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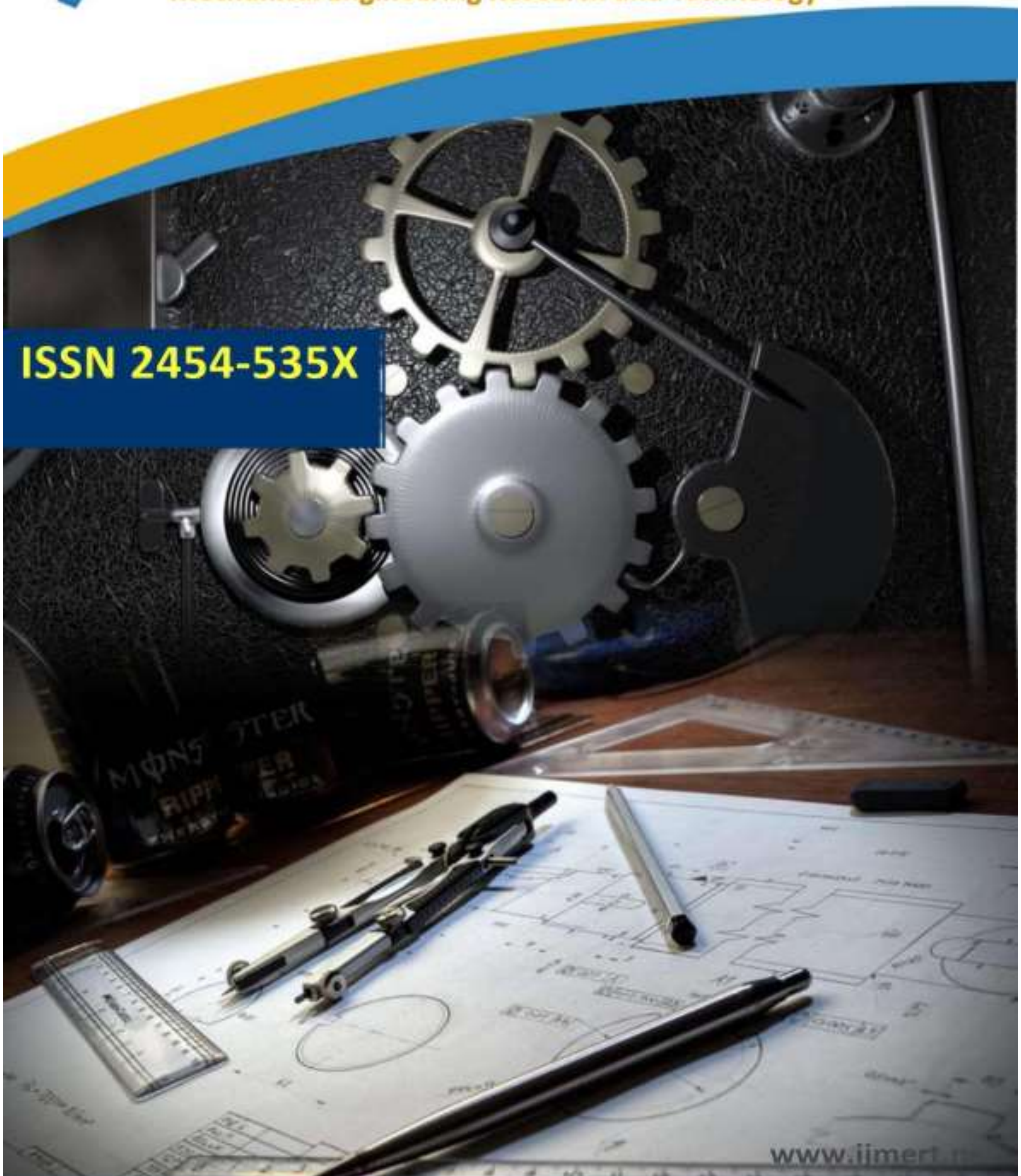

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WEAR CHARACTERIZATION OF AlSi10Mg ALLOY MANUFACTURING BY SLM PROCESS

