maintained / condition	Purpose
Solution treatment	Around 535 °C	Dissolve soluble phases and modify the silicon network
Holding time	Around 3 hours Class 2 (±6°C / ±10°F) circulating air furnace	Allow sufficient microstructural change
Quenching	Bath Temperature: 40°C Rapid cooling, commonly in agitated clean water	Retain a supersaturated solid solution
Artificial aging	Around 170°C	Develop strengthening precipitates
Aging time	6 hours, still air cooling to room temperature.	Obtain the desired hardness and strength

Steps of Wear Testing Sample preparation

Preparation of Sample for conducting wear test as per ASTM G99 used standard for pin-on-disc wear testing. For LPBF AlSi10Mg

Step 1: Design and print the wear specimens: Design the specimens according to the dimensions required by the available pin-on-disc apparatus. Print AlSi10Mg specimens in the selected build orientation.

A typical configuration uses a cylindrical pin with a flat contact face. However, some apparatus uses a disc-shaped specimen against a stationary pin or another counter face. Follow the geometry specified by your machine.

Step 2: Remove specimens from the build plate: Remove the specimens using wire EDM or another suitable cutting process. Avoid excessive heating, deformation and damage to the intended wear surface.

Step 3: Machine the specimens: Machine the specimens to the required diameter, length and contact-face geometry. The pin must fit securely in the holder and maintain stable contact with the rotating counterface.

Step 4: Grind and polish the contact surface

Prepare the pin's contact face using suitable abrasive papers, progressing to a finer grit as required. Remove machining marks and obtain a flat surface.

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For comparative testing, aim for a consistent initial surface roughness across the as-built and T6-treated specimens. Record the final roughness, preferably as \(R_a\), using a suitable surface profilometer.

Step 5: Clean the specimens

Remove abrasive particles, oils and debris using a compatible cleaning method. Dry the specimens completely before weighing or testing.

Step 6: Measure the initial mass

Use a calibrated analytical balance to record the initial mass, \(m_i\), if mass loss will be used to calculate wear. Use the same balance and weighing procedure before and after testing.

Step 7: Inspect the counterface disc

Select the counterface material specified by your test plan, such as hardened EN31 steel. Record its hardness, surface roughness and condition. Clean the disc before each test and maintain consistent preparation between runs.

Step 8: Mount the specimen

Secure the AlSi10Mg pin in the specimen holder. Ensure that the flat contact face is correctly aligned with the rotating disc and that the applied load acts in the intended direction.

Step 9: Record the test conditions

Wear testing of AlSi10Mg on pin on disc is a common method for evaluating the wear behavior of this alloy. The wear behavior of AlSi10Mg alloy produced by laser-based powder bed fusion (PBF-LB) was evaluated using a pin-on-disc (P o D). The pin-on disc (P o D) test is a simple and widely used method for evaluating the wear behavior of materials. The test involves placing a pin-shaped specimen on a rotating disc, which is typically made of a harder material. The pin and disc are brought into contact, and the pin is loaded against the disc with a specific load.

The pin and disc are then rotated relative to each other, and the frictional force and wear of the pin are measured. The assessment of friction behavior commonly involves the examination of the wear rate and the coefficient of friction (COF). The wear rate data for SLM AlSi10Mg can be observed in encompassing applied load of 20N, slide speeds of 200 rpm, and time intervals of 5 minutes. Throughout these experiments, the sliding distance remained consistent, and all tests were executed under ambient temperature conditions



Figure 3: schematic diagram of Wear testing Machine

Table.3 Wear Load and Spead

Load in N	Speed in rpm	Time in minutes
20	200	5

Wear can be estimated by conducting a tribological test where a constant normal load of 5 Newtons is applied on the specimen. The specimen is rotated or rubbed at a speed of 200 revolutions per minute (RPM) for a duration of 5 minutes, resulting in a total of 1000 revolutions. During this period, the material undergoes continuous frictional contact, and the wear can be quantified by measuring the loss in mass or volume before and after the test

Table 4: Wear calculation results

Samples	Initial weight (in gms)	Final weight (in gms)	Wear rate (m^3/m)
As-built S1	4..4479	4.393	7.161*10-7
As-built S2	4.7535	4.729	6.498*10-7
As-built S3	4.3142	4.3084	4.93*10-4
T6 S1	4.6048	4.5796	2.228*10-7
T6 S2	4.1119	4.1021	1.733*10-7
T6 S3	3.9578	3.9578	1.018*10-6

The formula used to calculate the wear rate is as follows Wear Rate = V / F x D

V = Volume loss due to wear (mm^3)

F = load applied (N)

D = Sliding distance (m)

To calculate the sliding distance Velocity / Time = 1.047 / 300 = 0.003



Figure 4: wear samples

Hardness Testing

Hardness testing is a fundamental technique used to evaluate the resistance of AlSi10Mg alloy to localized plastic deformation. In this study, the hardness of AlSi10Mg specimens fabricated via SLM-based powder bed fusion (PBF-LB) was measured using the Vickers hardness test method. This test involves applying a specified load through a diamond indenter in the shape of a right pyramid with a square base, which is pressed into the surface of the material.

