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SUSTAINABLE PRODUCTION OF ALUMINUM POWDER FOR ADDITIVE MANUFACTURING: A COMPREHENSIVE INVESTIGATION OF ALUMINUM POWDER CHARACTERISTICS FROM WATER ATOMIZATION TECHNIQUES

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Abstract

In this paper, the qualities of aluminum powder made from industrial aluminum scrap through water atomization for use in Additive Manufacturing were examined. This investigation aims at determining what factors the water atomization process have on the quality of the powder, and if it can be utilized as a sustainable method of manufacturing. Aluminum powder was created under controlled conditions by altering some of the primary aspects of the process; specifically, water pressure and the molten metal's temperature. We used two types of spectroscopic analysis, Energy Dispersive X-ray Spectroscopy (EDX), and X-ray Fluorescence (XRF) to measure the chemical makeup of the aluminum powder, as well as particle size distribution, particle morphology, and compatibility with additive manufacturing processes. The results indicate that water atomization creates aluminum powder with particles that are generally in the size range of 20–100 μm. The EDX and XRF showed that the aluminum powder contained approximately 80.63% aluminum, and there were variances in elemental composition and relatively large amounts of oxygen content that averaged approximately 43.5%. Small amounts of other minor elements, including silicon, copper, and iron were also observed, which may be due to the alloying elements within the scrap material. Additionally, the powders demonstrated irregular shapes to their particles, which is representative of the inherent properties of the water-atomized powders produced from recycled aluminum feedstocks. Overall, this research has shown the viability of producing powder from aluminum scrap as an alternate source of raw material for powder production, and will help to increase sustainability of the supply chain for Additive Manufacturing, by reducing dependence on virgin material, decreasing energy requirements and minimizing environmental impacts of traditional powder production methods.

1.0 INTRODUCTION

With the growing demand for aluminum powder in material science and additive manufacturing, researchers and manufacturers alike find themselves at a crossroads regarding sustainable production and application [1]. The rapid evolution of additive manufacturing (also referred to as three-dimensional printing) has transformed traditional manufacturing principles to include greater freedom of design and greatly decreased waste generation [2]. Aluminum is

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particularly well-suited for use within the additive manufacturing field due to its exceptional strength-to-weight ratio and corrosion resistant capabilities making it highly desired in the aerospace, automotive, and high technology fields [3]. Conversely, aluminum powder is typically produced using high energy consumption processes with significant detrimental effects upon the environment [4].

There is an extensive body of literature detailing the use of aluminum powder in additive manufacturing, and the benefits associated with its high thermal conductivity, and low weight [5]. Nagaraju et al [6] indicated that the increased demand for aluminum powder exists primarily in aerospace and automotive sectors due to the high strength-to-weight ratio. Further, Alo et al. [7] stated that the particle size distribution and morphology of aluminum powder directly affects the additive manufacturing process with regards to the mechanical properties and surface quality of the resulting final product.

Traditionally, aluminum powder was produced via methods that were energy intensive and had environmental consequences. Pletzer-Zelgert and Traverso [8] stated that the primary disadvantage of the most common methods used for aluminum powder production (gas atomization) is that they have a large carbon footprint. Conversely, de Mattos Nascimento et al. [9] advocated for sustainable practices in the production of aluminum powder to help achieve global environmental objectives.

As a result of these disadvantages, water atomization has become an emerging method of producing aluminum powder in a sustainable manner. Yang et al. [10] demonstrated that water atomization uses much less energy than traditional methods of aluminum powder production. Brika et al. [11] further provided information on the efficiency of water atomization to produce finer particles of aluminum powder that are beneficial for use in additive manufacturing. Persson, [12] further explained the ability of water atomization to produce powders with beneficial morphologies.

Although there are many advantages to utilizing water atomization to produce aluminum powder, there are also challenges that must be overcome. Mandal et al. [13] indicated that there are challenges with regard to the consistent particle size of aluminum powders produced via water atomization and the additional processing steps that are necessary. Powell et al. [14] indicated that further research is needed to optimize the process of water atomization, specifically with respect to controlling the characteristics of the powder that are necessary to satisfy the strict requirements of additive manufacturing.

This study evaluates the feasibility of using water atomization as an environmentally friendly alternative to conventional aluminum powder production. Water atomization is characterized by lower energy consumption and lower environmental impact, therefore presenting a feasible path toward the sustainable manufacture of fine aluminum powders. This manuscript examines the characteristics of aluminum powders produced via water atomization including particle size distributions, morphology and chemical purity, along with their implications for the additive manufacturing processes.

Additionally, this research aims to reconcile the requirements of sustainable manufacturing with the increasing needs of the additive manufacturing sector. Through an examination of the characteristics of aluminum powders produced by water atomization, this manuscript strives to clarify how sustainable production techniques can be easily incorporated into present day manufacturing workflow [15]. Insights gained from this study could provide significant contributions to the development of sustainable and efficient production of materials, necessary for the rapidly developing area of additive manufacturing. This study is intended to comprehensively evaluate the characteristics of aluminum powder produced via water atomization, a technique being recognized as an effective way to advance both environmental sustainability and technological advancements [16]. The rationale behind this inquiry is twofold: first, to address the growing demand for high-quality aluminum powders for use in additive manufacturing Tong and Tong [17], and second, to emphasize the importance of using sustainable manufacturing methods to reduce negative environmental impacts. [18].

2.0 METHODOLOGY

This section describes the experimental procedures adopted for the production of aluminum powder via water atomization and the characterization techniques used to evaluate powder morphology and chemical composition. Details of the equipment, operating parameters, and analytical specifications

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are provided to ensure clarity and reproducibility[19].

2.1 Materials and Water Atomization Equipment

Recycled aluminum scrap was employed as the feedstock for aluminum powder production. The initial mass of each sample (1000 grams) was placed in a high-temperature resistance furnace and then processed via a small-scale laboratory water atomizer. The equipment included a high-temperature (up to 800°C) melt furnace; a preheated tundish to control the molten metal discharge rate; a four-nozzle water atomizer chamber; and a single melt delivery nozzle with a 4 mm inside diameter. During the atomization operation, the molten aluminum was maintained at 650°C and discharged vertically upward through the melt delivery nozzle into the atomizer chamber, where it was impacted by high velocity water jets operating under a pressure of 200 Bar. The water sprays traveled approximately 52 mm prior to impacting the molten aluminum stream. In addition, the distance from the water jet nozzles to the centerline of the molten aluminum stream was approximately 15 mm, and the nozzle angle was adjusted to 40 degrees to enhance the disintegration of the molten aluminum stream. The resultant water-aluminum droplets rapidly solidified upon impact with the water, producing aluminum powder. A summary of key water atomization parameters is provided in Table 1. The water atomization parameters listed in Table 1 were selected based on typical values reported in the literature for laboratory scale water atomization of aluminum and aluminum alloys and on the operational limitations of the experimental apparatus. The water pressure of 200 bar was selected to provide sufficient kinetic energy to effectively fragment the molten aluminum stream into finer droplets while ensuring stable operation of the process. The molten aluminum temperature of 650°C was selected to provide sufficient fluidity of the molten aluminum to minimize the effect of viscosity related flow instabilities while avoiding excessive superheating which would have resulted in increased oxidation and increased energy consumption. The 4 mm inside diameter of the nozzle and 40 degree nozzle angle were selected to promote consistent break-up of the molten aluminum and controlled interaction between the molten aluminum stream and the water jets. Therefore, these parameters were selected to provide a repeatable basis for aluminum powder production from recycled aluminum materials. Optimization of the water atomization parameters to produce aluminum powders with improved sphericity, reduced oxygen content, and refined particle size distributions was not investigated in this study and is suggested as an area for future research.

