Effect of Build Orientation and Heat Treatment on Erosion Behavior of Al10SiMg Fabricated Using Laser Powder Bed Fusion

Pooja Angolkara,*, M. Manzoor Hussainb

aResearch Scholar, Department of Mechanical Engineering, JNTU Hyderabad, Telangana, India,
bSenior Professor in Mechanical Engineering, JNTU Hyderabad, Telangana, India.

Keywords:
Additive manufacturing
Aluminum
Orientation
Erosion
Heat Treatment

A B S T R A C T

Laser Powder Bed Fusion (LPBF) is a form of additive manufacturing that can directly make metal components and has begun to be employed in a variety of industrial situations. Moreover, the erosion characteristics of SLM-produced items have been documented relatively infrequently. In the current work, the erosion behavior of a heat-treated Al-Si-10% Mg alloy generated via laser powder bed fusion (LPBF) has been investigated. The samples were printed in three directions (horizontal (0°), vertical (90°), and inclined (45°)) on the build platform using the Direct Metal Laser Sintering (DMLS) system (EOS M 290) machine. Al%Si-10%Mg samples were given treatment (T5, T6). Optical and scanning electron microscopes (SEM) were used to examine the microstructure under both printed and heat-treated conditions. Energy Dispersive Spectroscopy (EDS) and X-ray Diffraction (XRD) were used to investigate the alloy's elemental composition and compound production. The erosion test was executed in each of the three orientations, plus heat-treated samples and as-printed samples. The selected input parameters were impingement angle and flow velocity. The erosion rate was examined and contrasted across orientations for printed and heat-treated conditions to establish the best orientation. The post-eroded surface was analysed using SEM, EDS, and XRD to evaluate possible erosion processes. The key findings were: T5 heat-treated samples sustain well and have the least mass loss; Horizontal (0°) oriented samples undergo less erosion compared to other orientations; T6 heat-treated samples show maximum erosion on printed samples, and hence it is not recommended. T5 heat treatment is proven to be superior in providing high erosion resistance, followed by printed and T6 heat-treatment, respectively. The heat treatment effects are more significant than the orientation effects in determining the erosion resistance of the Al10SiMg alloy. The erosion mechanisms, such as ploughing, melting, and cratering, were identified.

© 2023 Published by Faculty of Engineering
1. INTRODUCTION

The UK Foresight Report 2013 emphasised the significance of additive manufacturing (AM) as a major transformation in manufacturing that is anticipated to happen shortly. While it may still be too early to say whether AM heralds a third industrial revolution, AM has undeniably significant advantages over conventional production methods in particular sectors such as aircraft, space, defence, oil and gas industries, and biomedical. Presently, one of the most popular commercial additive manufacturing (AM) processes is laser Powder Bed Fusion (LPBF). In this process, the parts are built by scanning the powder layer by layer selectively using a high-power laser. Design freedom, part consolidation, minimization of inventory spares, digital and green manufacturing, suitability to serve low order quantities, and a low buy-to-fly ratio are some of the distinct advantages of the LPBF over traditional processes such as casting, forging, rolling, and so forth. R. Casati et al [1] proved that the trend towards improved lightweight and high load-bearing capacity is now pressing for enhanced material strength, which may be accomplished either through alternate aluminium alloy compositions or by optimised thermal treatments of existing Al alloys. Godino Martinez et al [2] stated that Al10SiMg alloy is the most sought-after Al alloy grade in the LPBF process due to its high hot cracking resistance, castability, weldability, high strength-to-weight ratio, and corrosion resistance. J. Zou et al [3] found that this alloy finds a significant place in aerospace and automobile interior components, as well as functional prototypes. Functional systems such as fuel systems, electrical pipelines, brake structural parts, gear box casings, and airframe structural elements such as elbows, casings, sensor holders, connectors, links, spars, etc., typically use Al alloys. Particularly, this alloy is proven for the above applications where the strength requirements are less than 300 MPa and the safety margin required is above 1.25. Though this alloy is easily additively manufacturable, it develops a preferred grain orientation based on the direction of heat flow or removal due to the layer-by-layer deposition of powders. This causes the properties to vary among the various directions (0°; 45°; 90°) [4]. Even though LPBF’s advantage of rapid heating and cooling results in fine scale microstructure, it also causes residual stress in the part. To relieve the residual stress, the manufacturer often uses a stress-relieving process. This heat treatment causes a significant increase in alloy ductility by coarsening grains and forming globular Si particles [5–9]. The solution treatment eliminates the fine-scale microstructure of the as-printed state, dissolves all of the Si into the Al matrix, and relieves the residual stress at that elevated temperature. Subsequent quenching and ageing instigate controlled precipitation of Mg2Si precipitates and change the Si particle morphology to globular. The precipitation increases the strength due to the loss caused by the microstructure coarsening in the solution treatment. The change in Si particle morphology and distribution helps restore ductility [10–13]. N. Paramitha et al [14] According to recent studies on the heat treatment of Al10SiMg, direct ageing (T5 cycle) from the as-printed state is preferable to the T6 cycle in terms of maintaining strength from the as-printed state and improving ductility. The T5 cycle starts precipitation from the fine-scale microstructure, does not alter majorly the as-printed microstructure or coarse the microstructure, and relieves residual stress. As a result, ductility increases without a significant reduction in strength properties. P. Wei et al [15] conducted a comprehensive study of the influence of process parameters (laser power, scanning speed, and hatch spacing) on the densification level and mechanical properties of bulk Al10SiMg alloy samples produced by selective laser melting (SLM). With higher laser power or slower scanning, the Si content in the Si-rich cellular borders rises. This microstructural refinement caused the hardness of the materials treated using SLM to be greater than the hardness of the cast samples. The tensile characteristics of SLM-processed samples improve as the porosity decreases [16]. X. Yu, K. Benarji M. Albu, N. Takata et al [17–20], reported the effects of the orientation and spatial location of struts on the microstructure and porosity. The upwardly oriented component of the Al10SiMg SLM as-built inclined strut has a fine microstructure, a greater hardness in the melt pool, and low porosity, whereas the downwardly oriented component has a coarse microstructure, a lower hardness, and excessive porosities. Due to Si precipitate development and spheroidization, a T6 heat treatment results in a small hardness decrease. Likewise, several investigations have been carried out to study the importance of build orientation and processing parameters on the microstructure and mechanical behaviour of Al10SiMg. A. W. Momber et al [21] conducted an experimental
study on the kinetic energy of wear particles produced by abrasive water jet erosion. The impact force of an abrasive jet was measured before and throughout the machining operation. Only 0.3 percent of the input energy was found to be used for erosion. The kinetic energy of a wear particle was related to the depth of erosion. M. Tocci et al [22] noticed that due to the distinct microstructural properties of the alloys, particularly the cellular network of extra-fine Si particles present in the Al10SiMg alloy, which can positively aid material removal, H. Ding et al. H. Ding et al [23] concluded that the microstructures of the SLM-fabricated sample were found to be significantly different when the construction orientation was changed. Cavitation damage will be significant in a sample with a high density of grain boundaries.