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The standard Vickers hardness test was conducted in accordance with ASTM E92, employing a load of 500 gf and a dwell time of 10 seconds. Multiple indentations were made across the sample surface to ensure statistical accuracy and account for potential inhomogeneities due to the layer-wise additive manufacturing process

The hardness values obtained provide insight into the material's mechanical properties and its suitability for wear-resistant applications. Factors influencing the hardness, such as microstructural refinement, residual stresses, and possible heat treatment effects, were considered during data interpretation



Figure 5: Vickers Hardness Test

Tables 5**:** Hardness Testing calculation results

Sample Condition	**Indentation No.**	**Hardness (HV)**	**Average**
As-built	1	129	
As-built	2	132	

As-built	3	130	
As-built	4	131	
As-built	5	128	130
As-built	6	130	
As-built	7	133	
As-built	8	127	
As-built	9	129	
As-built	10	131	
T6 Heat Treated	1	80	
T6 Heat Treated	2	78	
T6 Heat Treated	3	79	
T6 Heat Treated	4	77	
T6 Heat Treated	5	80	79
T6 Heat Treated	6	81	
T6 Heat Treated	7	79	
T6 Heat Treated	8	78	
T6 Heat Treated	9	80	
T6 Heat Treated	10	79	

RESULTS AND DISCUSSION

All experimental data—including hardness values, wear rate are collected, compared, and discussed. This section analyzes:

Wear Behavior of As-Built AlSi10Mg Samples

The wear characteristics of the as-built AlSi10Mg samples were evaluated through linear wear tests conducted over a time interval ranging from 0 to 300 seconds. As shown in Figure 16, the wear depth exhibited a linear increase with time, reaching approximately 200 microns at 300 seconds.

This linear wear trend suggests a steady-state wear regime, indicating that the material experiences uniform and consistent wear under the applied load and rotational conditions. Such behavior is characteristic of mild abrasive and adhesive wear mechanisms, where the material removal is stable over time. The uniformity of the wear rate implies a stable tribological interface with no significant structural degradation, cracking, or delamination observed during the test duration.

This result demonstrates that as-built AlSi10Mg, despite lacking post-processing treatments, shows predictable wear performance, making it suitable for low-to- moderate stress sliding applications. However, the relatively high wear depth observed highlights the potential for further improvement in wear resistance through surface or heat treatments.

Effect of Rotational Speed on Wear Rate of T6 Heat-Treated Samples presents the relationship between rotational speed (RPM) and wear rate for T6 heat- treated AlSi10Mg samples tested under a constant load of 20 N over a fixed duration of 5 minutes. The wear rate was observed to decrease significantly as the RPM increased:

- At 100 RPM, the wear rate was approximately 18 microns
- At 300 RPM, the wear rate reduced to around 11 microns

This inverse relationship indicates that higher speeds result in lower wear rates. Possible explanations include:

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- Reduced contact duration per revolution, lowering the severity of frictional interactions
- Improved heat dissipation or potential micro-lubrication effects at higher speeds
- Enhanced surface integrity and hardness due to the T6 treatment, leading to better tribological performance

These findings suggest that T6 heat-treated AlSi10Mg performs better under dynamic operating conditions, making it a suitable candidate for components subjected to continuous rotational or sliding motion. The observed trend also confirms the effectiveness of heat treatment in enhancing wear resistance.

Vickers Hardness Analysis

A comparison of Vickers hardness values between as-built and T6- are as follows:

As-built sample: 130.0 HV

T6 Heat Treated sample: **79.1 HV**

Contrary to expectations, the T6-treated samples exhibited lower hardness than their as-built counterparts. This outcome may be attributed to:

- Over-aging or improper artificial aging during the T6 cycle, which can lead to coarsening of Mg_2Si precipitates, thereby reducing overall hardness
- Stress relief during solution treatment and quenching, which may reduce internal strain hardening effects present in the as-built state
- Possible microstructural coarsening, leading to reduced dislocation density

Although a drop in hardness was observed, this did not correspond to poorer wear performance. In fact, the T6-treated samples showed significantly lower wear rates, highlighting that wear resistance is influenced by a combination of factors such as surface finish, grain refinement, and subsurface microstructural stability—not just hardness alone.

Correlation Between Hardness and Wear Resistance

The relationship between hardness and wear resistance is often assumed to be directly proportional; however, in this study, the T6-treated samples with lower hardness exhibited superior wear resistance. This can be explained by:

- More homogeneous and refined microstructure after heat treatment, which promotes stable wear behavior
- Elimination of microdefects and residual stresses that typically accelerate wear in the as-built state
- Improved bonding of alloying elements and precipitation of strengthening phases, resulting in enhanced surface performance

CONCLUSION

The final step draws conclusions based on the experimental results and modeling efforts. It summarizes the key findings, such as:

- Optimal process parameters for improved mechanical properties
- Benefits of T6 heat treatment on wear resistance
- Feasibility of using AlSi10Mg in industrial AM applications

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