Table 1: Key atomization parameters

Items	***Units/Value***
Operating pressure	200 bar
Number of nozzles	4
Ambient temperature	25°C
Angle of Nozzle (n^o)	40°
Velocity of molten aluminum	2.241 $\mathrm{m/s}$
Aluminum scrap metal(M_s)	1000 g
Molten aluminum temperature T_m	650°C
Turdish preheating temperature (T_T)	300°C
Water spray travel distance (L)	52 mm
Distance between the water nozzle and the melt (S)	15 mm
Diameter of melt nozzle (D_m)	4 mm

Prior to melting, the aluminum scrap was mechanically cleaned to remove loose surface contaminants such as dust, grease, and adherent debris. The scrap was then rinsed with distilled water and air-dried at ambient conditions to eliminate residual moisture. No chemical cleaning agents, flux treatments, or protective atmospheres were employed during melting. As a result, the presence of surface oxides and minor contaminants inherent to recycled aluminum scrap may have contributed to the elevated oxygen content observed in the atomized powders. Figure 1 illustrates the schematic of the water atomization setup used in this study and outlines the process flow for aluminum powder production. The system comprises a melting furnace, a preheated tundish for controlled molten metal delivery, a melt

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nozzle, and a water atomization chamber equipped with high-pressure nozzles. Molten aluminum flows from the tundish through the melt nozzle and is impinged by high-velocity water jets, causing the molten stream to fragment into fine droplets. These droplets rapidly solidify upon contact with water and are collected at the base of the atomization chamber as aluminum powder.

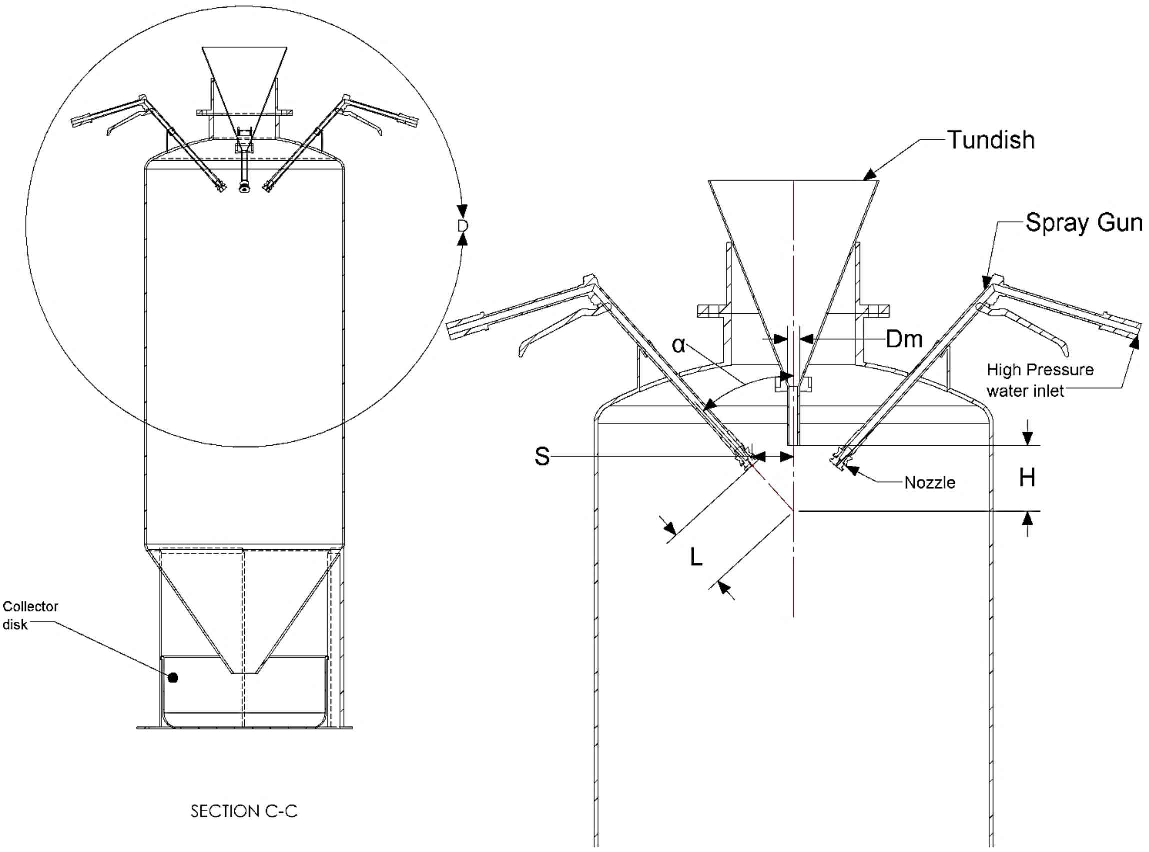

Figure 1: Atomizer setup showing key parameters

The key parameters such as water pressure, nozzle diameter, molten metal temperature, and flow rate were meticulously controlled. Following recommendations from Yenwiset and Yenwiset [20], water pressure of 200 bar, the nozzle diameter was set at 4 mm, and the molten metal temperature of 650°C. These parameters were selected for their significant impact on particle size and morphology, as identified in previous studies Brika et al [11].

2.2 Water Atomization Process

The water atomization process utilized in this study serves as the primary method for producing aluminum powder from recycled scrap, with the aim of evaluating its characteristics and potential applicability for laser-based additive manufacturing processes. This process involves the disintegration of molten aluminum into fine droplets using a high-velocity water stream, which rapidly solidifies the droplets into powder particles. Based on the experimental setup detailed by Yenwiset and Yenwiset [20], a specialized atomization chamber equipped with a high-pressure water nozzle and a molten aluminum delivery system was used.

2.3 Powder Collection and Preparation

Following atomization, the aluminum powder was collected from the base of the atomization chamber and thoroughly dried to remove residual moisture. The dried powders were gently sieved to remove oversized agglomerates and prepared for subsequent characterization. No additional post-processing treatments such as spheroidization or heat treatment were applied in order to preserve the as-atomized powder characteristics.

2.4 Morphological Observation and Particle Size Estimation

Powder morphology and approximate particle size distribution were examined using a **Scanning** Electron Microscope (SEM) equipped with Energy Dispersive X-ray Spectroscopy. SEM imaging was conducted to observe particle shape, surface texture, and qualitative size variation. Particle sizes were

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estimated directly from SEM micrographs using scale calibration. Dedicated powder image analysis or laser diffraction equipment was not available for this study and is therefore identified as a focus for future work.

2.5 Energy Dispersive X-ray Spectroscopy (EDX)

Elemental composition at localized regions of the aluminum powder particles was analyzed using Energy Dispersive X-ray Spectroscopy (EDX) integrated with a ThermoFisher Scientific Quattro S SEM-EDS system**.** The EDX analysis was performed at an accelerating voltage of 30 kV, with a total acquisition time of 58 seconds per region. Four distinct regions were analyzed to assess compositional uniformity and elemental distribution. The average count rate ranged from 622 to 1096 cps**,** depending on the region analyzed[21].

Table 2: EDX bombardment parameters for the experiment

EDX Parameter	*Region 1*	*Region 2*	*Region 3*	*Region 4*
Total Number of Counts	36,086	51,393	49,809	63,545
Total Acquisition Time	58 seconds	58 seconds	58 seconds	58 seconds
Average Count Rate	622 cps	886 cps	859 cps	1096 cps
Acceleration Voltage	30kV	30kV	30kV	30kV

2.6 X-ray Fluorescence (XRF) Analysis

Bulk chemical composition of the aluminum powder was determined using X-ray Fluorescence (XRF) analysis conducted with a Bruker S2 Puma XRF spectrometer. The instrument was operated in standardless evaluation mode to quantify major and trace elements present in the powder. XRF analysis provided complementary compositional data to EDX by offering higher accuracy for bulk elemental concentration and improved detection of alloying elements. As described by Tiwari [22], XRF involves irradiating the powder with X-rays and measuring the secondary (or fluorescent) X-rays emitted by the elements in the sample. This technique is particularly relevant for quantifying the presence of specific alloying elements and ensuring consistency across different batches of powder, a factor critical for maintaining uniform material properties in printed objects. In summary, the combination of water atomization for powder production and the subsequent EDX and XRF analyses forms a robust methodology for investigating the characteristics of aluminum powder. This approach not only ensures the production of powder with desirable physical properties but also verifies its chemical integrity, making it suitable for high-quality additive manufacturing applications.