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ABSTRACT

In this Project, the wear and mechanical properties of an AlSi10Mg alloy made by selective laser melting (SLM) were studied. The given process parameter influence of laser power energy densification behaviour and the effect of as build conditions on wearcharacterization were investigated. However, the wear and mechanical properties of the AlSi10Mg alloy showed better results than the Al6061-cast alloys. The SLM printed partsqualified for a structural geometric change from using the standard powder particle morphology (powder particle distribution range of 20 to 63 µm). The highest AlSi10Mg theoretical density of 2.67 g/cm^3 and after SLM manufactured parts density was achievedby 99.6%. The laser energy density was calculated based on the given process parameteras 150 J/mm^3. The results obtained showed that the AlSi10Mg alloy had the lowest wear(both as built conditions) compared to the cast Al6061 material. Finally, at 200 rpm witha load of 60 N, the AlSi10Mg alloy produced the least wear rate of 1.39×10^{-8} mm^2/N anda wear coefficient of 0.01mm^2/N. The wear rate and wear coefficient increased as the slide speed increased. The hardness of the SLM-AlSi10Mg alloy Vickers was measured at 126±5 HV (as built).

Keywords: Laser Powder Bed Fusion (LPBF), Selective Laser Melting (SLM), AlSi10Mg alloy, Wear Characterization, Hardness, Microstructure.

INTRODUCTION

3D printing technology has originated from the layer-by-layer fabrication technology of three-dimensional (3D) structures directly from computer-aided design (CAD) drawing. 3D printing technology is a truly innovative and has emerged as a versatile technology stage. It opens new opportunities and gives hope to many possibilities for companies looking to improve manufacturing efficiency. Conventional thermoplastics, ceramics, graphene-based materials, and metals are the materials that canbe printed now by using 3D printing technology. 3D printing technology has the potential to revolutionize industries and change the production line. The adoption of 3D printing technology will increase the production speed while reducing costs. At the same time, thedemand of the consumer will have more influence over production. Consumers have greater input in the final product and can request to have it produced to fit theirspecifications. At the meantime, the facilities of 3D printing technology will be located closer to the consumer, allowing for a more flexible and responsive manufacturing process, as well as greater quality control. Furthermore, when using 3D printing technology, the need for global transportation is significantly decreased. This is because, when manufacturing sites located nearer to the end destination, all distribution could be done with fleet tracking technology that saves energy and time. Lastly, the adoption of 3D printing technology can change the logistics of the company. The logistics of the companies can manage the entire process, offer more comprehensive and start-to-finish services. Nowadays, 3D printing is widely used in the world. 3D printing technology increasingly used for the mass customization, production of any types of opensource designs in the field of agriculture, in healthcare, automotive industry, and aerospace industries.

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Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. In Additive Manufacturing process digital 3D design data is used to build up a component in layers by depositing material. The term "3D printing" is increasingly used as a synonym for Additive Manufacturing. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal. Instead of milling a workpiece from solid block, for example, Additive Manufacturing builds up components layer by layer using materials which are available in fine powder form. A range of different metals, plastics and composite materials may be used. The technology has especially been applied in conjunction with Rapid Prototyping - the construction of illustrative and functional prototypes. Additive Manufacturing is now being used increasingly in Series Production. It gives Original Equipment Manufacturers (OEMs) in the most varied sectors of industry the opportunity to create a distinctive profile for themselves based on new customer benefits, cost-saving potential and the ability to meet sustainability goals. 3-D printing has monopolized the news for its massive potential in almost every market, including automotive, aerospace, medical/dental, robotics and even toys and action figures. 3-D printing fits under the umbrella of additive manufacturing, the industry term for all applications of technology that joins the materials together to make objects from 3-D model data layer by layer. Additive manufacturing is characterized by assembling parts using only the materials you need, as opposed to subtractive manufacturing, which involves cutting away what is not needed from larger pieces of the material.

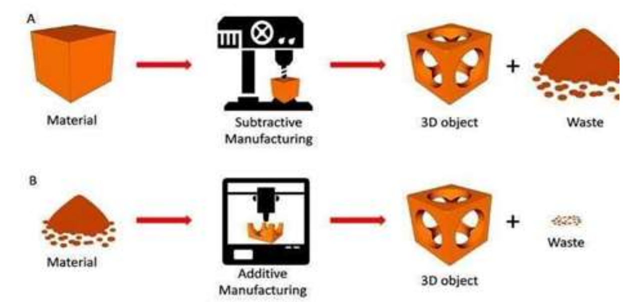

Fig 1.Difference between conventional subtractive manufacturing and additive manufacturing.

