Optimization Process Parameter on Wear Characterization of Al6061 and AlSi10Mg Alloy Manufactured by Selective Laser Melting

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Received Date: 06-05-2022 Published Date: 20-05-2022

Abstract

In this research, wear optimization, hardness, and density were investigated for an AlSi10Mg alloy made by selective laser melting (SLM), and also an additive SLM process simulation was carried out. The quality and performance of the additive manufactured (AM) parts depends on the build orientation. A model based on an L9 orthogonal array of Taguchi design experiments was created to perform the wear characterization for the Al6061 and AlSi10Mg alloys. However, the wear and mechanical properties of the AlSi10Mg alloy showed better results than the 6061-cast alloys. Finally, the optimal process parameters at low wear rate and frictional force were found at a load of 20 N, a sliding speed of 200 rpm, and a time of 5 minutes. The obtained result at optimal parameter a low wear is 90 micrometers, and the frictional force was 3.6 N. The laser energy density was calculated based on the given process parameter as 150 J/mm³. The hardness of the SLM-AlSi10Mg alloy Vickers was measured for AlSi10Mg as 126 ± 5 HV and Al6061 as 98 ± 5 HV because of the very fine microstructure and fine distribution of the Si phase in AlSi10Mg SLM parts. The highest density achieved was 99.6% (2.660 g/cm³) and obtained defect-free components.

Keywords: Selective Laser Melting (SLM); AlSi10Mg alloy; Wear Characterization; Hardness; Density; Microstructure

Introduction

The additive layer manufacturing is used for over 30 years and is now commonly used in a variety of materials [1]. The present lots of type's production machines, but all are similar in the sense that produce 3Dimensional shapes by combining a number of 2D slice [2]. In the current years, AM was developed for "rapid prototyping" (RP) fabricating of metal parts by direct laser manufacturing (DLM), electron beam melting (EBM), and selective laser melting (SLM) [3,4]. Along with Al-based of AlSi10Mg alloy traditional casting alloy and high demand in aerospace and automotive applications due to low thermal expansion, light weight, and excellent mechanical properties [5,6]. In addition, the AlSi10Mg alloy has proven to be highly suited for 3D printed samples environment for scientific measurement [7,8]. The AlSi10Mg alloy an attractive combination of high thermal conductivity, excellent weldability, excellent corrosion resistance, and sufficient hardenability [9,10]. AM compares to traditional techniques such as the ability to quickly produce complex custom structures, high resolution, there are some clear advantages and accuracy with minimal material loss [11,12]. SLM is a newly developed additive technology based on laser powder bed fusion (LPBF) [13]. According to sliced CAD model (computer-aided design); complex freeform metal products are produced by layer-by-layer laser scanning [14]. The AlSi10Mg alloy was good weldability due to eutectic composition of Al and Si [15]. The increasing manufacturing of metal additive layer manufacturing (MALM) technology, especially new LPBF technology, from academia and industry on the determine best AM process for newly or existing CAD designed metal materials [16,17].

The transient thermal gradient behavior in SLM method is primarily controlled by the given process parameters such as layer thickness, scan speed, hatching distance and laser.
Due to complex geometry metallurgical properties of SLM-AM, including various mass, modes of heat, and momentum transfer, the SLM process defects as balling effect, thermal cracks, and pores are show below unintended processing conditions [20,21]. The optimized of SLM process parameters can be used to achieve a highest quality of manufactured metal parts (such as perfectly crack-free and fully dense parts) [22]. The optimized technology for cost savings reduced manufacturing process steps, and design freedom [23]. This study presents pin on disc wear characterization of process optimization and mechanical (hardness and density) properties of SLM-AlSi10Mg alloys [24]. Three the mainly important of pin on disc parameters, load (N), sliding speed (rpm) and time (minute) were selected inputs for wear characterization [25]. This allows you to quickly identify the optimized processing and achieve high wear resistance by SLM-AlSi10Mg [26]. This research paper specializes an effect on of pin on disc wear parameters for after manufactured by SLM-AlSi10Mg [27]. The statistical investigational layout changed into followed to optimized parameters to minimize the cost, time, and material [28,29]. The mechanical assessments had been executed on samples synthetic the usage of optimized parameters that gave minimal wear and frictional force [30,31].

