FABRICATION OF METAL POWDER FOR ADDITIVE MANUFACTURING USING ULTRASONIC ATOMIZER

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DECLARATION

I hereby, declare that this manuscript, entitled "Fabrication of metal powder for additive manufacturing using ultrasonic atomizer", is the result of my own work except for quotations and citations, which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or intentional institution.

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ABSTRACTS

Complex geometries and patterns that are challenging or impossible to produce using conventional manufacturing methods can be produced using metal powders. This is due to the fact that layer-by-layer part construction is possible with additive manufacturing technologies, which enhances design flexibility and personalization.

This study investigated the feasibility of using ultrasonic atomization to fabricate Stainless Steel 316L powder for additive manufacturing. The powder was produced using an ultrasonic atomizer and characterized for its physical and flowability properties. The results were compared with commercially available Stainless Steel 316L powder. This study's objective is to assess and contrast these powders' physical properties and flowability. For the Stainless Steel 316L, the particle size distribution analysis showed that the ultrasonic atomized powder had a narrower size distribution and more spherical particles than the commercially available powder. The scanning electron microscopy analysis shows that the ultrasonic atomized powder had a smooth surface and fewer defects than the commercially available powder. The rheometer tests showed that the ultrasonic atomized powder had better flowability and packing characteristics than the commercially available powder. The Carr's index, porosity, tap density, and Hausner ratio measurements also showed that the ultrasonic atomized powder had better flowability and packing characteristics.

By 3Dprinting a typical tensile sample and performing tensile and hardness tests on it, the study evaluated the performance of SS 316L powder on SLM. As a result of the material's mechanical qualities falling within the permissible range, the results demonstrated that it is suitable for usage in projects or goods. This highlights the significance of reliable testing protocols and quality control systems. By modifying processing parameters for various powders, the study's conclusions can assist and enhance the effectiveness of additive manufacturing techniques.

These findings suggest that ultrasonic atomization is a promising technique for producing Stainless Steel 316L powder for additive manufacturing with improved physical and flowability properties. And it also provides valuable insights for optimizing the production process of Stainless Steel 316L metal powder for additive manufacturing applications.

Keywords: SLM, Additive manufacturing, Stainless Steel 316L, characterization, atomization hardness test, printing.

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AM		Additive manufacturing
RP		Rapid prototyping
CAD		Computer Aided Design
SLM		Selective Laser Melting
SEM		Scanning electron microscope
PSD		Particle size distribution
[μm]	Micrometer	[μm]
F	Frequency	[Hz]
A	Amplitude	[m]
T	Temperature	[°C]
C	current	[A]

1.0 INTRODUCTION

1.1 Research background

The manufacturing technology known as additive manufacturing (AM) is a manufacturing process which is specialized on the production of components for industrial or other uses. It is the ability to alter the conventional method of production, as recently employed. In the beginning, it is an alternative that replaced the conventional permitted rapid prototyping (RP) of complicated parts during early design stages. Numerous advantages of Additive Manufacturing components might save production costs since the process creates 3D items out of layers of material, including plastic, concrete, metal and perhaps even human tissue in the future[1]. Additive manufacturing typically involve a computer, 3D modelling software (Computer Aided design) machine hardware, and material layers. A 3D item is created by layering, following the creation of a CAD drawing with the aid of AM machinery that processes the data from the CAD file, successive layers of liquids, powder, filler metal, or other materials may be used. It can be utilized to make a variety of items, from small parts and prototypes to large-scale structures, using a number of materials, including composites, ceramics, metals, and plastics [2]. Additive manufacturing has the potential to revolutionize manufacturing by allowing for more customized, efficient, and sustainable production. It can also be used in various industries, including aerospace, healthcare, and architecture[3, 4]. Research carried out in 2016 and 2017 shows that there was surge in the metal additive manufacturing technologies and sales of equipment. With this, it was predicted that the AM market would grow by 25 to 30% as a result of the benefits it offers[5, 6]. In other to manufacture a component using the conventional or contemporary method, the raw materials is typically machined to produce the finished part with the least wastage not being more than 25% and maximum wastage of not more than 90%. However for the energy use, prices and waste of materials can all be reduced by the use of metal AM technology[7]. Most industrial sub-divisions are affected. For instance, Smartech forecasts that by 2023, the automotive industry's global market for additive manufacturing would bring in 5.3 billion USD and 12.4 billion USD by 2028.

1.2 Problem statement

Metal powder is the raw material for additive manufacturing. In the process of AM, Liquid metal is transformed into droplets via atomization, which cool to generate powder that can be treated further. As a result of recent advancements in powdered metal processes, there is now a desire for powders with finer grains, and powders with a grain size up to (not including) the nanoscale can be produced using atomization techniques[8]. Small particles called satellites adhere to larger particles, which significantly decreases the powder's ability to flow. This happens because within an atomizing chamber, smaller particles more quickly solidify than bigger ones and are transported by turbulent gas flows more readily[9].

When starting to charge raw materials into an induction furnace for gas atomization, it is common to use pure or new materials. This is because facilities that produce powder for AM typically have limited capability to handle scrap materials, largely due to the precise requirements for powder fineness[10]. Some bottlenecks such as large space requirement, limited list of materials, slow material change process, high price of atomizers, and high operating costs are encountered in the fabrication of metal powders for AM using the atomization techniques. To address these issues and yield a better performance and an increase in the AM revenues, the ultrasonic atomizer is introduced. This atomizer is aimed to address these bottlenecks and give a better powder quality. In this work commercially fabricated Stainless steel 316L metal powder was used to benchmark the fabricated ultrasonic atomized Stainless steel 316L metal powder. The fabricated SS 316L was 3Dprinted on the SLM and the printed part was tested for hardness and tensile strength.

1.3 Research motivation

Comparing additive manufacturing using metal powder to traditional production techniques like casting, forging, and machining reveals various advantages. One of the primary motivators is the opportunity to create complex geometries and designs that are difficult or impossible to manufacture using conventional procedures. Additionally, additive manufacturing enables quicker production turnaround times, lower waste output, and better material use. It also makes it possible to produce parts that are both lighter and stronger, which makes it ideal for aerospace and other high-performing applications. The fabrication of unique, low-volume components is also made easier by additive manufacturing, which also offers greater design flexibility. Overall, the creation of unique, high-quality metal parts is made affordable by the use of metal powder in additive manufacturing.

`1.4 Aim and objectives

The aim of this study is to investigate the feasibility of producing Stainless Steel 316L powder using ultrasonic atomization and benchmarking its quality against commercially available Stainless Steel 316L powder. Additionally, the study will evaluate the printability of the produced powder and perform mechanical characterization tests such as hardness and tensile testing to assess the quality of the printed parts. The overall objectives of the research are to:

1. Investigate & optimize the ultrasonic atomization process for stainless steel 316L powder production with desired characteristics.

2. To benchmark the commercially produced Stainless steel 316L powder with the ultrasonic fabricated Stainless steel 316L.
3. To investigate the printability characteristics of the fabricated powder.
4. To test the printed part for hardness and tensile strength

1.5 Thesis structure

This thesis work consist of the following chapters: In chapter 2 some literature review conducted according to some identified research questions and keywords with the possible solutions poised on the fabrication of metal powders using ultrasonic atomization techniques is given, the conducted literature review of several powder fabrication processes available, such as mechanical processes, chemical processes, atomization processes and finally the effect of the several produced powders on SLM printing.

Fabrication and characterization of the stainless steel 316L powder is described in chapter 3, this chapter is divided into three sections. The first section is the description and importance of metal powder usage in additive manufacturing. The second section answers the question "can stainless steel 316L powder be successfully fabricated using ultrasonic atomization?" by showing the fabrication process, input and optimization process parameters. The third section analyzes the quality of the fabricated Stainless Steel 316L powder compared to commercially available powder by using several characterization methods; FT4 powder rheometer, scanning electron microscope, particle size distribution. Chapter four is divided into two phases, first is the printability characteristics of the fabricated stainless steel 316L powder and secondly the mechanical performance of the printed parts produced from the fabricated powder as determined by hardness and tensile tests. Chapter five discusses further on the results and concludes the research also stating the future work.

2.0 LITERATURE REVIEW

2.1 Introduction

Most metallic elements and alloys that can be melted are susceptible to atomization. Fluid dynamics, mass and heat transmission, and physical metallurgy are principally responsible for the fundamental concepts of atomization[11]. Commercially there are three types of atomization[12] vacuum (soluble gas) atomization, which uses centrifugal force to break up molten metal, and two fluid atomization, during which the metal breaks up by impinging on water or gas. While producing a variety of nonferrous alloys, water atomization is most frequently utilized for ferrous compositions. Compared to other atomization techniques, it is less expensive, but there are some restrictions on the purity of the powder, particularly when working with reactive metals and alloys[13]. A gas with high velocity, like nitrogen, air, helium or argon, disrupts the liquid metal during the process known as gas atomization. Atomization is caused by the transfer of kinetic energy from the atomizing material to the metal. [14].

When a molten metal is exposed to a supersaturated gas at high pressure and then suddenly subjected to a vacuum, the gas expands and separates from the solution, causing the molten melt to be atomized, vacuum atomization, a batch manufacturing method used in industry, employs this idea [11, 15, 16]. The rotating electrode method is the main commercial application of centrifugal atomization. Centrifugal force causes the molten metal to be expelled from the bar's edge in droplets. Due to the lack of a molten metal confinement, the powders produced by this method are of a high purity. With about 200ml in size on average, the powders are spherical, satellite-free, and range in size from 50ml to 400ml. In comparison to atomizing water or gases, droplet cooling rates are lower [17, 18]. For ultrasonic atomization a portion of the vibrational energy is absorbed by a liquid film when it is applied to a smooth surface and made to vibrate in a direction perpendicular to the surface. Standing waves are then created from the vibrational energy. These waves, also referred as capillary waves, produce a grid-like pattern in the liquid on the surface with periodically alternating peaks and troughs stretching in both directions. [19, 20].

Table 1. Research questions and keywords

RQ1- Benefits & drawbacks of ultrasonic atomization	RQ2- effects of particle size & morphology	RQ3- effects of the ultrasonic atomization technique on the final properties of powder	RQ4- possible industrial uses for ultrasonic atomization in the manufacture of metal powder

2.2 Research questions

RQ1 - When compared to other atomization techniques, what are the benefits and drawbacks of ultrasonic atomization in the manufacture of metal powder?

High-frequency vibrations are used in the ultrasonic atomization process to separate droplets of a liquid metal stream into powder particles. For the manufacture of metal powder, this procedure has undergone substantial research, and both its benefits and drawbacks have been described in the literature.

Advantages:

- Fine particle size distribution: Ultrasonic atomization can provide metal powders with a high percentage of small particles and a narrow size distribution, which may be advantageous for some applications[21].
- Low oxygen content: Compared to other atomization methods, ultrasonic atomization can create metal powders with a lower oxygen concentration since it takes place in a sealed room filled with inert gas[22].
- Versatility: Unlike other atomization methods, ultrasonic atomization can be used to generate a wide variety of metal powders, even those with high melting points[23].

Limitations:

- Limited production rate: The comparatively slow nature of ultrasonic atomization may prevent it from being scaled up for large-scale production[21].
- Equipment cost: The cost of ultrasonic atomization equipment can be higher than that of other atomization methods, which may prevent its use in some applications[22].
- Limitations on materials: While some materials may be more challenging to atomize with ultrasonic atomization, not all types of metals or alloys may be acceptable[23].