3.0 RESULT AND DISCUSSION

3.1 Water atomization results

The shape of aluminum powder produced from the water atomization technique tends to be more irregular compared to that from the gas atomization technique due to several fundamental differences in the atomization processes and the nature of the cooling medium involved. [23]

One of the primary reasons for the irregular shape is the rapid cooling rate and the nature of the cooling medium [24]. The abrupt cooling leads to uneven solidification rates across the particle, resulting in irregular shapes. In contrast, gas atomization involves cooling with a gas (often inert gas), which allows for a more controlled and uniform cooling process, leading to more spherical particles [25].

The surface tension of water is higher than that of gases used in gas atomization [13]. When the molten metal comes into contact with water, the high surface tension can disrupt the formation of a smooth, spherical shape, resulting in more irregular particles as shown in figure 2(c). In gas atomization, the lower surface tension of gases like argon or nitrogen aids in forming smoother, more regular shapes. [26]

The interaction between molten aluminum and water leads to oxidation and other surface reactions [27]. These reactions can alter the surface characteristics of the particles, contributing to the irregularity in shape as seen in figure 2 (b). In gas atomization, especially when inert gases are used, the risk of oxidation and surface reactions is significantly reduced, promoting the formation of more uniform particles [28]. The particle breakdown as seen in figure 2(a) has a significant amount of oxygen which will increase surface reaction.

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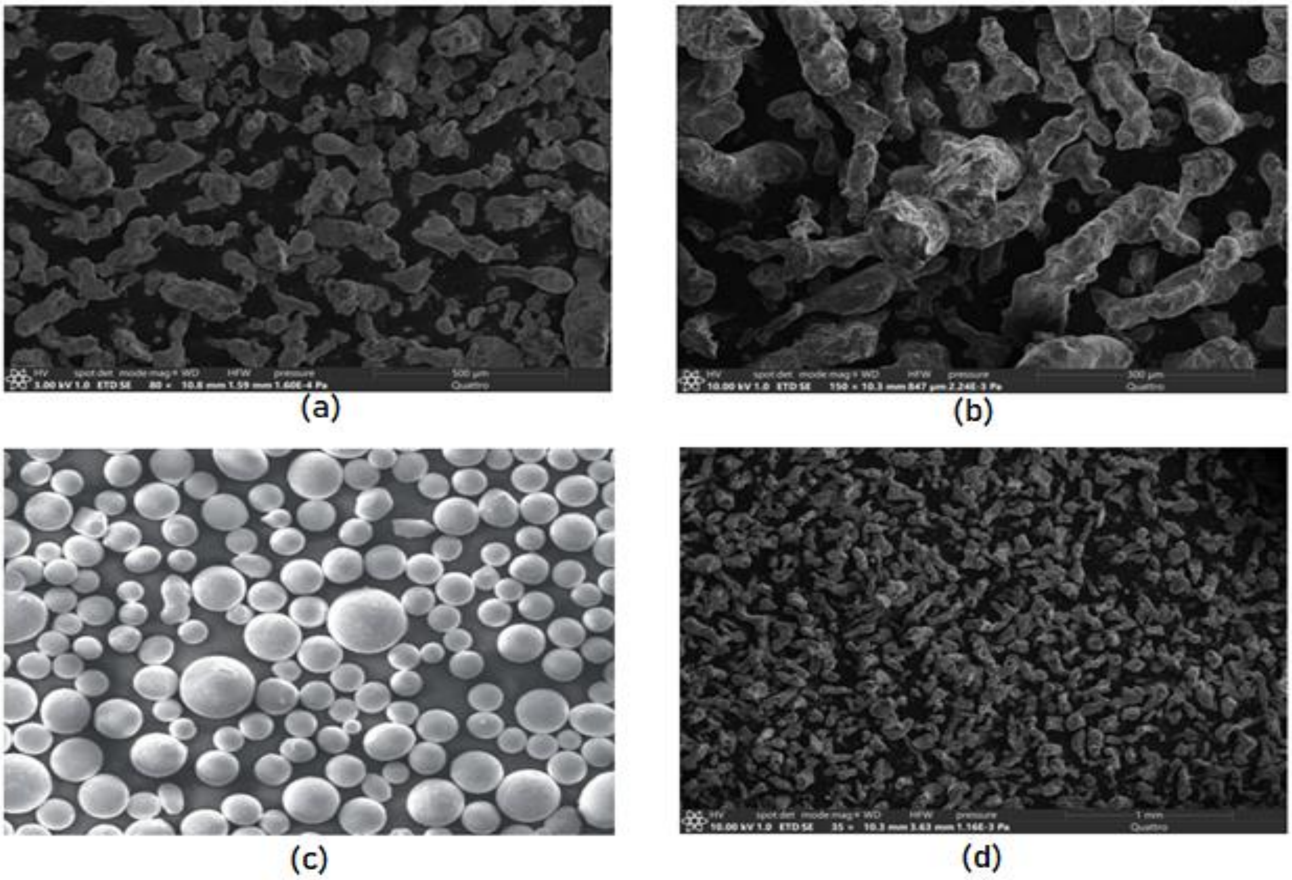

Figure 2: Shape of aluminum powder **(a)** Water atomized powder (500 µm) **(b)** Water atomized powder (100 µm) **(c)** Gas atomized powder (100 µm) **(d)** Water atomized powder (1 µm)

3.2 Energy Dispersive X-ray (EDX) Analysis

The Energy Dispersive X-ray Analysis (EDX) results obtained from the four regions of water-atomized aluminum provide valuable insights into the elemental composition of the samples. EDX is a powerful technique that enables the identification and quantification of elements present in a sample.

Table 3: Element detected in region 1

Element	Atomic %	Weight %
C	12.2	7.2
O	47.9	37.8
Al	35.9	47.8
Si	2.9	4.0
Ca	0.0	0.0
Fe	0.4	1.0
Cu	0.4	1.4
Zn	0.3	0.8

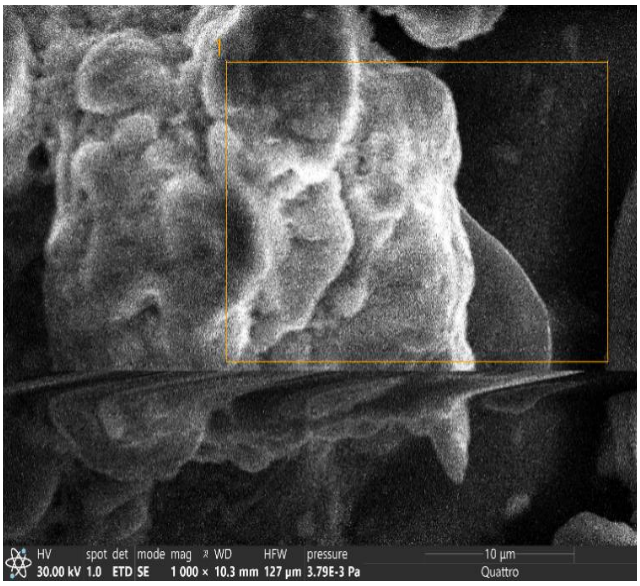

Figure 3: Energy dispersive X-ray analysis at region 1

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Table 4: Element detected in region 2

Element	Atomic %	Weight %
C	20.7	12.8
O	43.0	35.4
Al	32.1	44.5
Si	3.6	5.2
Fe	0.3	0.8
Cu	0.2	0.7
Zn	0.2	0.6