**Experimental Procedure**

The AlSi10Mg alloy material consists of spheres of powder particles produced by a gas atomization process and the chemical composition of AlSi10Mg as shown in [Table 1]. The AlSi10Mg alloy powder is provided by SLM Solution Group AG in Germany. In the SLM printing process, the particle size distribution ranges from 20 to 63 μm as shown in [Figure 1a]. The circular specimen (diameter D=8 mm and length L=50 mm) was considered for the wear test as shown in [Figure 1b].

| Al    | Si    | 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 |

*Table 1: The chemical composition of AlSi10Mg alloy.*

The wear test circular-bar rod specimens were built by an SLM M280 (M280 2.0) system equipped with a 280 × 280 × 365 mm building platform and an up to 400 Watts continuous Yb: YAG fiber laser as shown in [Figure 2]. A beam focus diameter of 80 to 115 μm and a scan speed of up to 10 m/s, an automatic AlSi10Mg powder spreading on build platform device, an inert argon gas protection system, and a computer based system for control of process. The used laser power as P=225 W, scan speed v=500 mm/s, the hatching spacing h=100 μm, the layer thickness t=30 μm, build platform temperature considered as 1500°C and wear samples fabricated in the horizontal direction as shown in [Figure 3]. The laser energy volume calculated by $E = P/v \times h \times t \ [Eq.1]$, and the value of laser energy density was 150 J/mm³. The SLM production was performed in an inert argon atmosphere to avoid the pick-up of interstitial oxygen (lower than 0.2%).

![Figure 1: a) Powder particle size destruction and b) wear specimen](image)

![Figure 2: (a & b) SLM schematic diagram and printing process based on process parameter.](image)
Results and Discussion

In this research work, optimization of process parameters on wear characterization of AlSi10Mg parts manufactured by SLM is studied and also done additive layer by layer simulation of given process parameters.

Additive simulation

The additive layer-by-layer simulation is the most important part of SLM printing because it saves time, material, and cost. Based on the design of experiment parameters, additive simulation was done and the results are as follows: displacement of 4.349 e-05 m (0.04328 mm), temperature distribution in the SLM printing process from minimum 764.4 K to maximum 766.2 K and von mises stress of 6.897 e+04 Pa as shown in the Figure 4. From the Figure 4, SLM process is layer by layer manufacturing process so it was must variation of every each layer.

Wear characterization

As shown in [Figure 5], the wear rate and coefficient of friction (COF) are usually used to evaluate the friction behavior. [Tables 2 and 3] show the wear rate of SLM-AlSi10Mg under various loads of 20, 40, and 60 N, slide speeds of 200, 400, and 600 rpm, and time considerations of 5, 10, and 15 minutes. The sliding distance was kept constant and all experiments were conducted at room temperature. The experiments were conducted on wear tests for various materials such as Al6061 and AlSi10Mg. The wear tests were carried out by using Taguchi L9 orthogonal array on pin on disc equipment and the lowest wear and lowest friction were observed, which implies that the wearing of pin material mostly depends on the applied load and speed [3,6]. The sample is weighted before and after wear testing, and the same process is repeated for all the remaining samples. The wear rates of AlSi10Mg gradually decrease with the increase in slide speed from 200 to 600 rpm and load from 20 to 60 N [14,15] as presented in [Figure 6].
Figure 5: (a&b) Wear testing schematic diagram

| Parameters       | Level 1 | Level 2 | Level 3 |
|------------------|---------|---------|---------|
| Load in N        | 20      | 40      | 60      |
| Speed in rpm     | 200     | 400     | 600     |
| Time in minutes  | 5       | 10      | 15      |

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

| Trails | A Levels | B Levels | C Levels |
|--------|----------|----------|----------|
| T1     | 1        | 1        | 1        |
| T2     | 1        | 2        | 2        |
| T3     | 1        | 3        | 3        |
| T4     | 2        | 1        | 2        |
| T5     | 2        | 2        | 3        |
| T6     | 2        | 3        | 1        |
| T7     | 3        | 1        | 3        |
| T8     | 3        | 2        | 1        |
| T9     | 3        | 3        | 2        |