RQ2 - How are measurements of the metal powders' shape and particle size generated affected by the ultrasonic atomization process parameters, such as frequency, amplitude, and liquid flow rate?

The frequency, amplitude, and the ultrasonic atomization procedure's liquid flow rate can have a big impact on the metal powders' particle size and morphology. Some research that looked into these effects are listed below:

- Frequency: The size and the resulting metal powder's particle dispersion can be affected by the frequency of the ultrasonic vibrations. For instance, a study on the ultrasonic atomization process for producing aluminum powders discovered that increasing the frequency from 20 to 40 kHz led to a reduction in average size of particles and a narrower particle size dispersion. Another investigation into the ultrasonic atomization of high-entropy alloy powder discovered that the powder's particle size decreased when the frequency was raised from 20 to 30 kHz[21].

- Amplitude: The metal powder particles' size and shape can be impacted by the ultrasonic vibrations' amplitude, which also affects their size. In a research on the ultrasonic atomization of Ti-6Al-4V, it was found that when the amplitude was increased for alloy powders, the average particle size decreased and the proportion of spherical particles increased. [22].
- Liquid flow rate: This additional variable can have an impact on the size and appearance of the metal powder created by ultrasonic atomization. Increasing the liquid flow rate led to a drop in the average particle size, according to research on the ultrasonic atomization of aluminum powders. In a different investigation into the ultrasonic atomization of Ti-6Al-4V alloy powders, it was discovered that increasing the liquid flow rate caused the percentage of spherical particles to rise. [23].

RQ3 - How does the technique affect the final properties of the powders and can regulated microstructures and compositions of metal powders be produced using ultrasonic atomization?

Metal powders with regulated microstructures and compositions may be created using ultrasonic atomization, and the method itself may have an impact on the powders' ultimate characteristics. The following studies looked into these effects:

- Improved mechanical characteristics may result from powders with regulated microstructures and compositions, according to a research on the ultrasonic atomization of Ti-6Al-4V alloy powders. A second investigation into the ultrasonic atomization of a Cu-Fe-P alloy revealed that the technique could create powders with a predetermined composition and a consistent distribution of the Cu and Fe phases[22].
- Impacts on final qualities: The metal powders' final characteristics may be impacted by the ultrasonic atomization process. For instance, a study on the manufacturing of aluminum powders by ultrasonic atomization indicated that the method may provide powders with a greater surface area and more reactivity than powders created by gas atomization[23]. Compared to powders created by gas atomization, the powders created by ultrasonic atomization of the phase fraction in the Ti-6Al-4V alloy was greater and with better mechanical properties[24].

RQ4 - What possible industrial uses for ultrasonic atomization in the manufacture of metal powder are there, and how effective and efficient is it compared to other manufacturing processes?

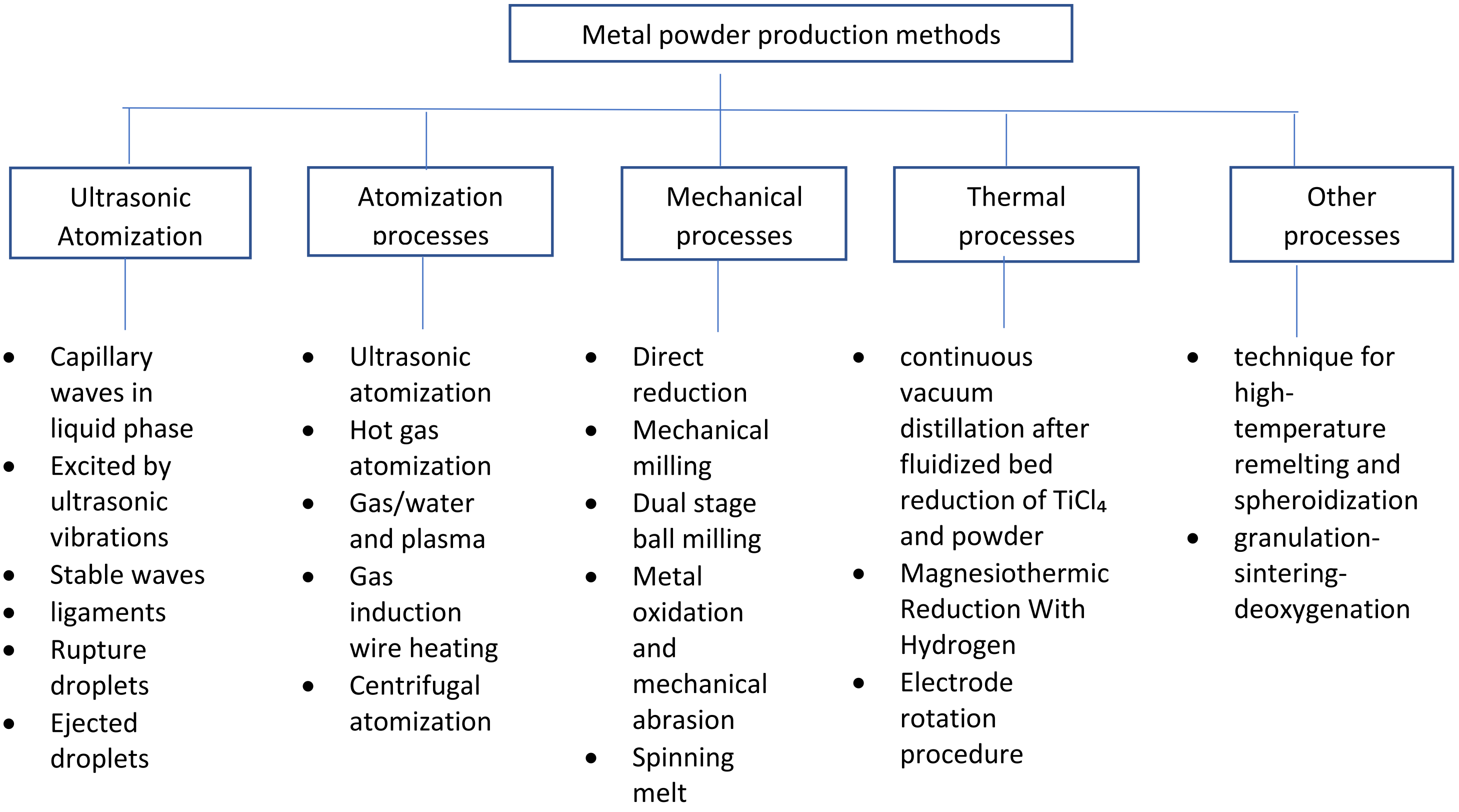
Metal powder production uses ultrasonic atomization and it has a number of potential industrial uses, including surface coating, additive manufacturing, and powder metallurgy. The following studies compared the effectiveness and cost-effectiveness of ultrasonic atomization to other manufacturing techniques:

- A study on the additive manufacture of stainless steel by ultrasonic atomization discovered that the procedure could create high-quality, dense parts with fine microstructures and superior mechanical properties in comparison to those made by conventional powder metallurgy[25]. Another study on titanium additive manufacturing using ultrasonic atomization discovered that the method could create high-quality, near-net-shape parts with a more homogeneous microstructure than parts made using gas atomization[26].
- Powder metallurgy: An investigation on the creation of Ti-6Al-4V alloy powders by ultrasonic atomization discovered that the procedure could produce powders with an increased β phase fraction and enhanced mechanical properties compared to powders synthesized by gas atomization, making it a promising method for powder metallurgy applications[22].
- Surface coating: According to a study on the ultrasonic atomization of nickel and iron powders for surface coating applications, the method can generate coatings with better wear resistance than coatings made by thermal spraying and at a lower cost[27].
- Efficiency and cost-effectiveness: When compared to other production techniques, ultrasonic atomization has been found to be a relatively efficient and cost-effective process for fabricating metal powder. According to research on the ultrasonic atomization of aluminum and magnesium powders, the procedure can generate powders with a greater yield and lower manufacturing cost than gas atomization[23].

2.3 Metal Powder fabrication processes

The manufacturing of metal powder involves a variety of techniques and methods. These processes includes atomization, mechanical, thermal, and others. As can be seen in table 2, various techniques, which are all component of a process, can be used to create metal powders, including ultrasonic, hot gas, water, centrifugal, and plasma atomization. Additionally, solid-state reduction, electrolysis, electrode rotation, melt spinning, metal oxidation, mechanical grinding, and other chemical processes have also been used[28]. Each of these processes produces metal powders with distinctive morphology, shape and size resulting in usually spherical particles with uneven surfaces[29].

Table 2. The several methods of metal powder production



Metal powder production methods

Ultrasonic Atomization	Atomization processes	Mechanical processes	Thermal processes	Other processes
• Capillary waves in liquid phase • Excited by ultrasonic vibrations • Stable waves • ligaments • Rupture droplets • Ejected droplets	• Ultrasonic atomization • Hot gas atomization • Gas/water and plasma • Gas induction wire heating • Centrifugal atomization	• Direct reduction • Mechanical milling • Dual stage ball milling • Metal oxidation and mechanical abrasion • Spinning melt	• continuous vacuum distillation after fluidized bed reduction of $TiCl_4$ and powder • Magnesiothermic Reduction With Hydrogen • Electrode rotation procedure	• technique for high-temperature remelting and spheroidization • granulation-sintering-deoxygenation

2.4 Mechanical processes

One method of producing metal powder for additive manufacturing is called reduction. This method involves reducing a metal compound, a metal salt or metal oxide, to the pure metal form using a reducing agent. This can be done through various methods such as chemical reduction, electro-reduction, and thermal reduction. One example of a chemical reduction method is the hydrogen reduction of metal oxides. This process involves heating the metal oxide with hydrogen gas, which reduces the oxide to the pure metal. A common example of this process is the production of iron powder from iron oxide[30]. Another example is electro-reduction, in which when a metal liquid sample is subjected to an electric current, the metal ions become reduced to the metallic form and deposited as a powder. Thermal reduction is a process in which a metal compound is heated having a reducing agent present, causing the metal to be reduced to the metallic form[31, 32]. The solid reduction method is a process used in additive manufacturing to produce metal powder. The method involves the use of a metal wire or foil, which is heated and fed through a nozzle to create a metal-molten stream. Then, this stream is directed toward a cooled surface, where it solidifies into small droplets or powders. The powders are then collected and can be used for additive manufacturing processes such as 3D printing[33-35]. Crushed metal ore is combined with another substance, typically carbon, after being crushed. The finished mixture is then heated to produce a reaction that lowers the amount of carbon and oxygen in the powder. The metal mixture resembles a less delectable sponge cake as a consequence of the decrease in carbon and oxygen. To get rid of non-metal particles, the “sponge” is crushed and filtered. The fact that the finished particles are still sponge-like is advantageous because it implies that they compress nicely. The previous procedure of solid-state reduction can take up to three days in a kiln to completely convert the iron ore to iron. A desirable finished product requires considerably large purity ore[36]. Copper electroplating can produce significant defects due to contaminants and gases generated during the process. The resulting copper coating may also have poor adhesion and be easily removed. To improve the quality of the coating, annealing can be utilized. Annealing is a cost-effective and simple method that can improve the performance of metal materials by reducing residual stress [37-42]

2.5 Chemical processes

Chemical powder processes, such as the removal of oxides, the formation of precipitates from solutions, and thermal breakdown are commonly used to produce powders with a wide range of properties while maintaining tightly controlled particle size and shape. Oxide-reduced powders have porous structures and are often referred to as "spongy." Solution-precipitated powders can achieve small particle size and high purity. Carbonyls are often processed through thermal degradation to produce particles with over 99.5% purity after milling and heating[43]. Metals may be formed as a spongy or granular substance form by adjusting factors such as the electrolyte composition and concentration, temperature, and current density. However, additional steps such as washing, drying, reduction, annealing, and crushing are often required to produce high-density powders. Electrolysis is primarily used to produce copper powder, but can also be used for iron, chromium, and magnesium. This usually only applied to highly valuable powders, like copper powders with high conductivity, due to the high energy costs involved[43].