Additive Manufacturing Processes

The strengths of Additive Manufacturing lie in those areas where conventional manufacturing reaches its limitations. The technology is of interest where a new approach to design and manufacturing is required so as to come up with solutions. It enables a design-driven manufacturing process - where design determines production and not the other way around. What is more, Additive Manufacturing allows for highly complex structures which can still be extremely light and stable. It provides a high degree of design freedom, the optimization and integration of functional features, the manufacture of small batch sizes at reasonable unit costs and a high degree of product customization even in serial production.

Additive Manufacturing Functional Principle:

The system starts by applying a thin layer of the powder material to the building platform. A powerful laser beam then fuses the powder at exactly the points defined by the computer generated component design data. The platform is then lowered and anotherlayer of powder is applied. Once again, the material is fused so as to bond with the layer below at the predefined points. Depending on the material used, components can be manufactured using stereolithography, laser sintering or 3D printing. EOS Additive Manufacturing Technology based on laser sintering has been in existence for over 20 years. Additive manufacturing (AM), sometimes referred to as rapid prototyping or 3D printing are technologies that use successive layers of material to create 3D objects directly from a computer-generated model. Although Additive manufacturing process flow vary between the 7 different additive manufacturing technologies it uses to create the 3D parts, each broadly follows these common steps in the process to create the final part.

Fig 2 Process of Additive Manufacturing

LITERATURE REVIEW

This chapter has attempted to provide a summary of the literature review relatingto the static performance of mechanical properties, i.e., tensile, hardness, density, microstructure evaluation, and process optimization. The dynamic performance of fatigueand wear characterization is also evaluated in this review.

Literature Review of Mechanical Properties

Kempen K et al. [1] in this study, the main goal is to optimize the process parameters, namely scan speed, scan spacing and laser power, to achieve almost full density and goodsurface quality taking productivity as a key issue. In this study a laser power between 170W and 200 W is used, in combination with scan speeds ranging from 200 mm/s to 1400 mm/s. A higher scan speed (1400 mm/s) was used for high density/productivity demands.A scanning productivity of 4.4 mm^3/s was reached to obtain 99.4% dense parts. The lowerscan speeds (1100 – 1200 mm/s) were used for parts with a high demand in top surface quality. Average roughness values of 20 µm Pa value were measured. The microstructural analysis showed that both spherical and irregular pores were present in the parts. The SLM-process typifies the very fine microstructure that can be observed under optical microscope. A relative density up to 99% is achieved with an average roughness (Ra) of about 20 µm measured on horizontal top surfaces while the scanning productivity is about 4.4 mm^3/s. The reasons spherical and irregular porosity formed are investigated.

Buchbinder D et al. [2] the results of the investigation demonstrate that the build rate for the production of AlSi10Mg parts can be increased by using a 1 kW laser. Due to the higher laser power the scanning velocity and scan line spacing have been enlarged while reaching densities above 99.5%. SLM machines provide laser power only up to 200 W The high reflectivity and thermal conductivity of aluminum require a laser power of atleast 300 W at a scanning velocity of 500 mm/s (build rate amounts to approx. 4 mm^3/s) to achieve densities approaching 100% for a layer thickness of 50 µm. The first investigations of the mechanical properties, e.g. hardness of approx. 145 HV 0.1 and tensile strength of around 400 MPa promises sufficient mechanical properties which have to be analysed in detail in the future.

Kempen K et al. [3] in this work, mechanical properties like tensile strength, elongation, Young‟s modulus, impact toughness and hardness are investigated for SLMproduced AlSi10Mg parts, and compared to conventionally cast AlSi10Mg parts. Itis equipped with a 200W fibre laser, has a laser beam diameter of about 150 µm, using ascan speed of 1400 mm/s and a spacing of 105 µm. The density can be further increased to 99.8% by re-melting every layer with the same parameters, but alternating directions over 90°. The SLM AlSi10Mg parts have mechanical properties is higher comparable to the casted AlSi10Mg material, because of the very fine microstructure and fine distribution of the Si phase. SLM samples show some anisotropy in elongation at break.This is because of the optimal density scanning strategy which causes Z-oriented tensile samples to form more borderline porosity. These pores make the Z-oriented tensile parts more sensitive to crack initiation, compared to XY oriented tensile samples.