V. Javaheri et al [24] investigated the worn surface morphologies, and has revealed that cutting and ploughing processes are the primary forms of material removal in ductile materials, whereas micro-crack development and deformation are the primary mechanisms of erosion in brittle materials. More research is required to fully understand how temperature affects erosion rates. This would be helpful in anticipating erosion at high temperatures, such as in chemical factories. When considering the erosion behaviour of metals like AlSi10Mg with specific impingement angles and jet velocities, such as a 45-degree impingement angle and a jet velocity of 150 m/min, certain observations can be made.

Impingement Angle (45 degrees): A 45-degree impingement angle represents an intermediate angle between normal (0 degrees) and oblique (90 degrees) angles. At this angle, the erosion behaviour of AlSi10Mg may display characteristics of both normal and oblique impacts. The impact energy of the particles is moderately high, and they strike the surface with a significant component of their velocity perpendicular to the surface [25]. At a 45-degree impingement angle, the erosion rate of AlSi10Mg is likely to be relatively higher compared to lower impingement angles. The increased impact energy allows the particles to penetrate the surface more effectively, resulting in enhanced erosion [26]. However, it is important to note that excessively high impingement angles could cause particle deflection or bouncing, reducing their ability to erode the metal surface efficiently [27].

Jet Velocity (150 m/min): A jet velocity of 150 m/min represents a moderate velocity for the fluid carrying the eroded particles. Higher jet velocities result in increased kinetic energy for the impacting particles. Consequently, the erosion rate of AlSi10Mg is likely to be relatively higher at this velocity compared to lower velocities. The higher energy levels enable the particles to penetrate the metal surface more effectively, resulting in enhanced material removal [28]. However, it is worth mentioning that the erosion behaviour may not continue to increase indefinitely with increasing jet velocity. Beyond a certain point, the erosion rate may start to plateau or even decrease. This can be attributed to factors such as changes in the particle impact dynamics, alteration in erosion mechanisms, and the ability of the metal to withstand high-energy impacts.

In conclusion, at a 45-degree impingement angle and a jet velocity of 150 m/min, the erosion behavior of AlSi10Mg is likely to exhibit a relatively higher erosion rate compared to lower impingement angles and velocities. However, further experimental testing and analysis are necessary to precisely characterise the erosion behaviour of AlSi10Mg under these specific conditions.

Strain is induced during the fabrication process and can be influenced by the build orientation. Different build orientations, such as horizontal, vertical, or inclined, result in variations in the direction and magnitude of strain within the material. This strain affects the microstructure and mechanical properties of the alloy, consequently impacting its erosion resistance.

Additionally, heat treatment plays a role in modifying the strain within the material. Heat treatment processes like T5 and T6 are commonly used to enhance the mechanical properties of aluminium alloys. These treatments involve heating and cooling the material to specific temperatures and durations, which can cause the redistribution of strain and affect the material's microstructure.