2.6 Atomization processes

Metal powders are created using the atomization process for use in additive manufacturing. Atomization entails turning metal into powder by using a spray of either a gas or a liquid, it involves breaking a stream of molten metal to produce small particles of powder form as they cool using high-pressure gases or liquids. This technique is the most important for creating metal powder particles. In order to break up the stream of liquid metal during gas atomization, inert gases such as nitrogen, helium, or argon are typically utilized. Two steps are involved in atomization process: shearing of molten metal occurs at the beginning, and metal droplets rapidly cool at the next stage[28]. The majority of the metal melts in a vast volume, breaking up into small metal droplets. There are several methods of atomization by which metal particles can be produced such as centrifugal atomization, atomization of water, and atomization of gases, Gas atomization involves the use of a high-pressure gas, such as argon, to fragment a jet of liquid metal into smaller droplets. This process is frequently employed to create powders with a restricted size distribution and a high degree of sphericity. Water atomization involves forming droplets out of a stream of liquid metal using a high-pressure water jet. Using this technique frequently will result in larger-size-distributed powders and a lower degree of sphericity. Centrifugal atomization involves using a disk that is rotating quickly to break a stream of droplets formed by molten metal. Powders with a specific size range and a high degree of sphericity are frequently created using this technique. [44-46].

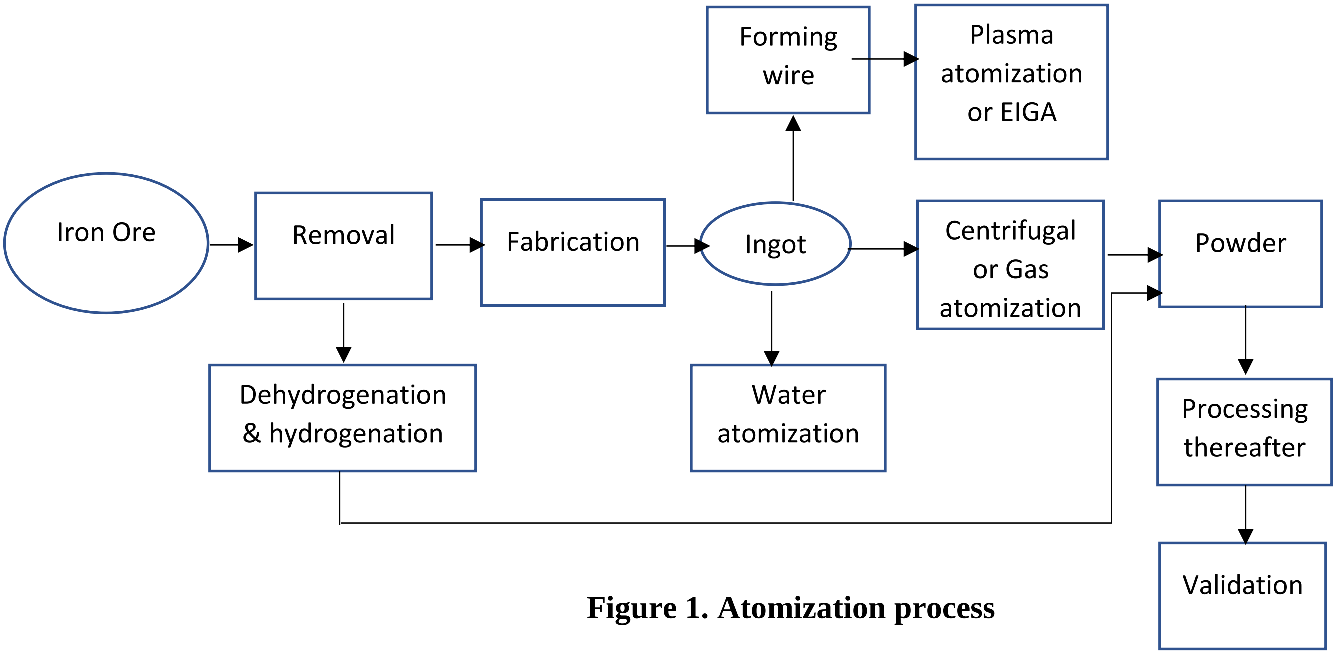


Figure 1. Atomization process

Centrifugal, plasma, or increased gas processes cause shearing of the metal drops at this point. As a result, centrifugal, gas, water, and plasma atomization processes are distinguished in a matching manner. Through the following stages, these droplets' shapes begin to evolve and progress, and spherical droplets begin to become solid, producing the polished powder particles. The process's efficiency and speed are influenced by the melted material surface tension and the heated melt droplets temperature. [28, 47]. Additive manufacturing procedures often use powders that are produced through gas atomization techniques. The main advantage of these powders is that they tend to form spherical particles naturally[48]. Consequently, atomization processes are categorized as centrifugal, gas, plasma melted induction guilding gas atomization (PIGA), water atomization, and electrode induction melting gas atomization (EIGA) as can be seen in fig.1.

2.6.1 Plasma rotating electrode process

A bar with a dimension of 63.5 or 89 mm serves as the starting material working medium in the plasma rotating electron process (PREP). High-speed rotation of the bar (3000–15,000 rpm) causes the end to melt under the influence of a powerful electric combustion arc causing droplets to be expelled off the spinning bar due to centrifugal force. The process can be carried out in a vacuum or an inert environment, because of the slow cooling rates, droplets can assume a spherical shape that prevents them from oxidizing. The gas that is used the most commonly is Helium

2.6.2 Electrode induction melting inert gas atomization

High-quality powder or reactive alloys like titanium, aluminum, and aluminum alloys, refractory alloys (such Zr-, Nb, Ta-alloys), as well as gold powder is frequently made using the EIGA process, which does not involve ceramics. The electrode used in EIGA is a metal disc that is vertically oriented and can have a diameter of up to 150mm. Like the GA process, the metal electrode is delivered into the induction coils while being continuously rotated; there, it melts and the melted stream is atomized [49-51].

2.6.3 Plasma atomization

During the plasma atomization process, a pre-alloyed wire of varying sizes is supplied to a group of non-transferred arc flame burners, where it is melted and pulverized without the use of a crucible. This the GA procedure is comparable, however does not require an induction furnace or tundish. The resulting powder is highly spherical in appearance, having a particle size distribution of roughly 40 μm and a higher percentage of tiny particles than powder produced through the GA process. The plasma arcs' high temperature and rapidity are considered to the reason behind this [52]. The final product made using a different method than GA has less small particles, but some may still be present. This method does not require a container, so the powder is as pure as wire. However, since the powder is finer, it may absorb more oxygen[53].

2.6.4 Water atomization

The method that is most frequently employed to create metal powders is water atomization for commercial application, with a capability of 500kg/min or more. Generally speaking, this technique is employed for ferrous alloys, however it can also work for other types of alloys. Although it is cheaper than other methods, it has limitations in terms of purity, especially when dealing with volatile elements and alloys. Different nozzle designs such as multiple discrete nozzles and an annular slit, as well as nozzle geometries like angular cone and v-shaped jet, are used in water atomization. A popular configuration is the "freefall" method, where liquid metal drops from the bottom of a container and is impacted by water jets[54].

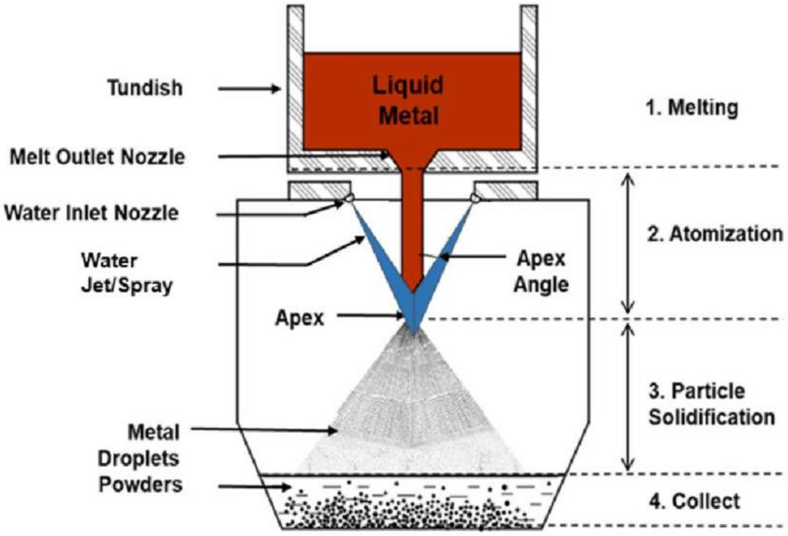


Figure 2. Water atomization process[55]

2.6.5 Gas atomization

Atomizing gas, such as helium, argon, nitrogen, or air, disrupts the flow of liquid metal. The production compared to water-atomized powders that of gas-atomized particles is lower with approximately 300,000 tons per year for air atomization and 50,000 tons per year for nonferrous alloys. Compared to water atomization, the melt's volume and feed rate are smaller, typically less than 120 kg per minute. To atomize gas, nozzles can be designed as "free-fall" or "restricted." The latter, which is primarily used with annular nozzles, improves the process' effectiveness by making the gas' velocity to drop quickly as it exits the jet[56].

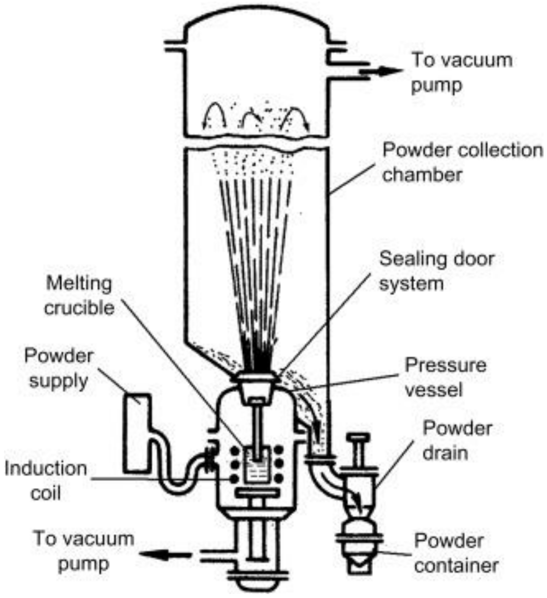


Figure 3. Gas atomization process[57]

2.6.6 Centrifugal atomization

In industry, the primary application of spinning electrode is used in centrifugal atomization. This technique involves the use of a disposable cylinder electrode, which holds the atomizing metal or alloy and has a diameter of 65mm and a length of 1524mm. The electrode is rotated at a high speed, approximately 15000 rpm, and melts at the anode or cathode end.

The molten metal is then expelled from the electrode's wedge through centrifugal force, forming droplets. To prevent contamination from tungsten, the helium gas torch is a transferred arc type. Flame stability and cooling effectiveness are increased by the chamber's helium gas. This method results in powders that are extremely pure and have a median size distribution of 200µm, that are spherical, without satellites, and ranging in size from 50µm to 40µm. The droplet cooling speed is lower than atomizing water or gas, it is less than 100 degree Celsius per second[56].