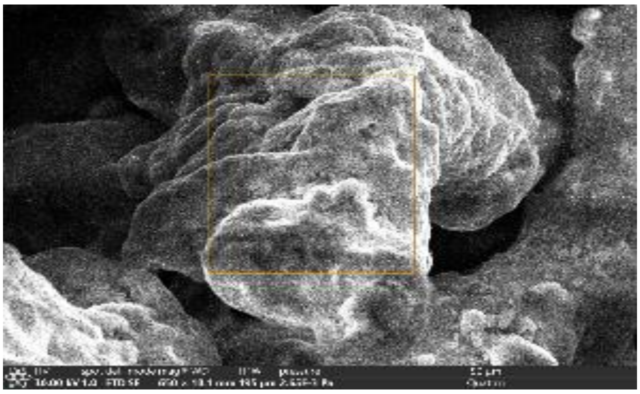

Figure 4: Energy dispersive X-ray analysis at region 2

Tables 3, 4, 5 and 6 present the atomic percentages of various elements in the four analyzed regions (Region 1, Region 2, Region 3, and Region 4). The varying carbon content across the areas indicates potential differences in the sample composition or surface contamination. In table 6, region 4 particularly stands out with a significantly higher carbon percentage, suggesting a distinct composition. The oxygen content is relatively high in all areas except for Region 4, where it is notably absent as seen in figure 10 in the corresponding EDX spectrum graph. The absence of oxygen in region 4 might be indicative of a specific region with a different composition, possibly a cleaner or purer aluminum region. The variations in elemental composition among the four region indicate heterogeneity within the water-atomized aluminum sample.

Table 5: Element detected in region 3.

Element	Atomic %	Weight %
C	14.1	8.3
O	42.4	33.0
Al	38.4	50.4
Si	4.1	5.6
Fe	0.4	1.0
Cu	0.4	1.1
Zn	0.2	0.6

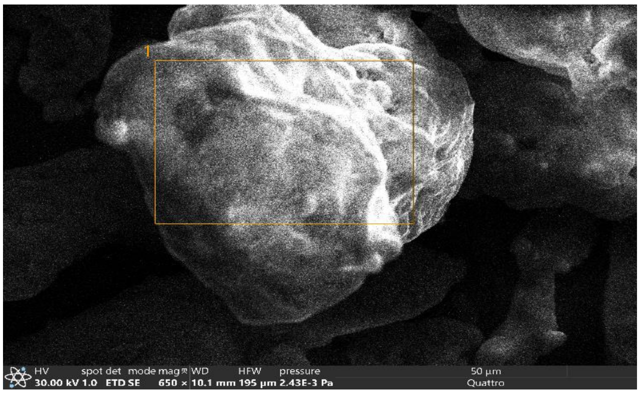

Figure 5: Energy dispersive X-ray analysis at region 3

Table 6: Element detected in region 4.

Element	Atomic %	Weight %
C	53.1	33.1
Al	46.1	64.4
Fe	0.4	1.1
Cu	0.4	1.5

The surface appears rough and irregular, which is typical for powders produced by water atomization. The rough surface can increase the surface area, which might influence properties like reactivity or sinterability in subsequent processing. The high amount of oxygen suggests that the surface of the aluminum particles has oxidized, forming aluminum oxide (Al_2O_3) figure 7,8 and 9). This oxide layer can protect the underlying metal from further oxidation and influence the material's processing and performance. The presence of silicon, iron, copper, and zinc indicates that the powder is not pure aluminum but may be an alloy. These elements can be intentionally added to modify the alloy's properties or could be impurities from the atomization process.

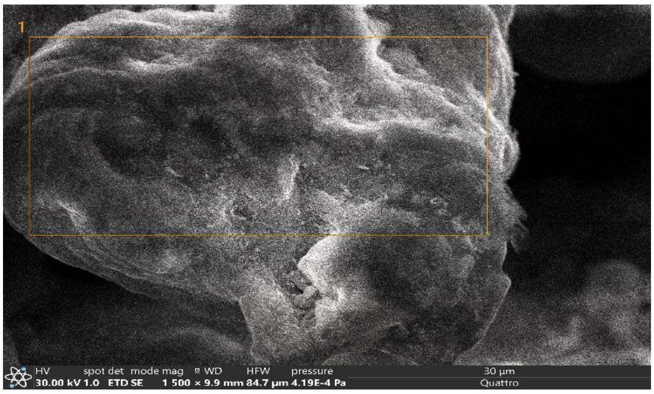

Figure 6: Energy dispersive X-ray analysis at region 4

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The analysis suggests that while aluminum is the primary element, the powder's purity is affected by oxygen and other elements. This will need to be considered when using the powder for manufacturing processes. For practical applications, the presence of the oxide layer and other elements means that the powder will have different sintering behavior and mechanical properties than pure aluminum powder. The information can be used to adjust processing techniques and to anticipate the properties of the final product made from this powder. The compositional variations observed across the analyzed powder regions are expected to have a significant influence on additive manufacturing performance. The high oxygen content detected by EDX suggests the formation of surface aluminum oxide (Al_2O_3), which can adversely affect powder flowability by increasing interparticle friction and reducing packing density. Poor flowability may result in non-uniform powder spreading during powder-bed additive manufacturing processes, leading to increased porosity and reduced dimensional accuracy. From a sintering and melting perspective, oxide layers on aluminum powder particles can hinder effective laser–material interaction by increasing reflectivity and acting as diffusion barriers. This may lead to incomplete melting, lack-of-fusion defects, and reduced interlayer bonding. Consequently, parts fabricated from powders with elevated oxygen levels often exhibit inferior mechanical properties, including reduced tensile strength and ductility.