The T5 and T6 heat treatment processes are commonly used to minimise strain-induced vulnerabilities in aluminium alloys, including Al10SiMg. These processes involve a combination of heating, quenching, and ageing steps. Here's a brief overview of T5 and T6 heat treatments and their effects on strain reduction:
T5 Heat Treatment: In the T5 heat treatment, the material is solution heat-treated by heating it to a temperature below the eutectic point of the alloy. This helps dissolve the alloying elements into a solid solution. The material is then quenched rapidly in a suitable medium, such as water or polymer. This quenching process freezes the alloying elements in a supersaturated solid solution state, reducing the strain within the material.

T6 Heat Treatment: The T6 heat treatment follows the T5 process and involves a precipitation step to further strengthen the material. After the solution heat treatment and quenching, the material is artificially aged by reheating it to a moderate temperature, typically below the eutectic point but above room temperature. This ageing step promotes the precipitation of fine particles, such as intermetallic compounds, within the material. These particles act as strengthening agents, reducing strain-induced vulnerabilities and improving the mechanical properties of the alloy.

Both the T5 and T6 heat treatments help minimise strain-induced vulnerabilities by redistributing internal stresses and optimising the microstructure of the material. The solution heat treatment and quenching steps alleviate residual stresses and strain, while the ageing step enhances the strength and stability of the alloy.

It is important to note that the specific parameters of the T5 and T6 heat treatments, such as temperatures and durations, may vary depending on the specific alloy composition and desired material properties. These parameters are typically optimised through experimentation and are crucial to achieving the desired balance between strain reduction and mechanical performance. The combined effect of build orientation and heat treatment on strain distribution influences the erosion behavior of the Al10SiMg alloy. Strain can affect the material’s hardness, strength, and ductility, all of which contribute to its resistance against erosive forces [29]. Understanding the relationship between strain and erosion behaviour is essential for optimising the fabrication parameters and heat treatment conditions to improve the erosion resistance of Al10SiMg components [30].

Spherical powders of inert gas with atomized particle sizes of 20–60 μm were used to print the samples. The apparent and tap densities and the flow rates of the powders were 2.54 g/cc, 4.1 g/cc, and 31 s/50g, respectively. The moisture on the powders was removed by pre-heating the powders at 100°C for 12 hours in a vacuum furnace before loading them for the printing process. The samples were printed in an Argon gas environment to avoid oxidation. The built plate was maintained at 80°C to minimise the thermal gradient during the build. This helps reduce the residual stress in the samples. The laser power of 280 W, laser spot size of 0.1 mm, hatch distance of 0.11 mm, 67° rotating angle scan strategy, layer thickness of 0.04 mm, and scanning speed of 950 mm/s are used to print the samples. The chemical composition of Al10SiMg is given in Table 1.
The process parameter data are standardised by EOS [31]. According to the EOS, the samples printed in this data set are expected to have an average tensile property (yield strength: 270 MPa, ultimate tensile strength: 460 MPa, % elongation: 10% in the horizontal direction; yield strength: 230 MPa, ultimate tensile strength: 470 MPa, % elongation: 6% in the vertical direction) and a sample density of 2.67 g/cc [32]. The as-printed samples were given two different heat treatment cycles. The cycles are given in Table 2. The samples were prepared by the standard metallography method. The polished samples were etched using Keller's reagent (95% pure H₂O, 1% HF, 2% HCL, and 3% HNO₃) etchant for 10 s.

The microstructure was studied using an optical microscope (ECLIPSE LV100N POL) and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDAX) (FESEM, Zeiss SupraTM 40) for the as-printed, T5 and T6 conditions. The elemental composition of the samples was studied using EDAX (Make: Oxford 7353). The compound formation on the alloy was studied using X-ray diffraction (XRD) (Philips PW3040, equipped with a monochromator, Cu Kα radiation).

For the erosion study, test specimens of 5 mm thickness were sliced into circular shapes with an electron beam cutter. Electron beam cutting was chosen for test specimen preparation in the erosion study due to its precision, reproducibility, and minimal mechanical disturbance. Despite being a thermal process, it offers clean and smooth cut surfaces with controlled heat-affected zones. The method ensures consistency in comparative studies and allows accurate evaluation of intrinsic erosion resistance. While microstructural changes near the cut edge are acknowledged, the controlled nature of the process mitigates their extent. Consideration of these effects enhances understanding and interpretation of erosion behaviour, resulting in valuable insights. The erosion behaviour of the as-printed and heat-treated (as per ASTM F 3318) samples was studied using the TR-471-1200, DUCOM air-jet erosion set-up. The image of the erosion set-up (TR-471-1200, DUCOM) is shown in Figure 2.

**Table 1.** Chemical composition of the Al0SiMg.

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Mg</th>
<th>Fe</th>
<th>Ti</th>
<th>Zn</th>
<th>Mn</th>
<th>Cu</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. %</td>
<td>10.6</td>
<td>0.38</td>
<td>0.15</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The erosion testing condition is given in Table 3. The ASTM G76 test standard is followed for the erosion test.