SLM PROCESS OPTIMIZATION

Methodology Flow Chart

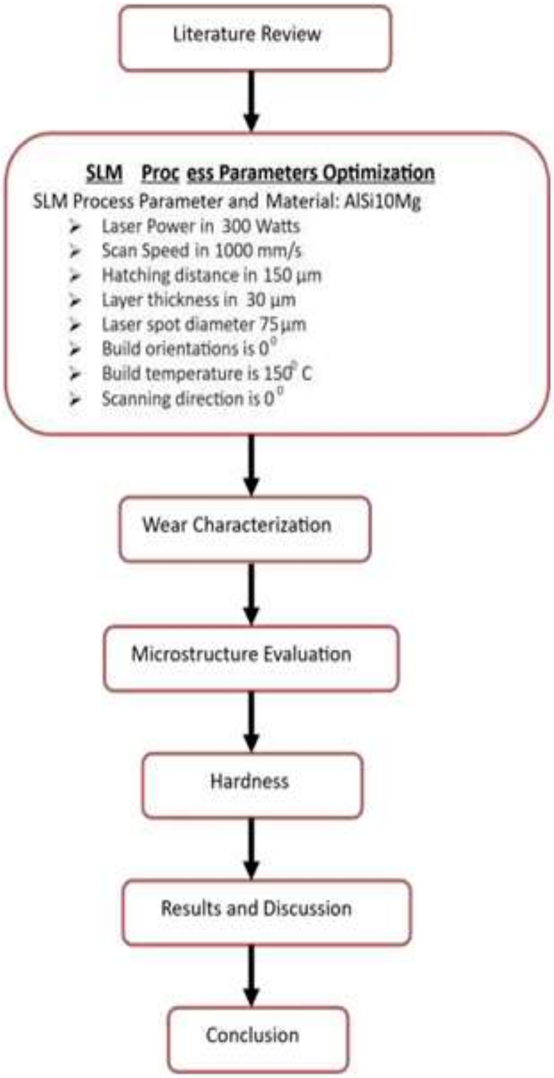

Fig 3 Research Work flow chart

Powder Characterization

AlSi10Mg AlSi10Mg powder showing composition Table 3.1 is provided by SLM solution Ltd.

The offered powder size range 20-63 µm from SLM solution Germany.

Table 3.1: Chemical composition of AlSi10Mg

Al	Su	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn	Other total
Balance	9.00–11.00	0.55	0.05	0.45	0.20 – 0.45	0.10	0.15	0.05	0.05	0.05	0.15

ASTM Specimen design

The sample prepared for SLM printing for wear characterization test specimen dimensions was 50 × 8 mm as shown in Figure 3.2.

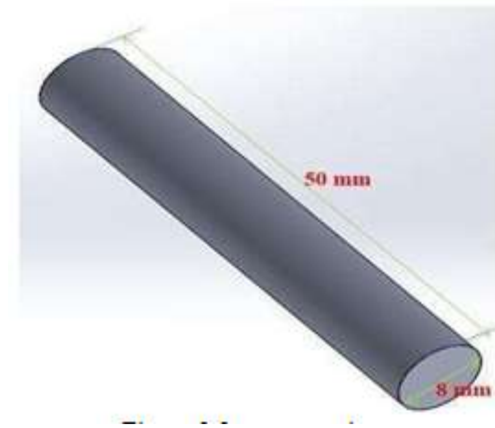

Figure 4 wear specimen

SLM Process

The selective laser melting (SLM) uses a variety of alloys, allowing prototypes to be functional hardware made out of the same material as production components as shown in Figure 3.3 and specification of SLM as Table 3.2 . Since the components are built layer by layer, it is possible to design organic geometries, internal features and challenging passages that could not be cast or otherwise machined. SLM produces strong, durable metal parts that work well as both functional prototypes or end-use production parts. The process starts by slicing the 3D CAD file data into layers, usually from 20 to 100 micrometers thick, creating a 2D image of each layer; this file format is the industry standard .stl file use most layer-based 3D printing or stereolithography technologies. This file is then loaded into a file preparation software package that assigns parameters, values and physical supports that allow the file to be interpreted and built by different types of additive manufacturing machines. The selective laser melting, thin layers of atomized fine metal powder are evenly distributed using a coating mechanism onto a substrate plate, usually metal, that is fastened to an indexing table that moves in the vertical (Z) axis. This takes place inside a chamber containing a tightly controlled atmosphere of inert gas, either argon or nitrogen at oxygen levels below 500 parts per million. Once each layer has been distributed, each 2D slice of the part geometry is fused by selectively melting the powder. This is accomplished with a high-power laser beam, usually an ytterbium Fiber laser with hundreds of watts. The laser beam is directed in the X and Y directions with two high frequency scanning mirrors.