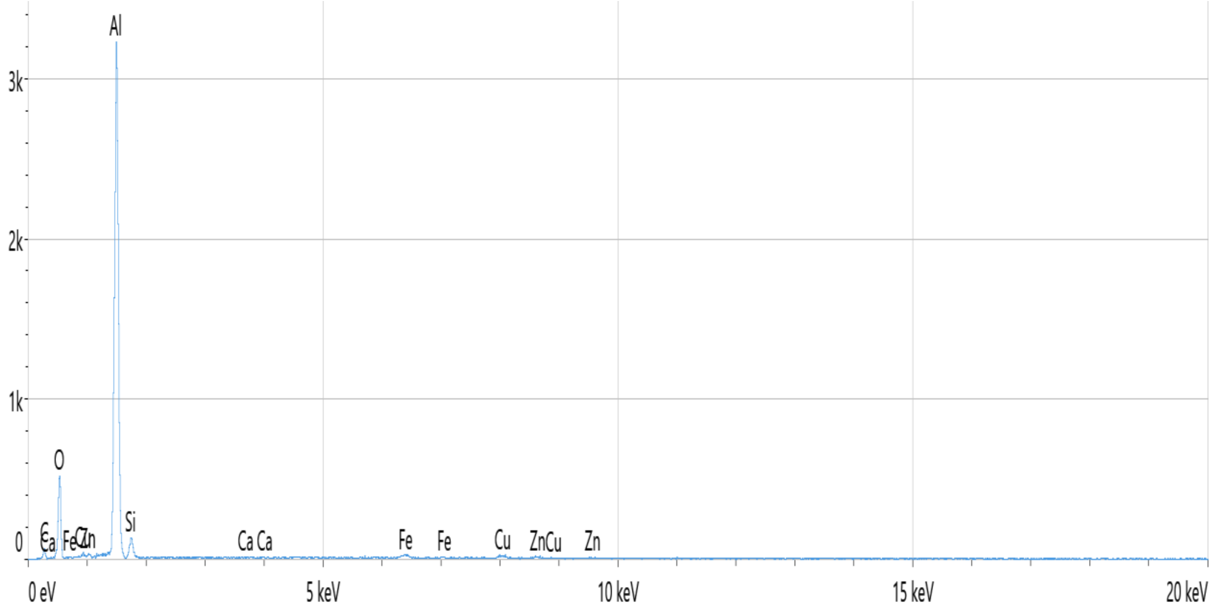

Figure 7: Corresponding EDX spectrum for region 1

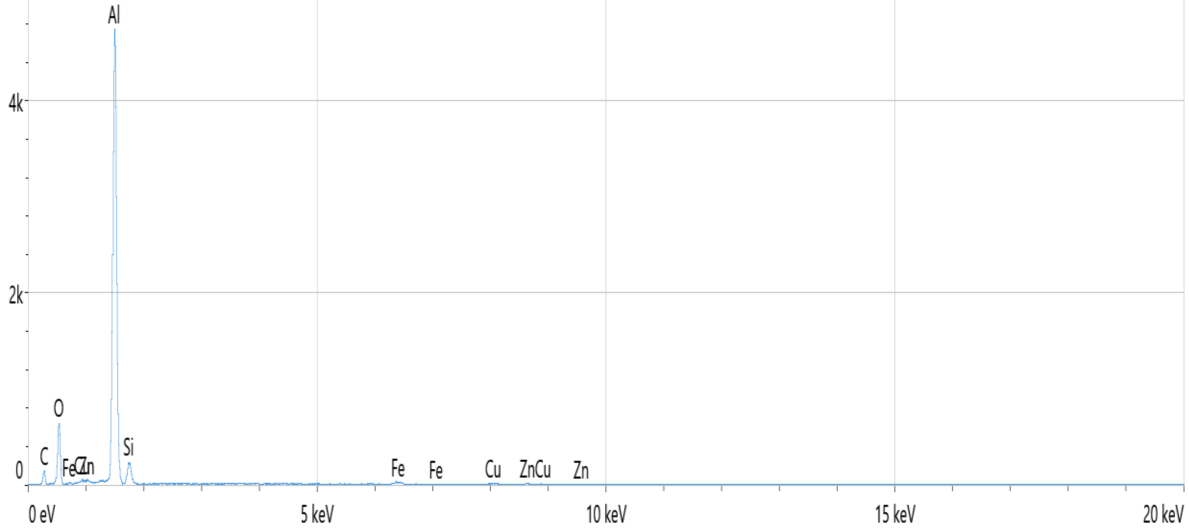

Figure 8: Corresponding EDX spectrum for region 2

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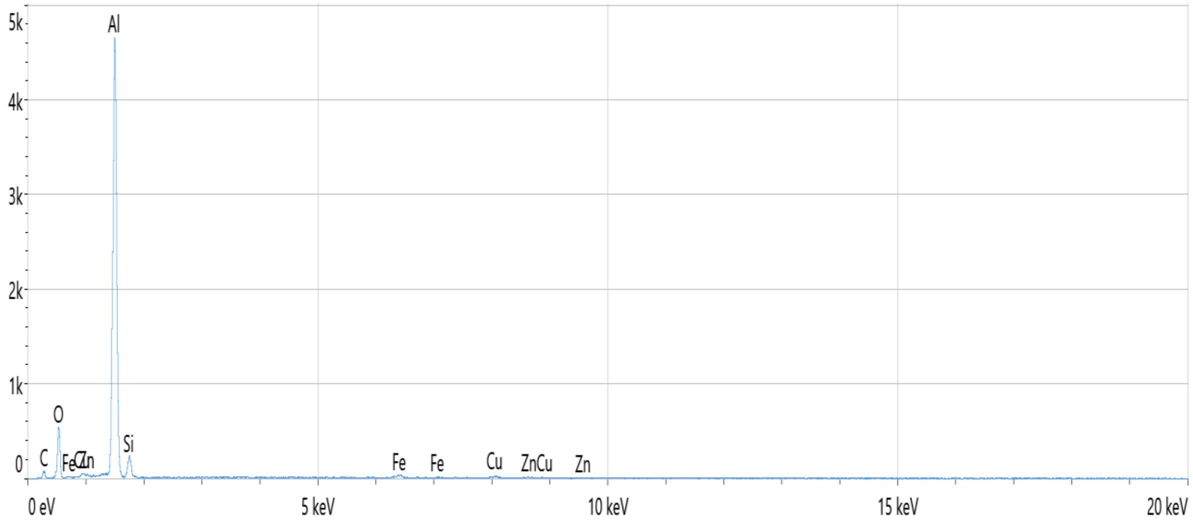

Figure 9: Corresponding EDX spectrum for region 3

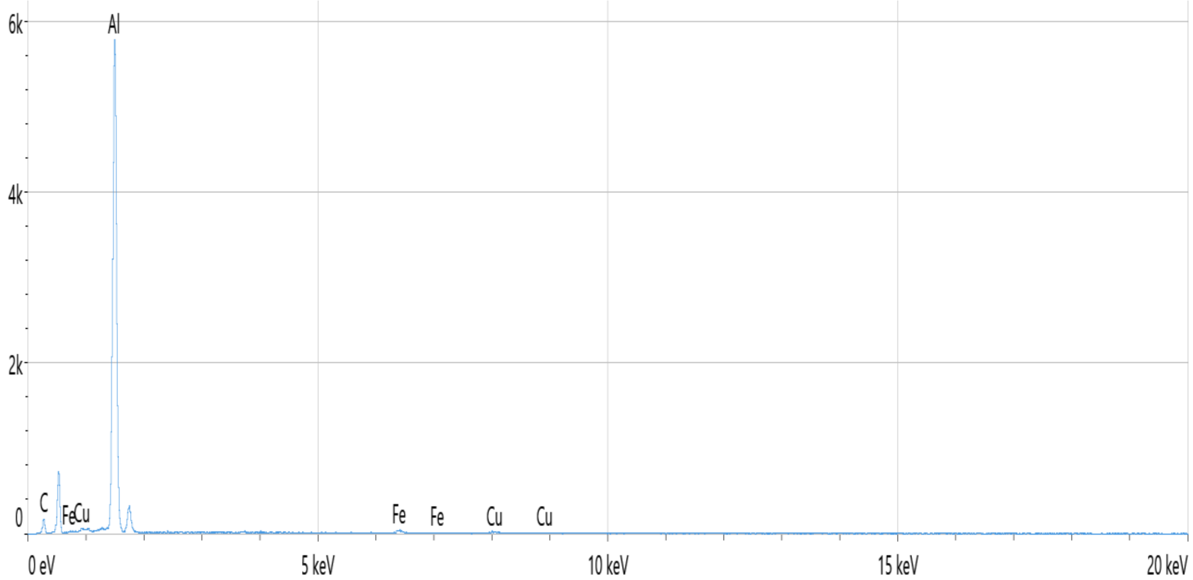

Figure 10: Corresponding EDX spectrum for region 1

3.3 X-ray Fluorescence (XRF) Analysis

The X-ray Fluorescence (XRF) analysis results obtained from the water-atomized aluminum powder provide valuable information about the elemental composition of the sample.

Aluminum, been the primary component of the powder, making up 80.63% of the total composition, indicating a high purity level of aluminum in the sample. Silicon (Si) at 7.055%, this is the second most abundant element in the powder. Iron (Fe) constitutes 3.790% of the sample. Copper (Cu) was detected at 5.089%, a significant amount for an aluminum alloy. Zinc (Zn) comprises 2.269% of the powder. Other Elements: Titanium (Ti), Chromium (Cr), Manganese (Mn), Nickel (Ni), and Lead (Pb) are present in smaller quantities ranging from 0.05148% for Ti to 0.1265% for Pb. The Lead (Pb) content, although small, is notable because its presence in aluminum alloys can have both beneficial effects on machinability and potential health/environmental concerns [29].In summary, the XRF analysis indicates that the aluminum powder is not pure aluminum but an alloy containing several other elements, which could be designed for specific industrial applications.

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Table 7: Concentrations of various elements in the water-atomized aluminum powder.