**Table 2.** Heat treatment cycle of the SLM Al10SiMg samples.

<table>
<thead>
<tr>
<th>As built</th>
<th>No treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5</td>
<td>Stress Relieving 300 °C- 2 hrs.</td>
</tr>
<tr>
<td>T6</td>
<td>540°C/2 h, 65°C water quench, 160 °C/12 h, aging air cooling</td>
</tr>
</tbody>
</table>

**Table 3.** Experimental testing parameters of erosion test using abrasive jet.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive</td>
<td>Silica sand (300μm), SiC (250μm)</td>
</tr>
<tr>
<td>Flow rate of abrasive</td>
<td>700 gm/min</td>
</tr>
<tr>
<td>Velocity</td>
<td>150 m/min</td>
</tr>
<tr>
<td>Pressure</td>
<td>6 kg/cm²</td>
</tr>
<tr>
<td>Nozzle bore diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Material of nozzle</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Life of nozzle</td>
<td>1.5 to 2 hours</td>
</tr>
<tr>
<td>Stand-off distance</td>
<td>6 mm</td>
</tr>
<tr>
<td>Impingement angle</td>
<td>45°[25]</td>
</tr>
<tr>
<td>Erodent hardness</td>
<td>9 (Moh’s)</td>
</tr>
<tr>
<td>Work material</td>
<td>Al10SiMg</td>
</tr>
</tbody>
</table>

Before experimentation, the samples were polished with emery and diamond paste cloth and cleaned in acetone to remove any contaminants such as grease, oil, lubricant, and oxide scales. The particle
velocity was calibrated using the double disc method. The hopper was filled with abrasive grits of silica sand with a grit size of 300 µm. Clamps were used to secure the sample to the cross slide. As the compressor began to run, the feeder gate valve was opened, allowing abrasive grit to mix with the air jet that emerged from the nozzle and was directed towards the specimen. An electronic weight balancing setup (Uni bloc Shimadzu microbalance, accuracy = 0.001 mg) was used to weigh the sample before and after the erosion test. The erosion rate is determined by the below equation.

\[ Erosion \ Rate \ (E_r) = \frac{(W_{before} - W_{after})}{(E_f \cdot t)} \]  

- \( W_{before} \) - Weight of the sample before the erosion test in g.
- \( W_{after} \) - Weight of the sample after the erosion test in g.
- \( E_f \) - Erodent flow rate in g/sec.
- \( t \) = Discharge time of the erodent in sec.

The samples were weighted before and after the erosion test with an electronic balance with an accuracy of ± 0.01 mg. By using the change in mass, erodent flow rate (\( E_f \)) and discharge time (\( t \)), the erosion rate (\( E_r \)) of each sample was calculated using

The test was repeated three times, and the average value was reported. The hardness of the samples was measured using the Vickers scale (WOLPERT universal hardness testing machine UH-930). A pyramid-shaped diamond indenter was used. The load applied was 10 kgf applied for 10 seconds in accordance with the UNI EN ISO 6507-1:2018 standard specification. Five indentations were taken, and the average value was reported.

The eroded surface topology was examined using SEM to understand and compare the erosion mechanism. The surface composition was studied using EDAX and XRD to understand the oxide and other compound formations during the erosion. As a work piece, Al10SiMg samples were employed. All specimens, including printed and heat-treated samples of all three orientations, were tested. The starting weights of the test specimens were measured using a digital balance [30]. After the erosion test, the final weights of the specimens were measured. The difference between the beginning and end weights is used to determine weight loss per unit time.

Silicon carbide (SiC) is a commonly used abrasive material in erosion tests due to its excellent hardness, high thermal conductivity, and resistance to chemical corrosion. It is widely employed as an abrasive grit in erosion testing to simulate the erosive wear experienced by various materials. The hardness of silicon carbide particles allows them to effectively remove material from the specimen’s surface, facilitating the measurement of erosion rates. Additionally, the high thermal conductivity of SiC helps dissipate the heat generated during the erosion process. Its chemical resistance ensures that the abrasive grit remains stable and does not undergo significant changes during the test, providing consistent and reliable erosion data. The experiment was carried out on a few process parameters and followed the procedure given in ASTM F 3318 and ASTM G 76 standards. For more information regarding the procedure of the testing and test parameters, ASTM F 3318 and ASTM G 76 standards may be referred to. The studies were carried out using silicon carbide (SiC) abrasive grits of size 250 µm.