Table 3. Summary on literatures on atomization processes

Production process	Material	Range of particle size µm	Advantages	Disadvantages	references
Rotating electrode plasma process	Tungsten wire	160-500	More spherical, ultra-clean particles.	Inefficient production at high cost	[58, 59]

Gas atomization	Ti Alloy	0-250	Used for a variety of alloy metals with reactive qualities that are available as ingots, spherical particles.	Broad particle size range.	[60]
Plasma atomization	Ti Alloy	25 - 125	Presence of spherical particles	Expensive wire or powder-based feedstock is required.	[61]
Water atomization	AlSi316L	44-106	Large range of particle sizes, high manufacturing speeds, ingredients in ingot form.	Water, a wide distribution of particle sizes and irregularly shaped particles are all removed by a separate procedure.	[62]
Centrifugal atomization of plasma	HSS, Ti Alloy, 45 steel	0-385	Round particles that are easily manufactured	The distribution of particle size's fractional content is highly diverse.	[63]
Centrifugal Atomization	Magnesium Alloy	50-800	There are many different particle sizes, but the dispersion is limited.	Creating high-quality powder is difficult.	[64]

2.7 Research gap analysis

Reviewing the recent works and studies on the different atomization processes which entails breaking a stream -of molten metal that condense into powder as they cool using high-pressure gases or liquids. After the production of this powders, it is noted that the outcome of their characterization determines how flowable the powder could be depending on several factors. Commercially produced powders by other processes as seen in the literature tends to have the following:

- Unpredictable quality: size, shape, and surface characteristics might vary among metal powders made using various processes or from various sources. The final product's functionality and dependability may be impacted by this.
- Costly to produce: metal powder production can be pricey, especially when high-purity powders are needed for specialized applications.

An analysis of the chemical and physical characteristics of AM powder, as well as bulk characteristics as tap density, compressibility, apparent density, and flow parameters are considered. Commonly, materials for structural and functional purposes are produced using high heavy metal powders without oxide contaminants, with precise particles size. However, because atomized powders (gas, liquid, centrifugal, plasma and ultrasonic) offer a high production rate and homogeneity, powders produced by these methods are used to benchmark the ultrasonic atomized powder. As there are no data about ultrasonic atomization found in literature, this research will advance knowledge of the viability of producing stainless steel 316L powder through ultrasonic atomization and its possible use in additive manufacturing techniques. The findings of this study will be useful for researchers and industry professionals working in the field of materials engineering and additive manufacturing.

3.0 FABRICATION AND CHARACTERIZATION OF SS 316L POWDER

3.1 Metal powders

The raw material for powder metallurgy is tiny particles known as powder with a size less than 1mm. The production of metals and alloys powders is possible by a number of procedures, including centrifugal atomization and atomization (gas and liquid) approaches and ultrasonic atomization, for use in additive manufacturing. For the commercial manufacturing of a variety of ferrous and nonferrous metallic powders, molten metals atomization has emerged as the leading technique. The estimated capacity for the entire world is > 1 x 10^6tyr^{-1}[54]. A rapid rate of production, the capacity to combine with the molten material, and the capacity to exert control over powder features, including size, size distribution and form, are what have caused atomization technology to advance more quickly than other techniques of producing powder. Fine particles of a metal element or alloy, usually smaller than 100 microns, are known as metal powders. They can be made via a number of processes, such as mechanical milling, atomization, and reduction of metal salts. These powders can be used for a variety of things, such as additive manufacturing, powder metallurgy, manufacturing processes, and use as catalyst in chemical reactions. In the production process known as powder metallurgy, metal particles are compressed and heated in order to solidify them. Complex, precise parts for the aviation, automotive, and pharmaceutical applications are frequently produced using this technique. Powder layers are combined using a laser or an electron beam in additive manufacturing, which uses metal powders as the starting material for 3D printing [65]. In a variety of chemical processes, metal particles are also utilized as catalysts. For instance, aluminum powder is utilized as a fuel in rocket engine propellants whereas platinum powder serves as a catalyst in the creation of nitric acid.

3.2 Powder production (ultrasonic atomizer)

Ultrasonic atomization is a method for disintegrating powder particles into finer molecules using ultrasonic waves. This method is beneficial for creating fine powders with narrow size distributions and high surface areas. The process of ultrasonic atomization involves passing metal powders through a high-frequency ultrasonic field, this results in the granules' disintegration into smaller particles. This is typically done using a special device called an ultrasonic atomizer, which generates high-frequency sound waves that are directed at the powders[66]. There are several advantages to using ultrasonic atomization for metal powders. It enables the creation of finer particles with a small size distribution and a large surface area, for instance. Additionally, ultrasonic atomization can be used to create powders with unique morphologies, such as hollow spheres or porous particles. This can be useful for creating materials with specific properties, such as improved conductivity or thermal properties[67]. Ultrasonic atomization also has some potential drawbacks. One limitation is that it can be difficult to regulate the resultant particles' size and shape. Additionally, ultrasonic atomization is typically only effective for powders with a specific range of particle sizes, so it may not be suitable for all types of powders [67-69].

Ultrasonic atomization – the process

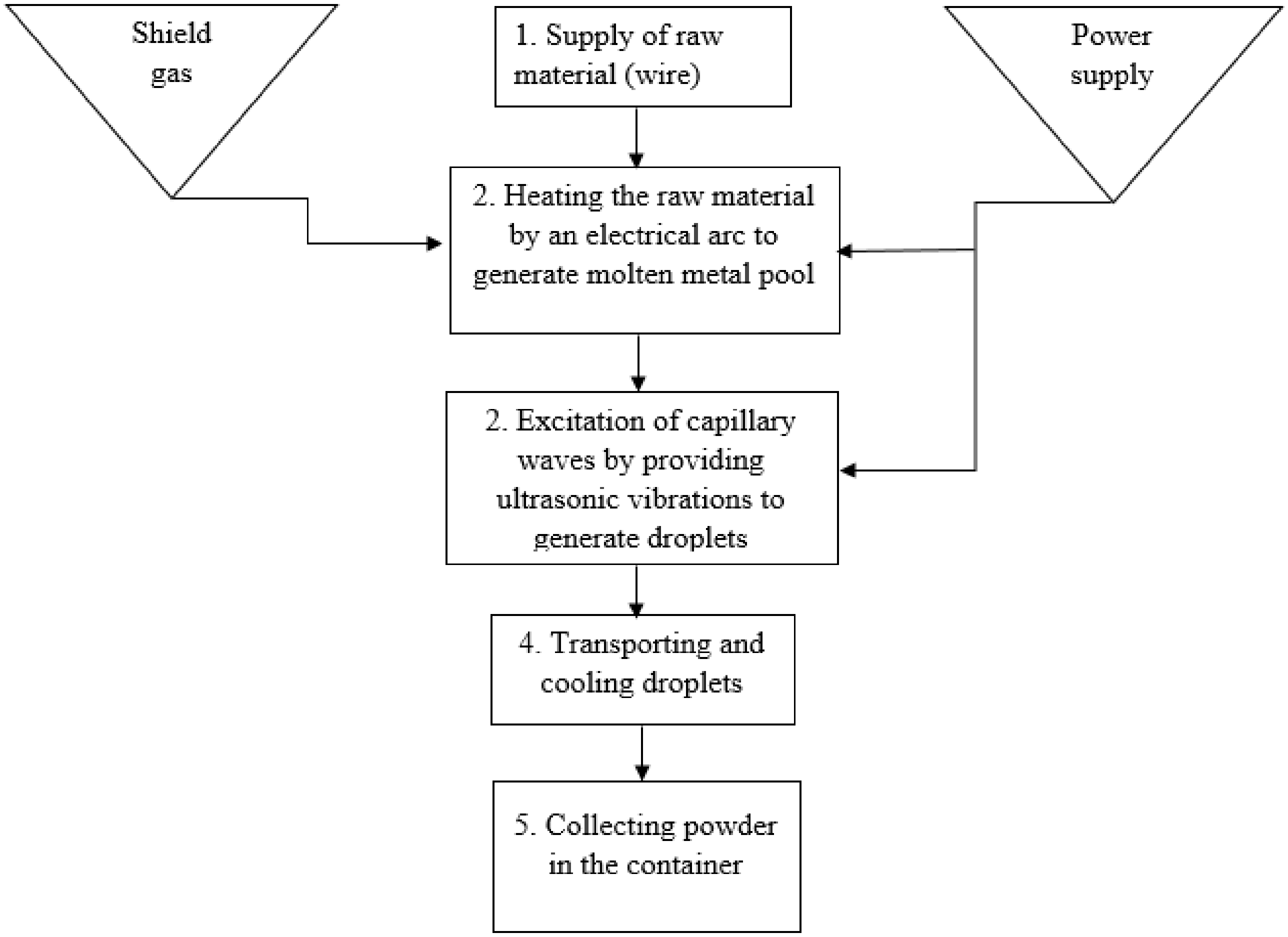


Figure 4.Process through which metal powder is produced

Table 4. Ultrasonic Atomization Fabrication Optimum parameters

Electrical current, A	Ultrasonic vibration amplitude, %	Main circuit pump flow, %	Argon flow, l/min	Feeder speed (%)	Voltage (V)
130	80	65	20	50	22.50

Table 5. Orthogonal Arrays (Taguchi Designs) for the fabrication of steel 316L (Wire Ø 1.2mm)

Experiment Number	Electrical current, A	Ultrasonic vibration amplitude, %	Main circuit pump flow, %	Argon flow, l/min	Feeder speed (%)	Voltage (V)
1	110	70	65	10	25	22.20
2	120	75		15	45	
3	130	80		20	50	

Table 6. Production of Stainless steel 316L at 0°

Exp. no	Time (hr)	Consumption of Argon (bar)	Amount of Powder in powder container (g)	Amount of sieved powder(g) 63µm	Amount of sieved powder(g) 100µm	Productivity Sieved Powder 63 µm (g/hr)	Amount of un-sieved powder (g/hr)
1	19	320	1457.6	1000	134.25	52.63	76.71
2	24	700	2086.4	1400	260.35	58.33	86.93
3	5	150	1100	800	110	160	220
total	48	1170	4644	3200	504.6		

Table 7. Effect of Current and Amplitude on the production of SS 316L

	Current (A)	**Time**	**Constant Parameter**	**Optimization parameter**		
				X	**Y**	**Z**
Effect of Current	120	1hr	120 A			
	130	1hr				
Effect of Amplitude	75%	1hr	80%	10.00	16.00	9.50
	80%	1hr				

3.3 Metal powder characterization

Metal powders characterization is the process of evaluating metal particles' physical and chemical characteristics to understand their behavior and performance in various applications. It is important to characterize metal powders because the performance of the finished product can be significantly impacted by the powder's qualities. For example, a metal powder's distribution, size, and shape of its particles can affect the final product's density, toughness, and surface quality. Additionally, the chemical composition of a metal powder can affect its corrosion resistance, melting point, and other properties [70-72]. Metal powders can be characterized using a variety of methods, such as energy-dispersive X-ray spectroscopy, X-ray diffraction, scanning electron microscopy, transmission electron microscopy, and scanning electron microscopy (EDS).