The laser energy is intense enough to permit full melting (welding) of the particles to form solid metal. The process is repeated layer after layer until the part is complete. The SLM machine uses a high-powered 400 watt Yb-Fiber optic laser. Inside the build chamber area, there is a material dispensing platform and a build platform along with a recoated blade used to move new powder over the build the focused laser beam. Parts are built up additively layer by layer, typically using layers 30 micrometers thick.

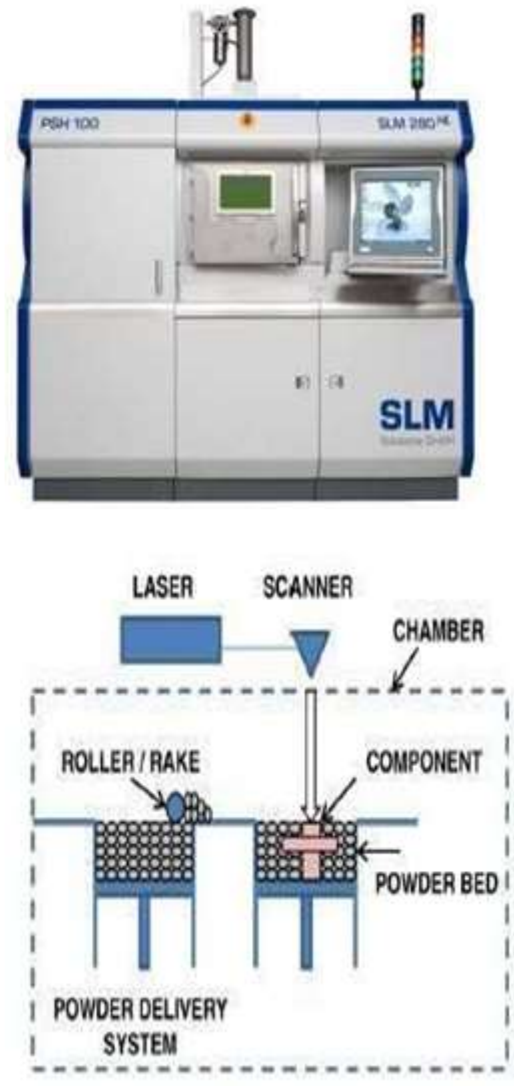

Fig : SLM process.

Table 3.2: SLM Specification data

Build Envelope (L x W x H):	280 x 280 x 365 mm 11 x 11 x 14 in (reduced by substrate plate thickness)
3D Optics Configuration:	Single (1x 400 W or 1x 700 W) IPG Fiber laser Twin (2x 400 W or 2x 700 W) IPG Fiber lase
Build Rate:	88 cm^3/h (400 W Twin)
Variable Layer Thickness:	20 µm - 75 µm
Minimum Feature Size:	150 µm
Beam Focus Diameter:	80 µm - 115 µm
Maximum Scan Speed:	10 m/s
Average Inert Gas Consumption in Process:	2.5 l/min (argon)
Average Inert Gas Consumption Purging:	70 l/min (argon)
E-Connection / Power Input:	400 Volt 3NPE, 63 A, 50/60 Hz, 3.5-5.5 kW
Compressed Air Requirement / Consumption:	ISO 8573-1:2010 [1:4:1], 50 l/min @ 6 bar
Dimensions (L x W x H):	2600 mm x 1200 mm x 2760 mm
Weight:	1300 kg dry 1800 kg with powder