3. RESULTS AND DISCUSSION

3.1 Micro-hardness

The thermal treatment condition also influences the micro-hardness properties, as shown in Figure 3. To investigate the material’s potential anisotropy by measuring hardness in three different directions (horizontal, inclined, and vertical). The as-printed specimen shows a hardness of 120±2 HV (horizontal) and 115±2 HV (vertical) in the building direction. The microhardness values fluctuate dramatically over long distances in all directions, demonstrating that microhardness is not consistent throughout. The presence of pores, unfused materials, and microcracks seem to have affected the microhardness of the specimen. Due to the random grain orientation, the average micro-hardness value for all the directions is not similar, indicating that the sample is anisotropic in its mechanical properties.
It was found that heat treatment (T6) negatively affected hardness with 110±3 HV (horizontal and vertical directions). In fact, the heat treatment is used to restore ductility at the expense of strength and hardness. After heat treatment, the hardness of the as-printed condition was reduced by about 6.3%, suggesting material softening. Owing to the homogenization microstructure, there are no more significant differences in hardness between the two directions. The as-printed condition exhibits higher hardness compared to the T6 condition. Due to the very fine structure of the supersaturated solid solution and the intercellular zones of the Al10SiMg material in its as-printed state, this material exhibits maximum hardness values. Considering that an important component of strengthening fails after solution treatment, the reduction in mechanical resistance may be very well justified. According to a recent study by B. Chen et al [33], in the as-printed condition, during plastic deformation of the alloy, multiple Orowan loops are formed due to dislocations gliding through the cell boundary, resulting in high hardness. Several dislocations are continuously produced during this mechanism, which leads to an increased hardness of the alloy. During solutionizing treatment, mechanisms transform the as-built microstructures of LPBF Al-Si-Mg alloys. The evolution of Si morphology leads to a reduction of supersaturation in the matrix. By varying treatment temperature and duration, the fine fibrous network that contributed to the eutectic network is completely replaced by more or less uniformly distributed blocky particles [35,36]. Initially, the supersaturated matrix's Si atoms are rejected and precipitated along the pre-existing cell boundaries [36]. As a result, the Si branches are fragmented and spheroidized, most likely as a result of Al and Si interdiffusion, which is energetically preferable to surface self-diffusion [37]. The solutionizing process also affects the distribution of other elements, but it can also affect precipitate dissolution and formation [38]. Si precipitates of nanometer size inside the Al matrix have been confirmed even after high-temperature solution treatment [11]. After ageing, Mg2Si precipitates do not cause the hardening, but pure silicon particles do. After additive manufacturing, the Mg2Si phase is already formed in the silicon-rich intercellular network. Consequently, Mg2Si precipitation cannot occur in the solid solution since Mg would otherwise preferentially react with Si. The solid solution contains no Mg, which would otherwise conversely react with Si, thus preventing the precipitation of Mg2Si. Due to a very large crystallographic misfit between silicon (diamond cubic) and the aluminium-rich Al (Si) solid solution (FCC), a very high supersaturation was needed for Si precipitation in Al-Si alloys. As Si crystals develop diamond cubic structures, they lose crystalline coherence after a certain period of time [40–42]. According to E. Cerri et al [43], Al-Si7 was treated with a high-pressure solution and subsequently aged at 150°C to obtain nanoscaled precipitates. A spherical shape of the Si precipitates is first observed, followed by rapid growth parallel to [111] planes (Si precipitates are oriented the same as the matrix). Growth ledge shortages on the [111] interfaces inhibit growth perpendicular to those planes, resulting in high aspect ratio triangles and plates. According to Y. J. Liu et al [43], platelets were 50–120 nm in length and 5–20 nm in thickness. Additionally, secondary phases (needle-like) have been extensively formed in T6, which can cause embrittlement and, in turn, harm the mechanical properties of the alloy [42].

A significant number of studies have also looked at the effect of heat treatment on mechanical properties, which is an important feature of LPBF parts since the unavoidable existence of porosity and defects might alter the materials' behaviour. Recent study results using X-ray computed tomography show that thermal treatments affect the location, size, number, or shape of pre-existing defects, even at high temperatures. In LPBF, porosity defects are typically classified as either gas pores or lack-of-fusion pores [44].

Gas porosities develop as a result of trapped gases and are typically tiny (< 100 m) and spherical, whereas lack-of-fusion pores (> 100 μm) develop as a result of the melted metal powder solidifying before it can completely fill any gaps that have already been created during the selective melting process. LPBF-fabricated alloys have anisotropic microstructures and defects, which simultaneously affect the alloy's mechanical properties [45].
J. J. Lewandowski et al [46] showed that LPBF Al10SiMg parts with a 5% reduction in relative density were treated with solutionizing. A new pore formation was attributed to this variation. The findings suggest that H atoms entrapped inside the metal during solidification lead to multiple atoms integrating into a molecular state, resulting in new gas micropores. Two significant aspects were emphasised in the comprehensive analysis of deformation in as-printed and T6 conditions. In the T6 condition, the deformation initially progressed through the α-Al matrix, occasionally breaking the spheroidal Si particles. Secondly, the generation of compressive residual stresses favours resistance. In the T6 condition, there was a decrease in resistance [8], which was attributed to a decrease in mechanical resistance.

Direct ageing (T5) has been observed to enhance the hardness of LPBF Al10SiMg alloys, although the difference between as-printed and T5 characteristics is comparable to that caused by T6 conditions. However, of the numerous thermal treatments that have been examined, T5 samples have consistently been identified to exhibit the maximum mechanical properties.