Figure 5. (a) Ultrasonic atomizer (b) Powder container

These methods allow for the analysis of the powder's chemical makeup as well as its crystal structure, distribution, and size, shape, and size of the particles. Other important properties that can be characterized are tap density, surface area, flow rate, and particle size dispersion. Particle size distribution is a crucial characteristic of metal powders due to the fact that it affects the powder's ability to flow and packing density. It is typically measured using laser diffraction or sieve analysis. Another crucial characteristic of metal powders is their surface area, which influences their reactivity and the speed of chemical surface-level interactions that take place with the particles. It is typically measured using the Brunauer-Emmett-Teller (BET) method. Tap density is a measure of how densely a powder is packed, which affects the flowability and compressibility of the powder. Typically, a powder tester is employed to quantify it. The rate of flow is a gauge of how easily a powder flows through a powder tester, and can be used to predict the powder's flowability.

Metal powders characterization is important because it helps to understand the behavior and performance of metal powders in various applications. On how well the finished product performs, the powder's characteristics can have a big influence. There are many techniques that can be used to characterize metal powders, including XRD, SEM, TEM, EDS, laser diffraction, sieve analysis, BET, powder tester and many more. The powder's physical properties can be altered in a number of ways, with the most of effects coming from powder particles that are either nearby the fuse pool or that are expelled from the weld pool. The following physical characteristics will affect how a metal powder performs in the AM system:

- Shape: a spherical morphology is preferable over an angular or sponge-like one
- Particle size distribution (PSD)
- Flow

PSD and shape have a direct impact on powder flow, which is crucial for accurate layering throughout the bed and silo dosing. If the PSD is too broad or bimodal, the smaller particles will accumulate in the gaps between the bigger particles, causing packing and obstructing movement. A melted part that has inadequate packing and porosity may result from a PSD that is too small. Utilizing the hall funnel method, the study assessed the flow of powder.

3.3.1 Scanning Electron Microscope (SEM)

An imaging device called the scanning electron microscope (SEM) uses an electron beam to produce high-resolution images of surfaces by scanning a concentrated electron beam across a sample. In the context of metal powders, SEM is frequently used to examine the size, shape, and dispersion of particles as well as to analyze the internal structure of particles, such as porosity or voids.

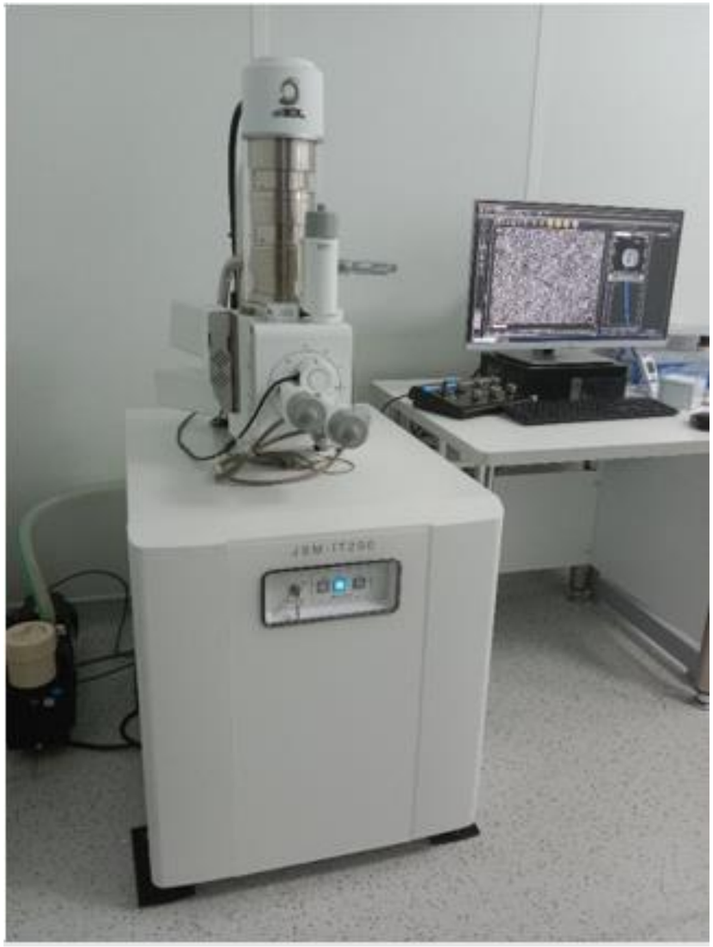


Figure 6.Scanning Electron Microscope JSM-IT200 (LA)

SEM can be combined with energy dispersive x-ray spectroscopy (EDS) to ascertain the particle's composition and identify impurities or contaminants in the powder. SEM can be used to optimize the process conditions of creating metal powders by analyzing the particle size, shape, and distribution. SEM is also used in powder metallurgy to analyze the microstructure of sintered metal parts and identify flaws that may impact the part's mechanical qualities. The particles were examined under a microscope using Scanning Electron Microscope JSM-IT200 (LA) as shown in figure 6. Applications for the electron optics system, which has a 3.0nm resolution and an accelerating voltage of 30kv, range from high-resolution observation to EDS analysis. SEM has long been a key tool for describing the underlying physical characteristics of oxide materials, and it can be used to determine the size distribution and particle form of various silica materials used as a substrate in chemically bonded separation processes for adsorption. SEM can establish surface structure at the micron to sub-micron level [73-76].

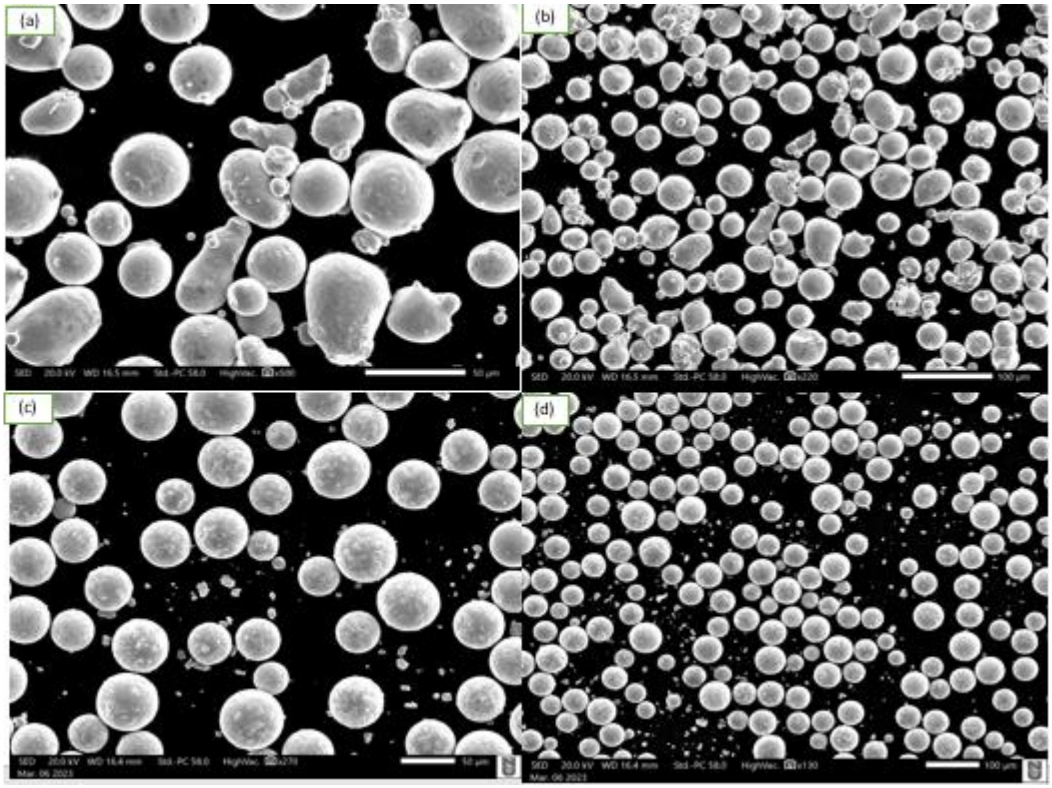
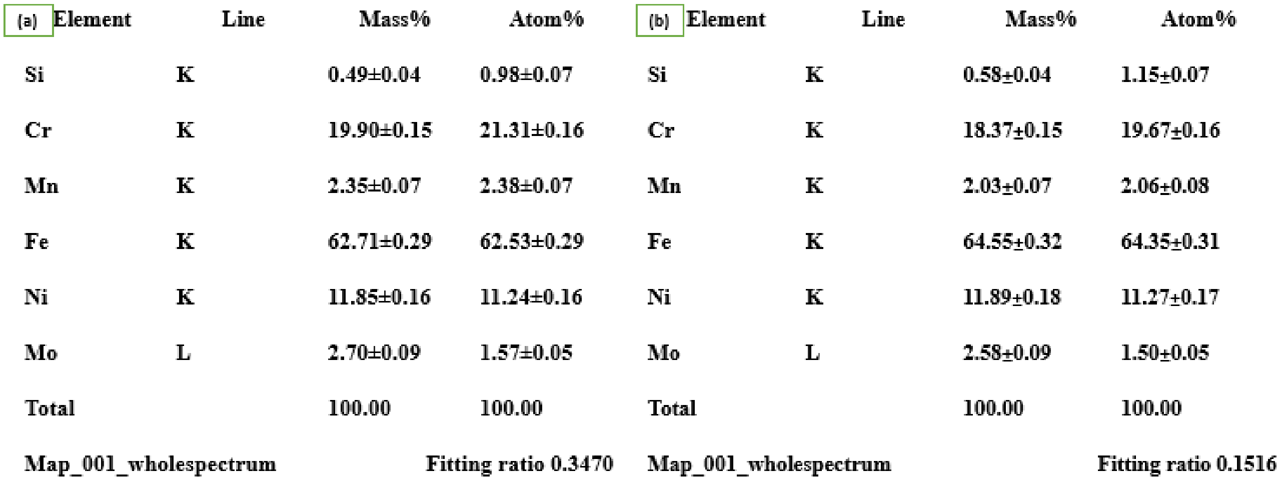


Figure 7. SEM images (a) and (b) commercially produced stainless steel powder at a scale of 50 and 100µm (c) and (d) ultrasonic fabricated stainless steel powder at a scale of 50 and 100µm

Table 8. Chemical composition of (a) Atomized SS 316L (b) commercial SS316L



(a)

Element	Line	Mass%	Atom%
Si	K	0.49±0.04	0.98±0.07
Cr	K	19.90±0.15	21.31±0.16
Mn	K	2.35±0.07	2.38±0.07
Fe	K	62.71±0.29	62.53±0.29
Ni	K	11.85±0.16	11.24±0.16
Mo	L	2.70±0.09	1.57±0.05
Total		100.00	100.00
Map_001_wholespectrum			Fitting ratio 0.3470

(b)

Element	Line	Mass%	Atom%
Si	K	0.58±0.04	1.15±0.07
Cr	K	18.37±0.15	19.67±0.16
Mn	K	2.03±0.07	2.06±0.08
Fe	K	64.55±0.32	64.35±0.31
Ni	K	11.89±0.18	11.27±0.17
Mo	L	2.58±0.09	1.50±0.05
Total		100.00	100.00
Map_001_wholespectrum			Fitting ratio 0.1516

In other to compare the commercially produced stainless steel 316L and the ultrasonic fabricated stainless steel 316L. As can be seen in figure 7, stainless steel 316L is an important material used in various industrial applications. It is a type of austenitic stainless steel that contains molybdenum, which makes it more corrosion-resistant than other types of stainless steel. In this report, we will discuss the analysis of atomized stainless steel 316L metal powder and commercial stainless steel 316L metal powder using Scanning Electron Microscope (SEM) and the impact of their morphology on flowability.