Z	Formula	Compound	Concentration	Evaluation Mode	LLD (PPM)
1	Ti	Titanium	0.05418	Stdless	6.66 PPM
2	Cr	Chromium	0.09372	Stdless	5.59 PPM
3	Mn	Manganese	0.4702	Stdless	5.81 PPM
4	Fe	Iron	3.790	Stdless	6.06 PPM
5	Ni	Nickel	0.1107	Stdless	5.17 PPM
6	Cu	Copper	5.089	Stdless	5.78 PPM
7	Zn	Zinc	2.269	Stdless	1.52 PPM
8	Pb	Lead	0.1265	Stdless	2.57PPM
9	Al	Aluminum	80.63	Stdless	521 PPM
10	Si	Silicon	7.055	Stdless	193 PPM
11	P	Phosphorus	0.135	Stdless	61.5 PPM
12	Ca	Calcium	0.1737	Stdless	11.3 PPM

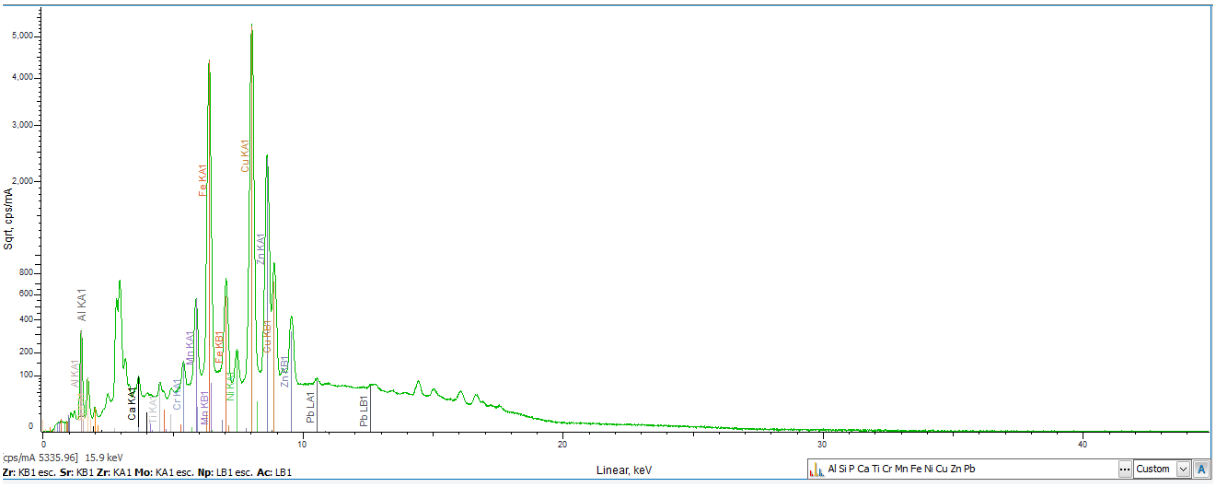

Figure 11: Spectrum from X-ray fluorescence analysis

The graph provided is the spectrum from an X-ray fluorescence (XRF) analysis. The horizontal axis (X-Axis): This axis represents the energy of the detected X-rays measured in kiloelectronvolts (keV). Each peak corresponds to X-rays of a specific energy that are characteristic of an element. The vertical axis (Y-Axis) shows the counts per second (cps), which is a measure of the intensity of the detected X-rays. Higher peaks indicate a greater concentration of the corresponding element in the sample.

Each peak is labeled with an element's symbol and a line series label (Kα, Kβ, Lα, Lβ, etc.), which refers to the specific electronic transition in the atom that emitted the X-ray. For instance, "K" lines are emitted when an electron transitions to the K shell (the closest shell to the nucleus), with "Kα" being the result of a transition from the L shell to the K shell, and "Kβ" from the M to the K shell. The tall peaks at around 1.5 keV and 1.7 keV are labeled as "Al Kα1" and "Al Kβ1," respectively, indicating the presence of aluminum (Al), which is the primary element in the sample, given that it's an "Al powder" sample.

3.4 Comparison of Aluminum Powder Production Methods for Laser-Based Additive Manufacturing

Laser-based additive manufacturing processes, particularly Laser Powder Bed Fusion (LPBF), require metallic powders with stringent specifications in terms of particle size distribution, morphology, flowability, and chemical purity. Several powder production techniques have been developed to meet these requirements, each with inherent advantages and limitations. Gas atomization is the most widely used method for producing aluminum powders for LPBF. It employs high-pressure inert gases (argon or nitrogen) to disintegrate molten metal, producing highly spherical powders with excellent flowability and low oxygen content. These characteristics make

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gas-atomized powders ideal for LPBF; however, the process is energy-intensive and costly, limiting its sustainability and economic accessibility, particularly when virgin feedstock is used. Plasma atomization produces powders with even higher sphericity and purity by melting metal wire using plasma torches. While this method yields superior powder quality, its high operational cost and reliance on refined feedstock restrict large-scale adoption. Centrifugal atomization (e.g., rotating electrode process) generates relatively spherical powders with low contamination levels. However, its production rate is low, and it is unsuitable for recycling-based feedstock, making it less attractive for sustainable manufacturing. Mechanical alloying and milling can produce fine powders but typically result in highly irregular particle shapes, poor flowability, and contamination from milling media. These powders generally require extensive post-processing and are rarely used directly in LPBF. Water atomization, as investigated in this study, offers a cost-effective and environmentally favorable alternative. It enables the direct use of recycled aluminum scrap and significantly reduces energy consumption compared to gas-based methods. However, rapid quenching in water leads to irregular particle morphology and elevated oxygen content, which limit direct applicability in LPBF without post-processing. Despite these drawbacks, water atomization plays an important role in sustainable powder supply chains and is increasingly explored for non-powder-bed AM processes or as a precursor for further powder refinement. These observations align with recent reviews by Yu et al. [30] and Essien and Vaudreuil [31], which emphasize the critical relationship between powder production routes, microstructure, and performance in laser-based additive manufacturing.

Table 8. Comparison of aluminum powder production methods

Powder	Particle	Oxygen	Cost	Sustainability	Suitability for
Gas	Highly	Low	High	Moderate	Excellent
Plasma	Near-perfect	Very low	Very high	Low	Excellent
Centrifugal	Spherical	Low	High	Low	Good
Mechanical	Highly	High	Low–	Low	Poor
Water	Irregular	High	Low	High	Limited

3.5 Mechanical Behavior of LPBF Aluminum Alloys Produced Using Spherical Powders

The mechanical performance of aluminum alloys fabricated via Laser Powder Bed Fusion (LPBF) is strongly influenced by powder morphology, particularly sphericity and chemical homogeneity. Spherically shaped powders, typically produced by gas or plasma atomization, exhibit superior flowability, packing density, and laser–powder interaction, leading to improved part density and mechanical integrity. Recent studies by Igwe et al.[32] have provided comprehensive insights into the mechanical, surface, corrosion, and failure behavior of LPBF-fabricated AlSi10Mg alloys produced using spherical powders. Igwe et al.[33] demonstrated that optimized LPBF process parameters significantly enhance surface quality and reduce defect formation in as-built AlSi10Mg components, directly influencing mechanical performance and fatigue resistance. Further investigations into machinability revealed that spherical powders contribute to uniform microstructures and predictable cutting responses, enabling improved post-processing efficiency[34]. In addition, corrosion studies conducted by Igwe et al.[34] showed that LPBF process parameters and powder quality critically affect corrosion resistance in chloride environments, with dense microstructures and minimal porosity yielding superior performance. Failure mode analyses further confirmed that spherical powder-derived components exhibit enhanced load-bearing capacity and reduced crack initiation sites compared to components fabricated from irregular powders. These findings collectively establish spherical powder morphology as a benchmark for high-performance LPBF aluminum alloys. In contrast, water-atomized powders, such as those investigated in the present study, typically exhibit irregular morphology and higher oxygen content, which limit direct LPBF application. However, understanding the mechanical advantages associated with spherical powders provides a valuable reference framework for evaluating the performance gaps and identifying necessary post-processing strategies such as spheroidization or surface modification to enable sustainable recycled powders to approach LPBF-grade material performance[35].