In the context of AlSi10Mg, the heat treatment cycles T5 and T6 play a crucial role in enhancing its properties and optimising its performance. The T5 heat treatment involves artificial ageing after the solution treatment, which aims to increase the material's strength and hardness while maintaining good formability. This treatment helps achieve a desirable combination of mechanical properties for applications that require both strength and ductility. The T6 heat treatment, on the other hand, includes solution treatment followed by artificial ageing, resulting in further improvement in the material's strength and hardness. The purpose of these heat treatment cycles in the study of AlSi10Mg is to understand how the ageing process affects the microstructure, mechanical properties, and ultimately, the erosion behaviour of the material. This knowledge is crucial for optimising the material's performance in erosion-prone applications, such as those involving high-velocity fluid flow or abrasive environments.

The T5 condition exhibits a higher hardness 127± 2 HV compared to all other conditions. The interest in the T5 condition of LPBF Al-Si alloys is primarily motivated by two factors originating from the T6 condition. During fast cooling, Mg and Si cannot diffuse to form thermodynamically stable secondary phases when cooling rates are higher. On the other hand, hardness may increase as solute concentrations rise. Compared to Al atoms, Si atoms have a smaller atomic radius, which causes lattice deformation that favours residual stress development and hinders dislocation movement [47].

Fine grains form in the T5 condition, which act as strengthening agents and contribute to the higher hardness value. Also, the controlled decomposition of supersaturated Al matrix results in nano-Si precipitation. That gives it additional strength. After the T6 treatment, the samples' performances were lower. There is a loss in hardness between the as-printed and T6 conditions, which is shown by a 6.3% decrease in density. This loss in hardness is caused by the coarsening of the microstructure, the loss of solid solubility, and the increase in porosity caused by the continuous exposure to high temperatures. In summary, it is hypothesised that solid solution strengthening, precipitation of nanoscale Si particles, and grain refinement generated by fast solidification result in T5 condition specimens exhibiting higher hardness [40].
4. EROSION

The total mass loss vs. orientation for three different conditions is shown in Figure 4. The results show that the three different orientations follow similar patterns irrespective of the material’s heat treatment state. The influence of orientation is minimal compared to that of the heat treatment. It implies that phases/Si particles type and size scale and Si super saturation in the Al matrix have a significant influence over the grain orientation. The orientation effect is insignificant for the high hardness materials (T5 condition). It starts to show its influence when the material’s hardness and density decrease. This is confirmed by Figure 4a.

Based on the alloy’s microstructure and hardness characteristics, erosion behaviour is determined. It is generally acknowledged that material degradation occurs in four stages: the incubation period, the acceleration period, the deceleration period, and the steady-state period [48]. The as-printed specimen loses only 0.00008 mg (horizontal), as compared with vertical, this mass loss is about 0.00007 mg lower. Patel As-printed specimens increase their mass loss after T6 heat treatment. It is attributed to the lower hardness and density of the material than those of the as-printed specimen. In contrast, the T5 condition shows superior erosion resistance compared to the other two conditions (T6 and as-printed). This finding lends support to the contention that the porosity level brought on by the T6 treatment also has a considerable effect on the characteristics of the alloy in addition to the hardness factor.

Air Jet Erosion tests were conducted to evaluate the erosive behaviour of Al10SiMg. There is material loss in erosion, which is largely caused by cutting and plastic deformation. Erosion occurs at low impact angles, while multiple plastic deformations occur at high impact angles, which ultimately results in higher material loss. The process of erosion involves the removal of material from the exposed surfaces due to plastic deformation caused by the kinetic energy of the eroding particles.

Erodent’s don’t utilise all their kinetic energy in erosion; instead, some may be lost as heat or in the process of rebounding [49]. According to
Figure 5, horizontal, vertical, and inclined specimens subjected to different conditions will exhibit degraded surfaces at an impact angle of 45°. Recent studies B. A. Raj C. Samuel et al [50] and [51] have shown that an impact angle of 45° causes a faster erosion rate, which is caused by an increase in the eroded surface area and the shearing effects of the eroded material. The higher solid particle velocity at a 45° angle results in a more effective impact on the material and thus a higher erosion and corrosion rate. When solid particles are present in the environment, the effects of erosion and corrosion are amplified because they cause additional mechanical and chemical damage to the material. This is because the particles create microstructural irregularities on the surface of the material, which can lead to an increase in the contact area and thus an increase in the contact force. This increased contact force can lead to an increase in localised attack and, thus, an increase in the material degradation rate [52].

T5 and T6 heat treatment methods can influence the erosion behaviour of Al10SiMg, particularly its density. T5 heat treatment consists of solutionizing and quenching, whereas T6 heat treatment also includes an ageing phase.

These processes can affect the microstructure of the alloy, including the size, distribution, and density of precipitates. The ensuing changes in microstructure can have an effect on the material’s density.

The manufacturing orientation of Al10SiMg can also affect erosion and density. Different orientations might cause variances in the solidification and grain structure of the alloy, potentially resulting in density discrepancies. The density distribution inside the material may vary according to orientation-dependent solidification conditions.

T5 and T6 heat treatment methods can have a significant influence on the erosion volume loss of Al10SiMg. T5 heat treatment consists of solution heat treating the alloy followed by quenching, whereas T6 heat treatment includes a further ageing phase. These heat treatments can alter the alloy’s microstructure and mechanical characteristics, thereby impacting its erosion resistance.