- Analysis:

SEM analysis of atomized stainless steel 316L and commercial stainless steel 316L was performed to check their morphology. The SEM images revealed that the commercial stainless steel 316L particles do not have satellites and are not spherical like atomized stainless steel 316L particles. The satellites on the commercial stainless steel particles are caused by the manufacturing process used to produce them. The atomized stainless steel 316L particles have a smooth surface, which reduces the surface area and enhances the flowability of the material. On the other hand, the commercial stainless steel 316L particles have a rough surface due to the satellites on them, this expands the surface area but decreases the material's capacity to flow.

- Effect on Flowability:

The flowability of a material is a critical factor that determines its performance in various applications. The flowability of stainless steel 316L metal powder is influenced by a number of different factors, including particle size, shape, surface roughness, and energy. The shape of the particles, or morphology, is important in determining the flowability of the material. The spherical shape of the atomized stainless steel particles enhances their flowability by reducing the surface area and minimizing the friction between the particles. In contrast, the asymmetrical form of the commercial stainless steel particles and the satellites on them increase the surface area and create more friction, which reduces the flowability of the material.

The particle size diameter of the images as gotten from SEM was analyzed using the image J software. Figure 8(a) displays the image for the particle diameter measurement and 8(b) shows the area measurement for the particles. The average particles diameters and areas for Stainless steel 316L as gotten from the scanning electron microscope are displayed in Table 8. For the study of powder particles, bar graphs representing particle size and area are crucial tools. Therefore the characterization of the powders information about the size and distribution of powder particles is critical as this information has been provided by these graphs which displays the frequency of the particle of a particular size, with the size of the particles on the x-axis and their frequency on the y-axis.

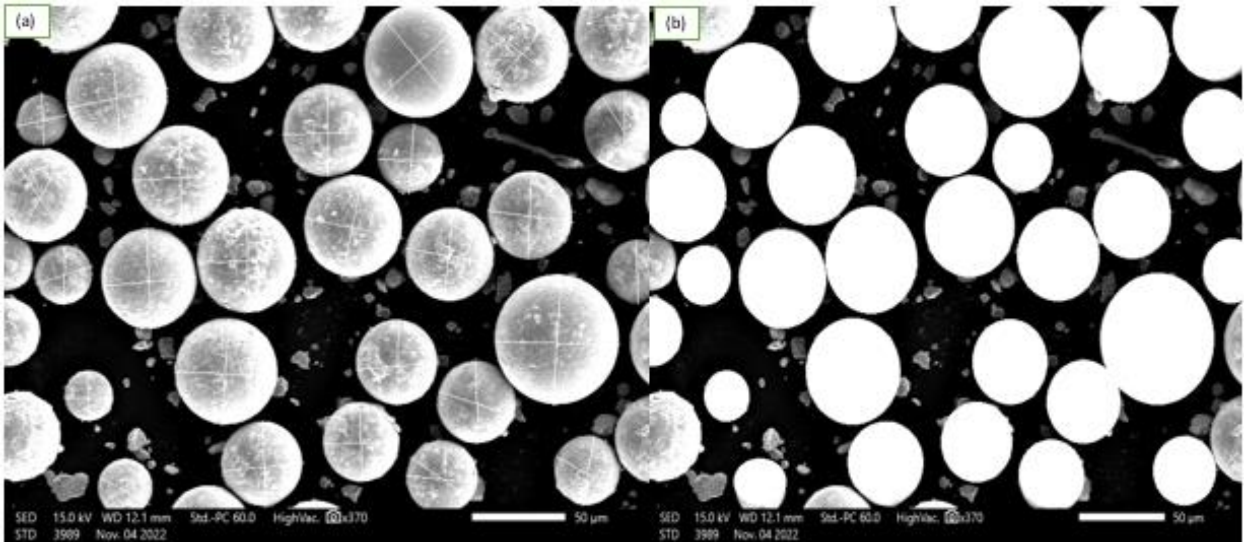


Figure 8. (a) Image J analysis using Origin software (a) diameter measurement, b. area measurement

These graphs provides important details about the characteristics of the powder samples, such as whether or not agglomerates or other anomalies in the size distribution are present. The area bar graphs offer more specific information on the distribution of the particle sizes. It shows the percentage of the entire sample that falls into a certain size range rather than the frequency of the particles of a particular size. This can give more detailed information regarding the distribution of particle sizes, especially when the sample has a wide range of particle sizes.

Table 9. Average particles diameters and areas of Stainless Steel 316L

Powder sample	Average particle diameters (µm)	Average areas (µm)
Commercial steel	29.36	730.37
Ultrasonic fabricated steel	43.82	1609.28

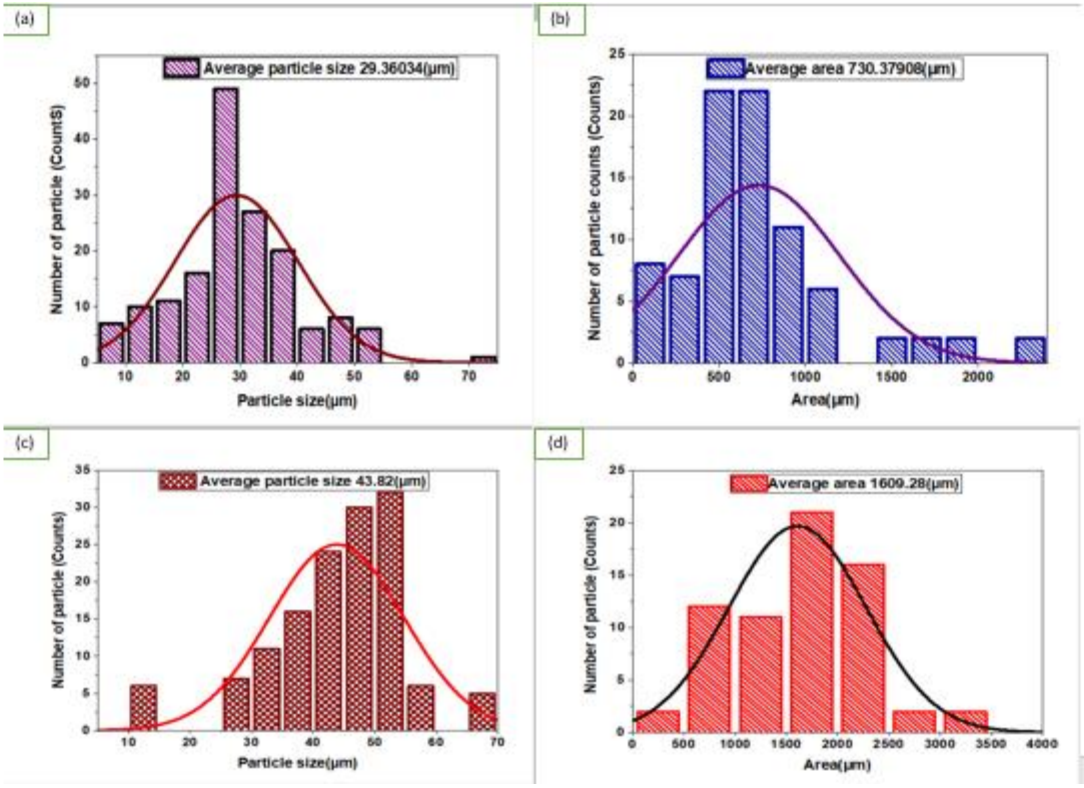


Figure 9. (a) & (b) diameter and area of commercial Stainless steel powder, (c) & (d) diameter and area of ultrasonic fabricated Stainless steel powder.

3.3.2 FT4 powder rheometer

The FT4 powder rheometer is a device that is used to characterize metal powders. It is a type of powder tester that measures the flow properties of powders, such as shear rate, shear stress, and viscosity. Additionally, it can be used to gauge other characteristics like compressibility, bulk density, and permeability. The device as shown in figure 10, consists of a shear cell that can be filled with the powder to be tested. The shear cell is then subjected to a range of shear rates, and the resulting shear stress is measured. This allows for the determination of the powder's flow properties and rheological behavior[77]. The FT4 powder rheometer is employed to research the metal powder industry, the flow characteristics of metal particles, including the internal angle of friction and the apparent viscosity. It is also used to evaluate the metal particles' level of compressibility and the permeability of the powder beds [70, 71]. The FT4 powder rheometer can also be utilized to research how various factors impact the flow properties of the powder, such as temperature, humidity, and the presence of other powders or liquids. This can be useful in the production of metal powders, as it can aid in process optimization and guarantee the manufacture of powders with consistent flow properties [78, 79].

Stability and variable flow are crucial factors in determining the flowability of metal powders. The term "stability" describes a powder's capacity to maintain its flow properties when exposed to different conditions, such as changes in temperature or humidity. Variable flow, also known as thixotropy, relates to a powder's changeable properties. Its flow properties in response to changes in shear rate or stress. Powders with good flow properties will have high levels of stability and low levels of variable flow[77].

Figure 10 FT4 Powder Rheometer

Permeability is another important factor in determining the flowability of metal powders. Permeability pertains to a powder's capacity to allow air or other gases to pass through it. Powders with good flow properties will have a low permeability, as they will be less susceptible to caking or clogging.

The shear cell is the device used to evaluate the metal particles' flow characteristics. It consists of a cylindrical chamber that can be filled with powder and subjected to different shear rates. The resulting shear stress is then measured and used to determine the powder's flow properties.

Aeration is another important factor in determining the flowability of metal powders. Aeration describes a powder's capacity to allow air or other gases to pass through it. Powders with good flow properties will have a high degree of aeration, as they will be less susceptible to caking or clogging.

Compressibility is another important factor in determining the flowability of metal powders. When a powder is said to be compressible, it means that it can change its volume under pressure. Powders with good flow properties will have a low compressibility, as they will be less susceptible to caking or clogging [77, 78].

Additionally, powders with good flow properties will have consistent properties over a range of conditions and will not change their properties significantly with changes in temperature or humidity. In general, powders with good flow properties will be stable, have low permeability, low compressibility and high aeration. These powders will have a consistent flow behavior and will not change properties significantly with changes in conditions [65, 70, 80].

Additive manufacturing suitability factor: $\boldsymbol{AMS = \frac{(\frac{1}{\rho_c} + CI + PD + SE + AE + BFE + C)}{7}}$

AMS indicates the printability of metal powders for 3D printing processes. The smaller the AMS values, the more suitable the powder is for the additive manufacturing process.

Metal powders undergo a variety of stressors during processing, including shear stress, compression, and consolidation, which can have an impact on the flow characteristics of the powder. These qualities, such as viscosity, yield stress, and flowability, can be measured using rheological tests and are crucial for figuring out whether the powder is suitable for processing. The following parameters were determined for the Stainless steel 316L powder samples as seen in Table 10.

- Conditioned bulk density (g/cm3) quantifies the mass of a substance per unit volume under pre-determined humidity and temperature ranges. It can reveal details about a material's compaction and packing characteristics.

- Compressibility index (%): It can reveal information about the flowability of powders and granules and is a measurement of a material's capacity to deform in the presence of an applied force.

- Pressure drop (mBar) is a unit of measurement for the pressure difference across a material as a fluid passes through it. It can offer details about a material's permeability, which is crucial in filtration and other separation procedures.

- The specific energy (mJ/g) unit estimates the amount of energy needed to fracture or deform a certain substance. It can reveal details about a material's durability and tensile strength.

- The amount of energy needed to aerate a substance is measured in millijoules (mJ). It can offer details regarding a material's fluidization potential, which is crucial in fluidized bed processes.

- Basic flow energy (mJ) is a unit of measurement for the energy required to initiate the flow of a substance from a stationary condition. It can offer details regarding the flowability of granules and powders.