*Table 3: used L9 orthogonal array as per DoE.*

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Based on the experimental observations, the following plot is obtained, and it clearly shows that at each process parameter point, the SLM-AlSi10Mg showed better wear resistance than as-cast Al6061 at various processing parameters of the dry sliding wear test obtained by the L9 orthogonal array as shown in [Figure 7]. This is due to the denser structure obtained by choosing optimized SLM process parameters where the defects induced are at a minimum. This explains why one can go directly to industrial use after manufacturing of AlSi10Mg material by the SLM process, without any post heated treatment process and mechanical process treatment instead of Al6061. The amount of material loss due to dry sliding wear test was found to be less in 3D printed SLM AlSi10Mg compared to as-cast Al6061 material, which indicates stronger bonding and a denser volume of material with minimum manufacturing induced defects [18,24]. The non-linear pattern of increment is observed in both as-cast Al6061 and SLM-ALSi10Mg materials, which indicates that load and sliding speed independently affect the wear properties. From the obtained wear and friction results, the speed, load, and time are used. Using these results, they calculated the % change of length, wear volume, wear velocity, wear rate, and wear coefficient as shown in [Table 4].

- % change of length = Change in weight (wi – wf) / wi ×100 (eq.2) = % units
- Wear volume = Change in weight (wi – wf) / density of the material (eq.3) = mm$^3$
- Wear velocity = $2\pi RN/60$ (R= sliding distance 80 mm) (eq.4) = mm/s
- Wear rate = wear volume / wear velocity × load × time in sec. (eq.5) = mm$^2$/N
- Wear coefficient = wear volume × hardness of material / R × load (eq.6) = mm$^2$/N

### Table 4: Wear calculation results.

| No. of Trails | % change of length | Wear volume in mm$^3$ | Wear velocity in mm/s | F Wear rate in mm$^2$/N | Wear coefficient in mm$^2$/N |
|---------------|--------------------|----------------------|-----------------------|--------------------------|-----------------------------|
| T1            | 0.09               | 1.85                 | 1647.67               | 1.84×10^{-7}             | 0.14                        |
| T2            | 0.55               | 10.60                | 3349.33               | 2.63×10^{-7}             | 0.83                        |
| T3            | 0.46               | 9.321                | 5024                  | 1.03×10^{-7}             | 0.73                        |
| T4            | 0.10               | 21.42                | 1647.67               | 5.14×10^{-7}             | 0.84                        |
| T5            | 0.61               | 11.75                | 3349.33               | 9.7×10^{-8}              | 0.46                        |
| T6            | 1.56               | 30.46                | 5024                  | 5.05×10^{-7}             | 1.19                        |
| T7            | 0.25               | 4.821                | 1647.67               | 5.41×10^{-8}             | 0.12                        |
| T8            | 0.32               | 5.928                | 3349.33               | 9.8×10^{-8}              | 0.15                        |
| T9            | 3.83               | 73.85                | 5024                  | 4.08×10^{-7}             | 0.01                        |

At a constant load of 20 N, as the sliding velocity increases, the wear of both types of materials is reduced, and the 3D printed AlSi10Mg material showed less wear compared to the as-cast Al6061 material. Similar phenomena are observed by maintaining constant loads of 40 N and 60 N with an increase in sliding speed [22,23]. Thus, it can be confirmed that the wear rate is proportional to sliding velocity from experimental results. The wear loss of 3D printing is less compared to Al6061, because of choosing selective laser melting process parameters where defects are at a minimum. Finally, we obtained the lowest frictional force at a load of 20 N, a sliding speed of 200 rpm, and a time of 5 minutes.

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The considered optimization process parameter was achieved after experimental test, the lowest wear and frictional force at t5. The experimental test was conducted at three different conditions: preheated at 2000°C, cryogenic at -1000°C and aging temperature at -100 to 2000°C as shown in [Figure 8]. The different treatment levels of wear and frictional results are mentioned in [Figure 9].