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3.6 Comparison of Gas Atomized and Water Atomized Aluminum Powders

Metallic powder production for additive manufacturing commonly employs gas atomization, which generates powders with characteristics that are often considered ideal for laser-based processes such as Laser Powder Bed Fusion (LPBF). In gas atomization, a stream of molten metal is disintegrated by high-velocity inert gases (e.g., argon, nitrogen), resulting in rapid cooling and high sphericity. Studies by Frazier, [36] and DebRoy et al.[37] report that gas-atomized aluminum powders typically exhibit spherical morphology**,** narrow particle size distributions**,** and low oxygen content, which contribute to excellent powder flowability and layer packing efficiency in additive manufacturing processes. For example, Sun et al.[38] demonstrated that gas-atomized AlSi10Mg powders exhibited a relatively tight particle size distribution (15–45 µm) with high sphericity and minimal satellites, which directly improved powder spreadability and reduced porosity in LPBF samples.[3] Similarly, Gorsse et al. [39] highlighted that the lower oxygen content and homogeneous particle structure of gas-atomized powders positively influence mechanical performance in additive manufacturing parts. In contrast, water atomization, as investigated in the present study, employs high-pressure water jets to fragment molten metal. While water atomization offers process speed, lower cost, and the ability to use recycled feedstock, it typically results in irregular particle shapes and higher oxygen contents due to rapid quenching and interactions with water.

Table 9. Comparison of gas atomized and water atomized aluminum powders

Feature	Gas Atomization	Water Atomization
Particle Morphology	Highly spherical	Irregular, angular
Particle Size Distribution	Narrow, controlled	Broader range
Oxygen Content	Low	Higher (due to water interaction)
Flowability	Excellent	Limited, often poor
Suitability for AM (LPBF)	Direct use	Requires post-processing
Cost	Higher per unit mass	Lower, especially with recycled feedstock
Environmental Impact	Moderate to high energy use	Lower energy, supports recycling

CONCLUSION

This study investigated the production and characterization of aluminum powder derived from industrial aluminum scrap using the water atomization technique, with the aim of evaluating its potential as a sustainable feedstock for additive manufacturing. The results demonstrate that water atomization is a feasible method for converting recycled aluminum scrap into fine powders, producing particle sizes predominantly within the range of 20–100 µm. However, the powders exhibited irregular morphology and relatively high oxygen content, characteristics inherent to the rapid quenching and water–metal interactions associated with this process. Elemental analyses using EDX and XRF confirmed aluminum as the major constituent of the powder, with an average concentration of 80.63%, alongside detectable amounts of silicon, copper, iron, zinc, and trace impurities. While some of these elements may be beneficial for certain aluminum alloy systems, their variability and elevated oxygen levels are likely to influence powder flowability, laser–powder interaction, and sintering behavior, thereby limiting the direct suitability of the powders for laser powder bed fusion without further processing.

Compared to conventional gas-atomized powders, which are widely used in additive manufacturing due to their high sphericity and low oxygen content, water-atomized powders offer advantages in terms of lower production cost, reduced energy consumption, and the ability to utilize recycled feedstock. This highlights a trade-off between powder quality and sustainability that is critical for the development of environmentally responsible additive manufacturing supply chains. From an industrial perspective, water atomization presents a scalable and cost-effective route for converting aluminum scrap into powder feedstock, particularly for applications where ultra-high powder sphericity is not strictly required or where post-processing steps can be economically justified. Such applications may include non–powder-bed additive manufacturing processes, hybrid manufacturing routes, or secondary powder refinement workflows. Overall, this work provides a foundational understanding of the characteristics of water-atomized aluminum powders produced from

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recycled scrap. The findings underscore the need for future studies focusing on powder refinement techniques—such as spheroidization, oxygen reduction, and detailed particle size analysis as well as mechanical performance evaluation of additively manufactured components. These efforts are essential for bridging the gap between sustainable powder production and the stringent material requirements of advanced additive manufacturing applications.

REFERENCES

[1] Ingarao, G. Priarone, P. C. Deng, Y. and Paraskevas, D. "Environmental modelling of aluminum based components manufacturing routes: Additive manufacturing versus machining versus forming," *Journal of Cleaner Production*, 176, p. 261–275, 2018.http://doi.org/10.1016/j.jclepro.2017.12.115

[2] Srivastava, M. and Rathee, S. "Additive manufacturing: Recent trends, applications and future outlooks," *Progress in Additive Manufacturing*, 7 (2), p. 261–287, 2022.http://doi.org/10.1007/s40964-021-00219-8

[3] Kumawat, Y. K. Sehgal, R. Ayoub, L. Sehgal, R. and Kumar, V. "Recent Progress in the Development of Metallic Composite for Advance Technologies," Nanoparticles Reinforced Metal Nanocomposites: *Mechanical Performance and Durability*, p. 53–87, 2023.https://doi.org/10.1007/978-981-19-9729-7_3

[4] Gopal, M. Lemu, H. G. and Gutema, E. M. "Sustainable Additive Manufacturing and Environmental Implications: Literature Review," *Sustainability*, 15 (1), p. 504, 2022.http://doi.org/10.3390/su15010504

[5] Ghio, E. and Cerri, E. "Additive Manufacturing of AlSi10Mg and Ti6Al4V lightweight alloys via Laser Powder Bed Fusion: A review of heat treatments effects," *Materials*, 15 (6), p. 2047, 2022.http://doi.org/10.3390/ma15062047

[6] Nagaraju, S. B. Priya, H. C. Girijappa, Y. G. T. and Puttegowda, M. "Lightweight and sustainable materials for aerospace applications," *Lightweight and Sustainable Composite Materials*, p. 157–178, 2023. https://doi.org/10.1016/b978-0-323-95189-0.00007-x

[7] Alo, O. A. Otunniyi, I. O. and Mauchline, D. "Effects of reuse on morphology, size and shape distributions of PA 12 powder in selective laser sintering and quality of printed parts," *Journal of Polymer Research*, 30 (2), p. 48, 2023.https://doi.org/10.1007/s10965-022-03423-6

[8] Pletzer-Zelgert, L. P. and Traverso, M. "Development of a Comparative Assessment Method for Additive and Conventional Manufacturing with Regard to Global Warming Potential," *Gottfried Wilhelm Leibniz Universität Hannover*, 2023.

[9] de Mattos Nascimento, D. L. Nepomuceno, R. M. Caiado, R. G. G. Maqueira, J. M. Moyano-Fuentes, J. and Garza-Reyes, J. A. "A sustainable circular 3D printing model for recycling metal scrap in the automotive industry," *Journal of Manufacturing Technology Management*, 33 (5), p. 876–892, 2022.http://doi.org/10.1108/JMTM-12-2020-0460

[10] Yang, M. Keshavarz, M. K. Vlasea, M. Molavi-Kakhki, A. and Laher, M. "Supersolidus liquid phase sintering of water-atomized low-alloy steel in binder jetting additive manufacturing," *Heliyon*, 9 (3),2023.https://doi.org/10.1016/j.heliyon.2023.e13882

[11] Brika, S. E. Letenneur, M. Dion, C. A. and Brailovski, V. "Influence of particle morphology and size distribution on the powder flowability and laser powder bed fusion manufacturability of Ti-6Al-4V alloy," *Additive Manufacturing*, 31, p. 100929,2020.http://doi.org/10.1016/j.addma.2019.100929

[12] Persson, F. "A Study of Parameters and Properties Influencing the Size, Morphology and Oxygen Content of Water Atomized Metal Powders," *Doctoral dissertation*, *KTH Royal Institute of Technology*, 2021.