The manufacturing orientation of the Al10SiMg component can also influence erosion volume loss. Variable orientations (horizontal, vertical, inclined) as shown in Figure 4b, might result in varied stress distributions and microstructural properties, resulting in diverse erosion behaviours. The surface’s direction in relation to the erosive particles might affect the erosion process and the exposure of sensitive regions to the erosive forces.

The erosion rate increased steadily with orientation; it was much greater in the T6 condition than in other conditions. According to the experimental results, in the horizontal direction, erosion rates for the T5 condition are 1.5 x 10⁻⁷/gram, while in the as-printed and T6 conditions, erosion rates are 2 x 10⁻⁷/gram and 2.75 x 10⁻⁷/gram, respectively. During T5 processing, an ultrafine microstructure was developed, resulting in improved parameters.

4.1 Analysis of erosion

SEM examined the eroded surface morphology of as-printed and heat-treated conditions in order to determine the behaviour and form of material loss during erosion. Figures 6a, 6b, and 6c show a micrograph of the eroded surface at a 45° impact angle for horizontal, vertical, and inclined specimens exposed to three different conditions. At a 45° impact angle, the damaged surface typically exhibits crater formation, lip formation, and uniform ploughing [56]. It is primarily caused by the erodent's shear force. The vertical component of kinetic energy is responsible for the erosion of the material, as the solid particles penetrate the material and cause physical and chemical damage. The horizontal component acts as a support and helps to create grooves and furrows in the material, which accelerate the erosion and corrosion process [27].
4.2 Erosion surface of the as-printed condition

Figures 7a and 7c show the erosion surfaces of the horizontal and inclined specimens. As a result of the 45° impact angle of erodent particles, deformed lips and ploughing marks can be observed on the erosion surface. In Figure 7b, indentation marks and lips in vertical orientation are comparatively smaller than in all other orientations. The impact of the erodent particles on the as-printed conditions results in a large amount of stress, which is then stored in the material. This stored energy eventually exceeds the fracture strength of the material, resulting in the brittle fracture of the aluminium material and the growth of cracks. The combination of these cracks results in the pull-out of material, forming the craters on the surface.

Fig. 6. Eroded surface of the as-printed samples impacted at 45° impact angle.

Fig. 7. High magnification images of the eroded surface of the as-printed samples impacted at 45° impact angle.
It also depicts a large crater and a heavily deformed region compared to other orientations. In as-printed specimens, tensile residual stress remains due to complex solidification [11], which results in a higher erosion rate under different orientations.

The vertical specimen undergoes quicker heat transfer than the inclined and horizontal specimens, resulting in the creation of higher residual stress in the vertical specimen, which leads to a higher erosion rate compared to other orientations. The columnar structure is more prone to erosion as compared to fine cellular grain structures [57]. The semi-elliptical melt pool face had more fine grain sections, as illustrated in Figure 7b, supporting the actual sequence of erosion rate.

The hardness of SiC particles influences their abrasive capabilities and wear resistance. Harder SiC particles have a larger potential for material removal and erosion. During erosion, the size of SiC particles determines their penetration depth and impact energy.

Larger particles cause more serious harm. SiC morphology, such as irregular forms or sharp edges, can improve cutting performance.

The hardness of SiC may be determined indirectly from the degree of material loss in SEM pictures, while the size and shape can be visually analysed, offering insights into their erosion mechanisms and efficacy in various applications.

### 4.3 Erosion surface of the T6 condition

Generally, in T6 conditions, metals are diluted; they become softer and easier to deform. The low critical resolved shear stress and low concentration of dislocation sources also make them more ductile, meaning that they can deform more easily without breaking. The eroded surface of the T6 condition is shown in Figures 8a, b, and c. Increasing the degree of erosion and degradation is attributed to the low hardness. In Figure 8b, dimples on eroded samples show signs of plastic deformation. In T6 conditions, grain coarsening and Si particle spheroidization take place.

Loss of solid solution, Si particle coarsening, and matrix grain growth make the material soft. Hence, the highest erosion rate occurs. The grain size of T6 is comparatively larger than that of all other conditions, regardless of orientation.

**Fig. 8.** High magnification images of the eroded surface of the T6 samples impacted at 45° impact angle.
With more cavitation and higher Surface Free Energy (SFE), larger amounts of plastic deformation occur, which leads to greater material removal. Additionally, the plastic shock wave can propagate further into the material, resulting in a deeper penetration of the material and more uniform material removal.

The easy cross-slip of the surface asperities also results in more efficient material removal [58]. According to Figures 8a and 8b, the T6 specimen showed ductile erosion, including lip deformation, craters, and deformed lips. At higher magnification, the T6 showed microindents and ductile, deformed dimples. These features support the fact that the material is soft and easily deformable. Compared to horizontal and inclined specimens with similar erosion surfaces, vertical specimens showed significantly smaller deformed lips and craters due to their higher hardness.