As per ISO/ASTM (52900-15) terminology SLM also referred to LPBF, is an AM technique developed to melt and fuse metallic powders via a high power-density laser. The principle of the SLM process starts with a building platform applied with very thin layers of metallic powders, which are completely melted later by the thermal energy induced by heat source with successfully binding. The cross-section area of the designed 3D part is built by selectively melting and re-solidifying metallic powders in each layer. The building platform is then lowered by a small distance and a new layer of powders aredeposited and leveled by a re-coater as shown in Figure 3.4. The laser beam can be directed and focused through a computer-generated pattern by carefully designed scanneroptics. Therefore, the powder particles can be selectively melted in the powder bed and form the shape of 3D objects according to the CAD (computer aided design). The SLM build platform dimensions have 280 × 280 × 365 mm and using a continuous IPG Fiber laser.

RESULT AND DISCUSSION

- This work was studied as an optimization of process parameters with horizontal build orientation and conducted on a wear test of AlSi10Mg parts manufactured by SLM.
- Identified the suitable powder particle sizes for the SLM printing process.
- The key parameters of the SLM printing process were identified.
- Developed the simulation of the part before SLM printing.
- The output dynamic performance was conducted as a wear test.
- Find out the mechanical properties of hardness with microstructure characterization.

Wear characterization

The wear rate and wear coefficient of friction are frequently used to evaluate friction behavior. In this experiment, the disc was rotated from 200 to 600 rpm with a constant load of 60 N while keeping sliding track diameter constant at 80 mm and time 300 seconds. The testing was done at room temperature as shown in figure 3.1.

Figure 5 (a&b) Wear testing schematic diagram

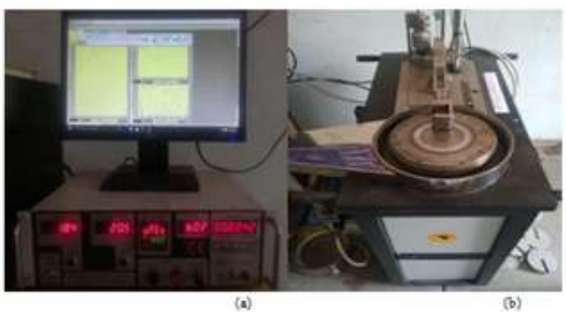

Figure 6 (a&b) Wear testing schematic diagram

From the obtained wear and friction results, the speed, load, and time are used. Using these results, they calculated the percent (%) change of length, wear volume, wear velocity, wear rate, and wear coefficient as shown in the table 3.1.

Calculation:

- % change of length = Change in weight (w_i – wf) / w_i ×100 = % units
- Wear volume = Change in weight (w_i – wf) / density of the material = mm^3
- Wear velocity = 2πRN/60 (R= sliding distance 80 mm) = mm/s
- Wear rate = wear volume / wear velocity × load × time in sec. = mm^2/N
- Wear coefficient = wear volume × hardness of material / R × load = mm^2/N

Table 3.1: Wear calculation results

Wear Conditions	% change of length	Wear volume in mm^3	Wear velocity in mm/s	Wear rate in mm^2/N	Wear coefficient in mm^2/N
Case-I: 200 rpm					
As Casting Al6061	1.14	29.25	1647.67	9.86×10^{-7}	0.548
As 3D printed AlSi10Mg	0.10	1.35		4.47×10^{-8}	0.03
Case-II: 400 rpm					
As Casting Al6061	1.90	47.92	3349.33	1.11×10^{-7}	0.13
As 3D printed AlSi10Mg	0.17	1.85		3.06×10^{-8}	0.05
Case-III: 600 rpm					
As Casting Al6061	2.38	59.42	5024	6.75×10^{-7}	1.21
As 3D printed AlSi10Mg	0.18	2.14		2.36×10^{-8}	0.06

Wear rate ranges from 1.39 x 10^8 (minimum) to 9.86 x 10^{-7} mm^2/ N (maximum) and coefficient of friction ranges from 0.01 (minimum) to 1.21 mm^2/ N (maximum) for AlSi10Mg at different slide speeds. As the slide speed increases from 200 to 600 rpm, the maximum change in AlSi10Mg wear rate and co-efficient is shown in the figure 3.2.