- The cohesion coefficient (kPa) measures the amount of force needed to separate a substance from cohesive forces. It can reveal details about a material's inter-particle bonds' tensile strength.

Table 10. Rheological properties of the stainless steel 316L powders

Test name	Commercial Stainless steel powder 316L	Ultrasonic fabricated Stainless steel 316L
Conditioned bulk density (g/cm$^{3)}$	4.77	4.73
Compressibility index (%)	2.85	3.00
Pressure drop (mBar)	5.87	3.26
Specific energy (mJ/g)	2.43	2.35
Aeration energy (mJ)	11.49	12.47
Basic flow energy (mJ)	845.69	828.4
Cohesion coefficient (kPa)	0.36	0.23

3.3.3 Angle of repose determination

A measurement of the maximum angle that a powder can be heaped without sliding is known as the angle of repose, it is the steepest angle, which is used to gauge a granular material's stability at which a pile of a material can be formed without the material sliding or collapsing, as shown in figure 11. The method for calculating the angle of repose is done with a Hall flow meter setup, which consists of a funnel-shaped hopper attached to a cylindrical measurement chamber. The powder is placed in the hopper and permitted to pass through the outflow and enter the cylindrical measurement chamber. The powder's height in the chamber is measured as a function of the radius. Next, using the slope of the powder pile, the following equation is used to calculate the angle of repose:

$\tan(\theta) = 2H/D$

Where D, H, and, θ are the powder pile's diameter, height, and angle of repose respectively.

It is an effective method for determining how well particles and grains flow, and can be used to compare the flowability of different powders and granules. Performance indicators including the flowrate (FR), and angle of repose (AOR) were gathered. A static AOR standard was used to calculate the flowrate of metal particles as shown in Table 10, and this explains how the samples' behavior changed using five different groups. In general, a smaller AOR denotes better flow characteristics[81].

Table 11. The AOR classification of flow characteristics[81]

AOR	Properties of flow
20° < Φ <30°	Very unconstrained
30° < Φ <39°	unconstrained
39° < Φ <44°	Acceptable to fair flow
44° < Φ <54°	adhesive
554° <Φ <69°	Very adhesive

Initially, a conical hopper (funnel) on a hall flowmeter with a volume V of 41.606 cm³ as calculated using (Eq. 2) was fed with the sample metal powder gradually and left to flow freely through the orifice. A gauge was used to measure the height and diameter of the piled platform when the powder produced a cone was taken. By taking the height of the powder cone in mm and dividing it by 50, one may calculate the tangent of the angle of repose using (Eq. 3) where Φ is the angle in degrees, h and D are the height and diameter of the conical pile respectively[82]. The results of the AOR for the two sample powders van be seen in Table 10.

$$V = \pi r^2 \frac{h}{3} \tag{2}$$

$$\Phi = \tan^{-1} \frac{2H}{D} \tag{3}$$

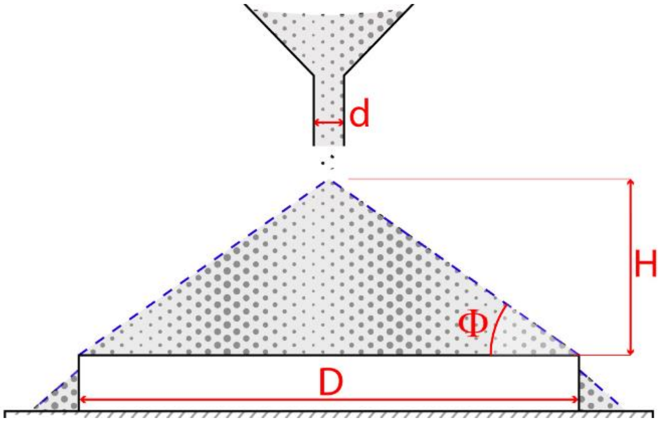


Figure 11Angle of repose

Figure 12. (a) Angle of repose determination using Hall flowmeter set-up (b) Tap density determination

3.3.4 Flow rate determination

A tool frequently used to gauge the rate of flow of powders is the Hall flow meter. It is a funnel-shaped container with a cylindrical outlet beneath. The funnel is filled with the powder and allowed to flow through, the length of time needed for a particular quantity of powder to flow out of the outlet is calculated. Following that, the flow rate is determined using the outlet diameter and powder mass flow rate. There are a few various techniques for figuring out how fast particles flow using the Hall flow meter, the weight approach, the volume method, and the timed method, among others. In the timed approach, the amount of time it takes for a known mass of powder to exit the outlet is measured and then calculated as the flow rate. The weight method involves weighing the powder before and after it flows through the outlet to determine the mass flow rate. The volume method involves measuring the volume of powder that flows out of the outlet over a certain time period and then calculating the flow rate. The timed approach was used in this experiment.

The Hall flow meter is a useful tool for measuring powder flow rate because it is simple to use, relatively inexpensive, and can be used to measure a wide range of powder flow rates. However, it is not without limitations. The Hall flow meter is not suitable for measuring powders with poor flow properties, such as those that are cohesive or have a high internal friction. Additionally, the Hall flow meter is not able to measure the flow rate of powders that are highly aerated or those that exhibit fluidization [65, 83].

Figure 13. Hall flowmeter setup for flowrate determination

Table 12. AOR and Flowrate readings for the sample powders

Powder sample	Commercial Stainless steel powder 316L	Ultrasonic fabricated Stainless steel 316L
AOR (degree)	28.1 ± 0.2	24.6 ± 0.1
Flowrate (minutes)	1.22 ± 0.1	1.14 ± 0.1

3.3.5 Physical characteristics of Stainless steel 316L

The performance and efficacy of a powder substance in the field of AM can be significantly influenced by its physical characteristics. To describe the physical characteristics of powder particles, a number of variables are frequently utilized, including tap density, particle apparent density, Hausner ratio, Carr’s index and porosity. The density of a powder or granule after it has been tapped or vibrated to settle the particles is referred to as its tap density as seen in figure 12(b), Because it can reveal details about the powder’s packing and flow characteristics, this metric is significant. Low tap density denotes inadequate packing and difficult flow, whereas high tap density denotes well-packed and easily flowable particles**.** Dividing a particle's mass by its volume which includes the vacant areas between particles, to determine its apparent density, this is important because it can reveal details about the size and shape of particles [65, 83]. A powder's flow properties, as well as its capacity to dissolve and be absorbed in the body, and can be influenced by the particle size and shape. The tap density to bulk density of a powder or granule is measured using the Hausner ratio. This metric is crucial because it can reveal details about a powder's flow characteristics. A high Hausner ratio denotes bad flow characteristics, whereas a low Hausner ratio denotes favorable flow characteristics. The proportion of the difference between the bulk and tap densities multiplied by 100, is known as Carr's index. The compressibility and flow characteristics of a powder can be revealed by this metric, which makes it important. Low Carr's index means good compressibility and good flow characteristics, whereas high Carr's index means poor compressibility and bad flow characteristics. The void volume to the total volume of a powder or granule is known as the porosity ratio. Bulk density and compressibility of a powder can be determined by this characteristic, which makes it significant. High porosity denotes inadequate compressibility and inadequate flow qualities, while low porosity denotes adequate compressibility and adequate flow properties. These metrics are shown in Table 12. ($\rho_{p,a}$**)** here means particle apparent density.

Table 13. Physical characteristics

Sample powder	Tap density (g/cm³)	$\boldsymbol{\rho_{p,a}}$ (g/cm³)	$\boldsymbol{\rho_{p,a}}$(g/cm³) literature	Hausner ratio	Carr's index	Porosity
Commercial SS 316L	4.92	7.0	8.0 [9]	1.10	9.20	0.33
Ultrasonic fabricated SS 316L	5.0	8.0	8.0 [9]	1.11	10.0	0.44

3.3.6 Particle size distribution

The distribution of particle sizes is measured by the particle size distribution (PSD) within a powder or granular material. There are several methods for determining PSD, including sieve analysis, laser diffraction, and dynamic light scattering. Sieve analysis is a simple and widely used method for measuring PSD. It involves passing a powder through many sieves with varying mesh diameters, with the powders being collected on each sieve. Then, using the mass of powder gathered on each filter, the percentage of particles within a specific size range is calculated[84].

Laser diffraction is a more advanced method that uses laser light to evaluate the size and dispersion of the particles. Laser light passes through the powders, and measures the diffraction pattern of the light as it is spread out by the particles. Following that, the size and distribution of the particles are determined using the diffraction pattern.

Dynamic light scattering (DLS) is another technique that uses laser light to evaluate the particle size and dispersion. DLS works by measuring the Brownian motion of particles in a suspension, and using this details to estimate the particle size and distribution.

Laser diffraction to measure the size and distribution of particles: Size and dispersion of particles in a powder are measured using the laser diffraction technique. It works by passing a sample through a laser beam, and measuring the angles at which the light scatters. The scattering angles are then used to calculate how the sample's particles are sized and distributed.

Laser diffraction is a non-destructive technique, meaning it doesn't alter the sample in any way. It can be used to measure particles in a variety of sizes, ranging from submicron to millimeters, and can be used with both dry powders and suspensions.

Figure 14. Malvern Mastersizer 3000

There are several different instruments available for laser diffraction, including the Malvern Mastersizer and the Beckman Coulter LS13320. These devices typically consists of three parts: a laser, a detector, and a sample dispersion mechanism. In order to spread the sample for laser diffraction, a liquid, such as water is used. The laser beam is then guided through the sample after it has been fed into the apparatus. The sample's size and particle dispersion are determined by analyzing the data, which is collected by the detector as the alight scatters at various directions.

The relative distribution of various aggregates in a powder is represented by the particle size distribution. The unrestrained material's density and permeability will be relatively low and its deformation resistance are increased moisture levels if the recycled material comprises an excessive amount of cohesive particles [85]. It will therefore be vulnerable to losing stability and strength. The distribution of particles size of the SS 316L powder samples were determined using master sizer 3000. The graphs from the experiment analysis shows that the commercial SS 316L has the largest particle size compared to the atomized SS 316L which has it particle size between 12 and 63µm as seen in figure 15.

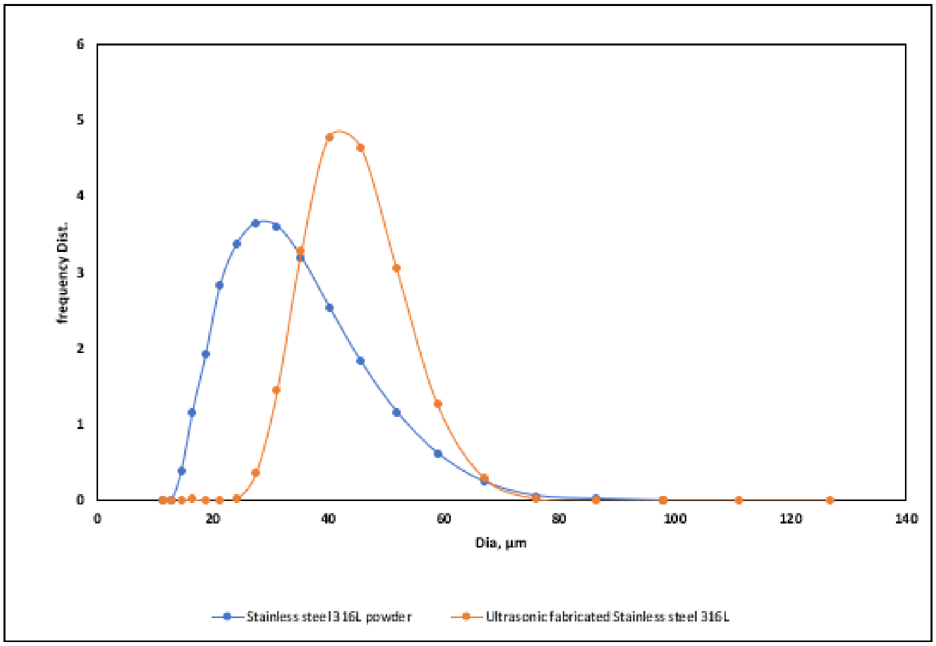


Figure 15. Particle size distribution of Stainless Steel 316L powders.