4.4 Erosion surface of the T5 condition

Figures 9a, 9b, and 9c show the T5 heat-treated deteriorated surface in horizontal, vertical, and inclined orientations. Strong surface protrusions, a high ridge, and deep ploughing are all discernible. It indicates that a sizable volume of eroded material has reached the target surface. The T5 surfaces have fewer crater marks, which indicates more toughness. An SEM image at a higher magnification was also taken to obtain further information on material removal mechanisms. A crater-like structure was observed in Figure 9a due to the cutting action of the erodent, and matrix cracking was also observed. Intermetallic phases present in the T5, however, are mostly responsible for resisting plastic flow. This is discussed in the section on microstructural observation.

Figure 9b shows the surface protrusion formed at the groove's eroded exit end. The erodent's repeated shearing action caused the protrusion's striations to accumulate the displaced material. After multiple eroded impingements, the protrusion separates from the surface. Erosion behaviour of materials is significantly influenced by heat treatment and build orientation, based on analysis of SEM surfaces. In all conditions, there is no evidence of preferential damage zones.

Fig. 9. High magnification images of the eroded surface of the T6 samples impacted at 45° impact angle.
Despite the uniform damage of all samples (Figures 9b, 9c), which exhibits visible ploughing, lip formation, and craters, the T5 conditions surface, which exhibits very high resistance to erosion, is only slightly eroded, based on the cumulative mass loss (Figure 9a). The finer dispersion of the precipitates allows for better segregation of the alloying elements, which results in a more homogenous distribution of the alloying elements throughout the microstructure. This leads to higher resistance to environmental factors such as erosion.

5. MATERIALS CHARACTERIZATION OF Al10SiMg IN DIFFERENT CONDITIONS

In Figure 10a, the XRD plot shows the orientation effects of the T5 heat-treated Al10SiMg specimens. There are four crystalline phases in these spectra: Al, Si, Mg, Si, and Al, FeSi. There are no significant differences among the XRD spectra except for more peaks of Al, FeSi in the horizontal direction. A supersaturated Al matrix weakens the Si reflections. Other alloys, such as AlSi12 [59], also exhibit this behaviour due to high cooling rates and repeated local remelting. In Figure 10b, the XRD plot shows the heat treatment effects of the horizontal Al10SiMg specimens.

There are four crystalline phases in these spectra: Al, Si, Mg, Si, and Al, FeSi in the T5 conditions, whereas only three crystalline phases are observed in these spectra: Al, Si, and Mg, Si for the as-printed and T6 conditions. This gives a clue that Al, FeSi plays a significant role in strengthening the alloy.

Further, the Mg, Si and Si peaks of T5 are broadened. This indicates that they are in very fine scale, probably at the nanoscale. This contributes to significant strengthening of the T5 treated alloy through dislocation strengthening, CTE and Young modulus mismatch, and Orowan strengthening.

The formation of Mg, Si in the LPBFed Al10SiMg was explored by [38]. Their thermodynamic study on the Al-Si system verified that the released enthalpy corresponded to the level of supersaturation attained in samples produced via various processing procedures. Further exothermic signals are attributed to the precipitation of Mg, Si (a signal identified exclusively for LPBF samples at 317°C), as cooling circumstances probably allow the Mg to reach equilibrium.

Fig. 10. (a) XRD of Al10SiMg-T5, (b) XRD of Al10SiMg - horizontal orientation.

Fig. 11. LPBF processed as-printed samples of Al10SiMg [20].
6. CONCLUSION

In this work, Al10SiMg alloy was printed by laser powder bed fusion. In order to avoid residual stress results and enhance the tribological properties, T5 and T6 heat treatments were attempted. The erosion behaviour, which is unreported yet in the literature, is extensively explored in this work. The erosion behaviour of the as-printed and heat-treated samples was studied for all three orientations to understand anisotropy effects on erosion behaviour. The hardness results are correlated with the erosion loss of the alloy. The key findings of the present investigation are:

- T5 heat treatment is proven to be superior in providing high erosion resistance, followed by as-printed and T6 heat treatment, respectively. The unspoilt as-printed fine scale microstructure and nanoscale Si precipitation are attributed to the erosion resistance of the T5 heat-treated alloy.

- The orientation effects on the erosion resistance are seen in the as-printed samples, whereas they are not observed for both the heat-treated samples (T5 and T6).

- The heat treatment effects are more significant than the orientation effects in determining the erosion resistance of the Al10SiMg alloy.

- Ploughing, lip, and crater formation are widely observed on the eroded surface. The intensity of the ploughing and crater regions is lower in the T5 heat-treated sample compared to the other two types.

- The hardness results complement the erosion trend for the as-printed and heat-treated samples. Also, the trend remains the same for orientation. Hence, it is proposed that erosion resistance and hardness are directly correlated.

Acknowledgement

The authors would like to thank Dr.T. Ram Prabhu, Scientist, DRDO Bangalore, for his support in experimentation work.

REFERENCES


[29] G. Tarakçı, H. M. Khan, M. S. Yılmaz, and G. Özer, “Effect of building orientations and heat treatments on AlSi10Mg alloy fabricated by selective laser


[31] "Professional 3D Printing Solutions | EOS." https://www.eos.info/