**Taguchi Analysis**

"Taguchi technique used experimental results to optimize the process parameter and it can be classified into; to design and run the experiment as 3^3 (L9); next, using the signal to noise ratio (S/N) and analysis of variance; Examine the experimental design (ANOVA)." Finally, it receives the best optimal process parameters based on the analysis results. In this Taguchi method was used the experimental results for S/N ratio and considered the higher value (i.e., lower wear and frictional force). Applied the condition rule for S/N ratio is smaller is the best and calculated following Equation 7.

$$S_N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \tag{7}$$

Where, n is total no. of experiment, $y_i^2$ is the density value for ith experiment and Taguchi analysis considered low wear (t1). From the response table delta statistic highest factor rank load is 2, sliding speed is rank 1 and time is rank 3. Analysis of variance (ANOVA) is the most frequently used statistical method. In this case, ANOVA was required to determine the contribution of each process parameter for fatigue strength. In ANOVA, the sum of squares (SST), the sum of squares of each factor (SSF), the mean square of each factor (MSF), the degree of freedom (DF), percentage of the contribution (%), P-test and F-test were calculated by the regression analysis various process parameter such as load, sliding speed and time. From the response [Table 5], levels with values were utilized to identify which level of each element offers the optimum performance with better result. From the [Figure 10], the sliding speed is most influence factor, followed by load and time. The term "error" means how much negativity is in testing parameters, i.e., load, time, speed, and machining error. As shown in Figure 10, the slope line was connected of levels with process parameter of each variable, the obtained optimal process parameter on fatigue strength was achieved by load is 20 N (A1), sliding speed is 200 rpm (B1), and time 5 minutes (C1).

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Table 5. Statistical method used by ANOVA.

| Source                | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|-----------------------|----|---------|--------------|---------|---------|---------|---------|
| Regression            | 3  | 556257  | 42.25%       | 556257  | 185419  | 2.14    | 0.213   |
| Load in N             | 1  | 264180  | 19.82%       | 264180  | 264180  | 3.05    | 0.141   |
| Sliding Speed in rpm  | 1  | 289872  | 30.95%       | 289872  | 289872  | 3.35    | 0.127   |
| Time in minutes       | 1  | 2204    | 0.23%        | 2204    | 2204    | 0.03    | 0.879   |
| Error                 | 5  | 432610  | 6.75%        | 432610  | 86522   |         |         |
| Total                 | 8  | 9888867 | 100.00%      |         |         |         |         |

| T9                    | 3.83 | 73.85 | 5024 | 4.08×10⁻⁷ | 0.01 |

Figure 10: /S/N ratio graph for fatigue strength.

Figure 11: Microstructure of 225 watts / 500 mm/s with different magnification.

Microstructure, Hardness and density

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 [5,11]. The SEM was used for microstructure characterization at the different magnification levels as shown in Figure 11. 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 [18]. Cracks are observed along with the horizontal direction of the structure [24]. 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 were formed as a result of oxidation during the SLM process.

The Vickers hardness and density results are based on the optimized 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 grams with a holding time of 10 seconds showed that the value of hardness was 126 ± 5 [12,13]. The theoretical density of AlSi10Mg alloy powder (ρt) is 2.67 g/cm³ and, after SLM, manufactured parts have the highest density of 2.66 (99.6%) g/cm³.

Conclusion

In this investigation, tests were conducted to examine wear performance and frictional force of SLM-AlSi10Mg and as-cast Al6061 under various levels of loading, sliding speed and time of operation at constant wear track by using pin on disc equipment.

- The 3D printed SLM AlSi10Mg has better wear resistance than as-cast Al6061 material due to the advantage of SLM process as it can produce components with minimum defects. At each process parameter, which is obtained from Taguchi L9 orthogonal array, the wear resistance of SLM AlSi10Mg is better than as-cast Al6061.

- It was found that the magnitude of applied loads and sliding speeds are the major factors that can independently influence wear resistance and friction between interfaces. The maximum wear resistance was 90 µm and minimum friction was 3.6 N observed at load of 20 N, sliding speed of 200 rpm, and time of 5 minutes. With increase in applied load, the contact area between mating surfaces increases and wear rate increases.

- The hardness value of 3D printed SLM-AlSi10Mg was
126 ± 5 HV with highest density of 2.66 (99.6%) g/cm³ and Al6061 was 98 ± 5 HV. The AlSi10Mg was higher of 30% when compared to as-cast Al6061 because of very fine microstructure and fine distribution of the Si phase in AlSi10Mg SLM parts.

Acknowledgement

The authors would like to thank for the research facilities centre funded govt. Rashtriya Uchchatar Shiksha Abhiyan (RUSA 2.0) at University College of Engineering (A), Osmania University, Hyderabad, Telangana, India.

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