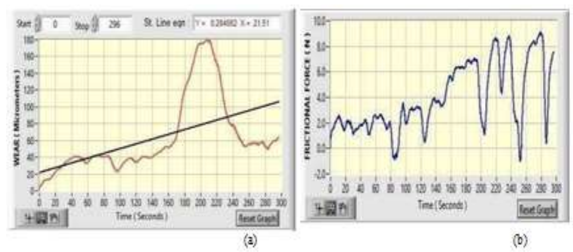

Figure 7: (a) wear, (b) frictional force and (c) Coefficient friction

It shows that the coefficient of friction decreases as the sliding speed increases within the observation range as shown in figure 3.3. Increased surface roughness and large amounts of wear particles are believed to be responsible for the reduced friction associated with normal load increases.

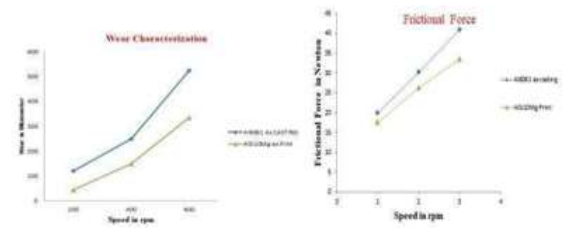

Figure 8: comparison of Al6061 and AlSi10Mg: (a) wear characterization and (b)frictional force results

Microstructure

The characterization of the microstructure evaluation was conducted by SEM at different magnifications and with high-resolution. The obtained microstructure used optimal process parameters and achieved a defect-free component with a high density of AM parts. The SEM was used for microstructure characterization at the different magnification levels as shown in figures 3.4. In terms of strength and performance, the hatching distance was the most important factor. The pores can be divided into spherical pores and irregular pores, and cracks are observed along with the horizontal direction of the structure. Due to the poor wettability of oxides and metals, long cracks were formed and spread along the surface. Due to the low cooling rate, some of the AlSi10Mg powder particles are formed as a result of oxidation during the SLM process.

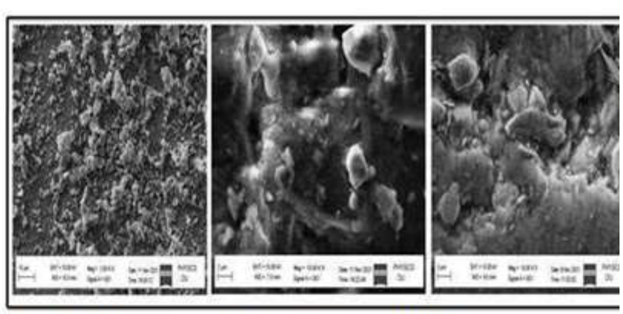

Figure 9: Microstructure of 225 watts/500 mm/s with different magnifications.

Hardness and density

The Vickers hardness and density results are based on the optimised process parameters. The hardness and mechanical property values are mainly dependent on the microstructure of pores, cracks, and porosity with thermal deviation. The results of microhardness tests under three different areas under an applied load of 1000 grammes each held for 10 seconds are given in table 3.2. The theoretical density of AlSi10Mg alloy powder (ρt) is 2.67 g/cm^3 and, after SLM, manufactured parts have the highest density of 2.66 (99.6%) g/cm^3.

Table 3.2: Microhardness results of AlSi10Mg and Al6061 alloy under the differentconditions.

Different conditions	Microhardness in HV
As-Built (SLM AlSi10Mg Printed sample)	126 ±5
As-Built (Casting Al6061 sample)	98±5

CONCLUSION AND FUTURE SCOPE

The AlSi10Mg alloy specimens were successfully manufactured by SLM-AM using optimised process parameters. The main results can be concluded as: The wear rate of theAlSi10Mg sample is about 33% lower than that of the cast Al6061 sample. The higher wear resistance of the AlSi10Mg sample with shallow and narrow wear grooves is due to the higher hardness induced by the unique binding of the microstructure with less pores and porosity defects.The obtained AlSi10Mg alloy wear test process parameters at preheated 200^{0}C conditions were load of 60 N, speed at 200 rpm, and time of 5 minutes, produced by low wear and friction compared to Al6061.

The hardness of the AlSi10Mg alloy is better than that of Al6061, such as the buildcondition from 126 ±5 to 98±5 HV and The theoretical density of AlSi10Mg alloy powder (t) is 2.67 g/cm^3, which was achieved after SLM manufactured density of 2.66 (99.6%).

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