[13] Mandal, S. Sadeghianjahromi, A. and Wang, C. C. "Experimental and numerical investigations on molten metal atomization techniques–A critical review," *Advanced Powder Technology*, 33 (11), p. 103809, 2022.http://doi.org/10.1016/j.apt.2022.103809

[14] Powell, D. Rennie, A. E. Geekie, L. and Burns, N. "Understanding powder degradation in metal additive manufacturing to allow the upcycling of recycled powders," *Journal of Cleaner Production*,

https://dx.doi.org/10.4314/njt.v45i2.1

268, p. 122077, 2020.http://doi.org/10.1016/j.jclepro.2020.122077

[15] Javaid, M. Haleem, A. Singh, R. P. Khan, S. and Suman, R. "Sustainability 4.0 and its applications in the field of manufacturing," *Internet of Things and Cyber-Physical Systems*, 2, p. 82–90, 2022.http://doi.org/10.1016/j.iotcps.2022.02.001

[16] Moghimian, P. Poirié, T. Habibnejad-Korayem, M. Zavala, J. A. Kroeger, J. Marion, F. and Larouche, F. "Metal powders in additive manufacturing: A review on reusability and recyclability of common titanium, nickel and aluminum alloys," *Additive Manufacturing*, 43, p. 102017,2021.http://doi.org/10.1016/j.addma.2021.10201

[17] Tong, C. and Tong, C. "Materials-based solutions to advanced energy systems," *Introduction to Materials for Advanced Energy Systems*, p. 1–86, 2019.https://doi.org/10.1007/978-3-319-98002-7_1

[18] Bag, S. and Pretorius, J. H. C. "Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework," *International Journal of Organizational Analysis*, 30 (4), p. 864–898, 2022.https://doi.org/10.1108/ijoa-04-2020-2120

[19] Khan, A. Khan, M. S. Hadi, F. Saddiq, G. and Khan, A. N. "Energy-Dispersive X-ray (EDX) fluorescence-based analysis of heavy metals in marble powder, paddy soil and rice (Oryza sativa L.) with potential health risks in District Malakand, Khyber Pakhtunkhwa, Pakistan," *Environmental Pollutants and Bioavailability*, 33 (1), p. 301–316, 2021. https://doi.org/10.1080/26395940.2021.1986427

[20] Yenwiset, S. and Yenwiset, T. "Design and construction of water atomizer for making metal powder," *Journal of Metals, Materials and Minerals*, 21 (1), 2011.https://doi.org/10.4186/ej.2016.20.1.187

[21] Kordijazi, A. Weiss, D. Das, S. Behera, S. Roshan, H. M. and Rohatgi, P. "Effect of solidification time on microstructure, wettability, and corrosion properties of A205-T7 aluminum alloys," *International Journal of Metal casting*, 15, p. 2–12, 2021.https://doi.org/10.1007/s40962-020-00457-8

[22] Tiwari, M. K. "Elemental Analysis Using Synchrotron Radiation X-Ray Fluorescence," *X-Ray Fluorescence in Biological Sciences: Principles, Instrumentation, and Applications*, p. 115–149,2022. https://doi.org/10.1002/9781119645719.ch8

[23] Goudar, D. M. Srivastava, V. C. and Rudrakshi, G. B. "Effect of atomization parameters on size and morphology of Al-17Si alloy powder produced by free fall atomizer," *Engineering Journal*, 21 (1), p. 155–168, 2017.http://doi.org/10.4186/ej.2017.21.1.155

[24] Schade, C. and Dunkley, J. J. "Atomization, "In *Powder Metallurgy* (pp. 58-71). ASM International. 2015.https://doi.org/10.1179/pom.1986.29.1.1

[25] Li, X. G. Zhu, Q. Shu, S. Fan, J. Z. and Zhang, S. M. "Fine spherical powder production during gas atomization of pressurized melts through melt nozzles with a small inner diameter," *Powder Technology*, 356, p. 759–768,2019.http://doi.org/10.1016/j.powtec.2019.08.063

[26] Kong, L. Lei, W. Wei, Q. Han, J. Suorong, Z. Li, Q. and Liu, Z. "Experimental investigations into the performance of die-sinking mixed-gas atomization discharge ablation process on titanium alloy," *Scientific Reports*, 12 (1), p. 2399, 2022.http://doi.org/10.1038/s41598-022-06327-8

[27] Manegin, S. Y. Rozanov, S. D. Gulyaev, I. A. Mezhevov, A. V. and Zhukov, P. O. "Oxidation Process of High-Alloy Steel Powders During Melt Atomization with Water," *Metallurgist*, 66 (1-2), p. 61–70, 2022.https://doi.org/10.1007/s11015-022-01300-7

[28] Zedan, Y. Samuel, A. M. Doty, H. W. Songmene, V. and Samuel, F. H. "Effects of free-cutting elements addition on the microstructure, hardness, and machinability

of Al-11% Si–Cu–Mg casting alloys," *International Journal of Metal Casting*, 16 (4), p. 1915–1931, 2022.https://doi.org/10.1007/s40962-021-00740-2

[29] Peinado, G. Carvalho, C. Jardini, A. Souza, E. Avila, J. A. and Baptista, C. "Microstructural and mechanical characterization of additively manufactured parts of maraging 18Ni300M steel with water and gas atomized powders feedstock," 2023. https://doi.org/10.1007/s00170-023-12686-2

[30] Yu, W. H. Sing, S. L. Chua, C. K. Kuo, C. N. and Tian, X. L. "Particle-reinforced metal matrix nanocomposites fabricated by selective laser melting: A state of the art review," *Progress in Materials Science*, 104, p. 330–379, 2019.https://doi.org/10.1016/j.pmatsci.2019.04.006

[31] Essien, U. and Vaudreuil, S. "Issues in metal matrix composites fabricated by laser powder bed fusion technique: a review," *Advanced Engineering Materials*, 24 (10), p. 2200055, 2022.https://doi.org/10.1002/adem.202200055

[32] Igwe, N. C. Akhrif, I. El Jai, M. and El Fahime, B. "An experimental investigation of the influence of SLM input factors on the as-built AlSi10Mg surface quality," *The International Journal of Advanced Manufacturing Technology*, 136 (2), p. 619–674, 2025.https://doi.org/10.1007/s00170-024-14657-7

[33] Igwe, N. C. Akhrif, I. and El Jai, M. "On the machinability of additively manufactured AlSi10Mg: factorial analysis and multi-objective optimization," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 19 (11), p. 7821–7862, 2025.https://doi.org/10.1007/s12008-025-02353-z

[34] Igwe, N. C. Salim, R. Ech-chihbi, E. Akhrif, I. Jai, M. E. and Hammouti, B. "The influence of laser powder bed fusion process parameters on the corrosion behavior of AlSi10Mg alloy in NaCl solution," *The International Journal of Advanced Manufacturing Technology*, 139 (7), p. 4045–4054, 2025.https://doi.org/10.1007/s00170-025-16153-y

[35] Igwe, N. C. Akhrif, I. and Jai, M. E. "Failure modes analysis and assessment of aluminum-based metallic matrix composites printed with LPBF technology," *The International Journal of Advanced Manufacturing Technology*, p. 1–27, 2025.https://doi.org/10.1007/s00170-025-15722-5

[36] Frazier, W. E. "Metal additive manufacturing: a review," *Journal of Materials Engineering and performance*, 23 (6), p. 1917–1928, 2014.http://doi.org/10.1007/s11665-014-0958-z

[37] DebRoy, T. Wei, H. L. Zuback, J. S. Mukherjee, T. Elmer, J. W. Milewski, J. O. and Zhang, W. "Additive manufacturing of metallic components–process, structure and properties," *Progress in materials science*, 92, p. 112–224, 2018.http://doi.org/10.1016/j.pmatsci.2017.10.001

[38] Sun, P. Fang, Z. Z. Xia, Y. Zhang, Y. and Zhou, C. "A novel method for production of spherical Ti-6Al-4V powder for additive manufacturing," *Powder Technology*, 301, p. 331–335, 2016.http://doi.org/10.1016/j.powtec.2016.06.025

[39] Gorsse, S. Hutchinson, C. Gouné, M. and Banerjee, R. "Additive manufacturing of metals: a brief review of the characteristic microstructures and properties of steels, Ti-6Al-4V and high-entropy alloys," *Science and Technology of advanced Materials*, 18 (1), p. 584–610, 2017.http://doi.org/10.1080/14686996.2017.1361306

https://dx.doi.org/10.4314/njt.v45i2.1