The average values of D10, D50, and D90 were calculated. The Gaussian distribution layout's breadth, as determined by the metric calculation, was presented by span 'S'[11]:

$$S = \frac{D_{90} - D_{10}}{D_{50}} \tag{1}$$

Table 14 shows the particle size distributions, slope , intercept and span of the two powder samples. As seen Reduced flowability was caused by powders with a wider size distribution span (Eq. 1). 1.5 is the maximum value. The powders in group 1 with a span value of S ≤ 1.5 show proper flow, while those with S > 1.5 showed flow resistance (group 2)[12]

Table 14. Particle size distribution for Stainless Steel 316L

Sample	Surface area(**m²/kg**)	D_{10}(µm)	D_{50}(µm)	D_{90}(µm)	slope	Intercept	Span
Commercial SS 316L	180.7	23.3	35.4	53.4	0.4025	3.45	0.85
Ultrasonic fabricated SS 316L	130.0	34.9	46.6	61.8	0.3875	3.61	0.57

4.0 PRINTING OF STAINLESS STEEL 316L ON THE SELECTIVE LASER MELTING (SLM)

4.1 Introduction

A form of additive manufacturing technique known as selective laser melting (SLM) uses a strong laser to melt and fuse together successive layers of metal powder to create three-dimensional objects. Metal particles are thinly coated and evenly dispersed over a build platform during the SLM printing of metal powders. The metal particles are then carefully melted and fused together to form the desired item as high-powered laser beam scans across the powder's surface. A second coating of metal powder is then melted and fused to the one beneath it by the laser beam. Layer by layer, this procedure is repeated until the entire object is created. SLM printing of metal powders have the advantage of making it possible for the creation of intricate and complicated geometries that would be challenging or impossible to manufacture using conventional manufacturing techniquess[86, 87]. Additionally, it enables the production of components with a high level of precision and accuracy. Though SLM printing of metal particles is not without its problems, controlling the metal powder's consistency and quality is one of the major challenges[88]. Use of high-quality, reliable metal powders is crucial because the size and form of the metal particles can have an effect on the end product's attributes. The printed object's mechanical properties may also be impacted by residual tension and distortion brought on by SLM process. Despite this difficulties, metal powder SLM printing is apromising technology with many uses in the aerospace, automotive, and biomedical engineering sectors[89].

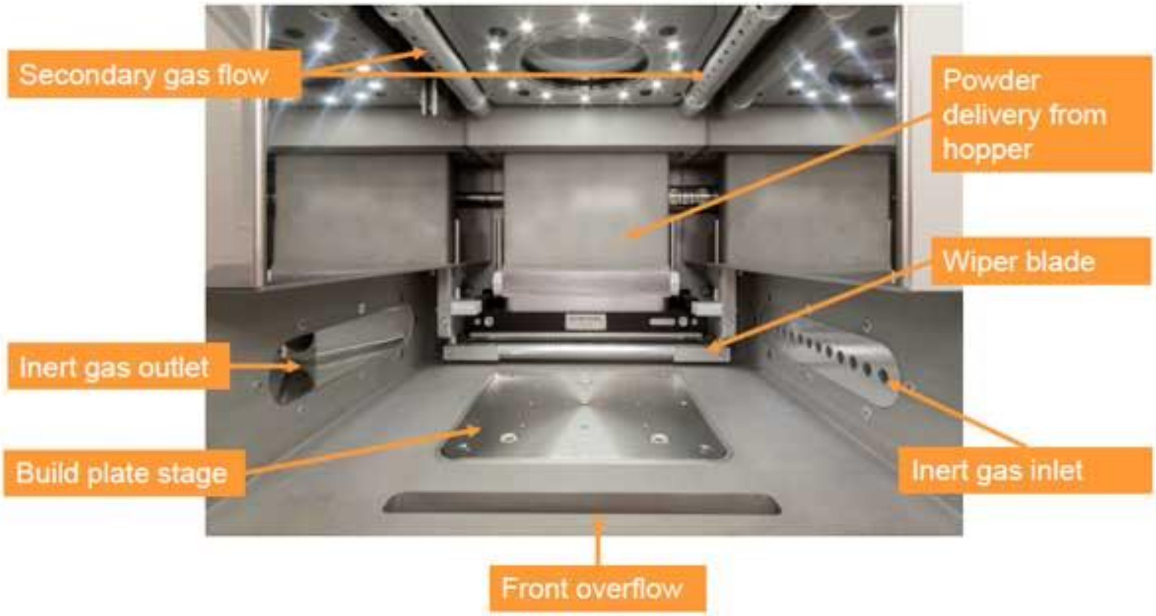


Figure 16. AM 400 Renishaw system overview

Figure 17. AM 400 Renishaw multi-view

4.2 Printability characteristics of SS 316L

The ASTM E8/E8M standard specifies both the testing method to be used as well as the test specimen dimensions and preparation. In order to create the sample, a rectangular specimen of the sample having a lower cross-sectional area is cut from the substance as shown in figure 22. By reducing the section, it is possible to make sure that the sample breaks in a dependable and predictable way. The sample is then inserted into the testing device and pulled until it snaps. The material’s tensile strength, yield strength, elonagtion, and other mechanical characteristics are ascertained using data collected during the test from measurements of the force and deformation.

The ASTM E8/E8M standard, which has gained widespread industry acceptance, is regarded as the ideal one for evaluating the tensile strength of the metallic materials. For ensuring the quality of the products, it offers a repeatable and reliable technique for assessing the mechanical properties of materials[90].

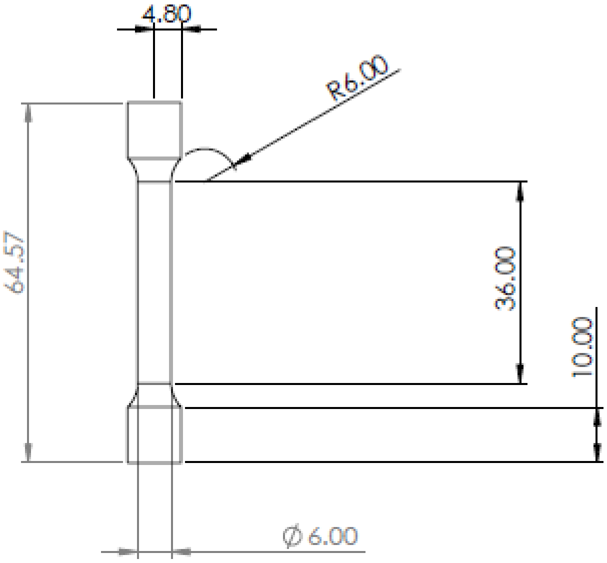


Figure 18. Dimension for Standard tensile sample printed parts

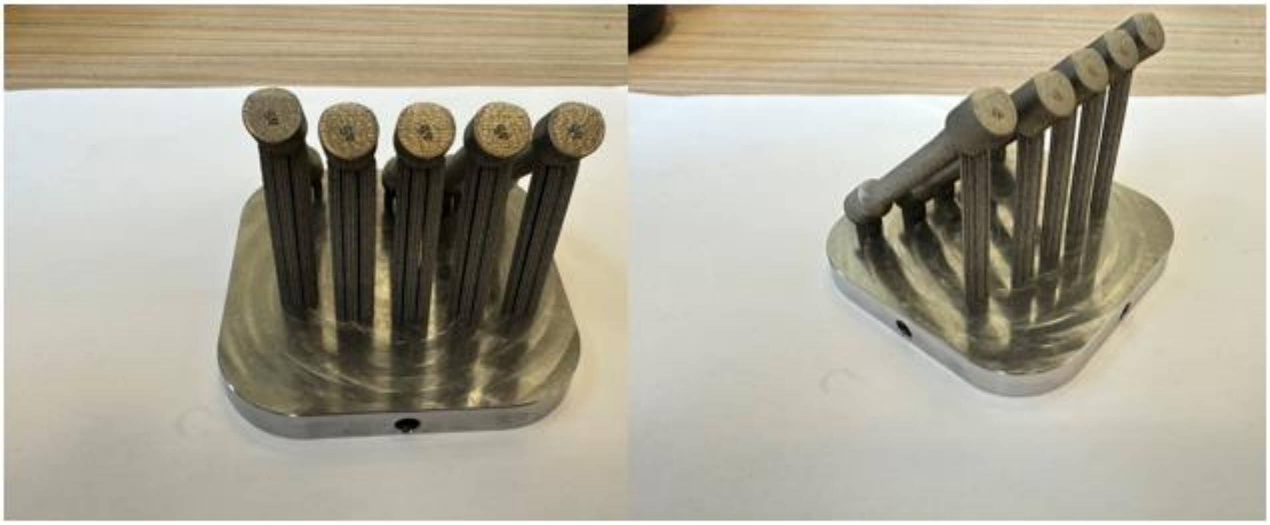


Figure 19. Standard tensile sample printed parts

SLM was used to print five pieces of the standard tensile sample on stainless steel plate with support height of 56mm, width 50mm and length of 50mm as shown in figure 23. The printability characteristics of the fabricated stainless steel 316L metal powder relates to the powder's suitability for additive manufacturing methods like selective laser melting (SLM), to create three-dimensional parts[91].

Some key printability characteristics of the fabricated stainless steel powder are[92]:

- Flowability: To ensure uniform material deposition during the printing process, the powder needs to have excellent flowability. The powder’s particle size, shape, and surface properties can have an impact on this.
- Density: The porosity of the printed component can be impacted by the powder’s density. A printed part that is denser and more solid will usually have a higher density powder.
- Sphericity: spherical particles are typically favored for additive manufacturing because they pack more effectively and cause fewer voids and flaws in the printed part.
- Consistency: for reliable printing outcomes, the powder’s properties must remain constant throughout the batch.
- Adhesion of powder Bed: To avoid shifting or deformation during printing, the powder must stick firmly to the build plate.
- Powder cleanliness: the powder should be free of impurities that could degrade the printed part’s quality, such as moisture or grease.

Items	Value
measurement conditions	
Acceleration voltage	20.00 kV
Probe current	-
Magnification	x 200
Process time	T3
Measurement detector	First
Live time	30.00 seconds
Real time	32.03 seconds
Dead time	6.00 %
Count rate	7819.00 CPS

Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
Si	K	0.46±0.04	0.91±0.07
Cr	K	18.10±0.16	19.46±0.17
Mn	K	0.57±0.06	0.58±0.06
Fe	K	65.09±0.34	65.16±0.34
Ni	K	12.70±0.20	12.10±0.19
Mo	L	3.09±0.10	1.80±0.06
Total		100.00	100.00
Spc_001			Fitting ratio 0.0190

Figure 20. SEM image and chemical composition of printed part

4.3 Tensile testing

To ascertain the samples' mechanical characteristics, a tensile test being a form of mechanical test, was utilized as seen in figure 25. A standard tensile sample that was 3D printed was placed in a testing device and secured in place by grips at both ends throughout the tensile test.

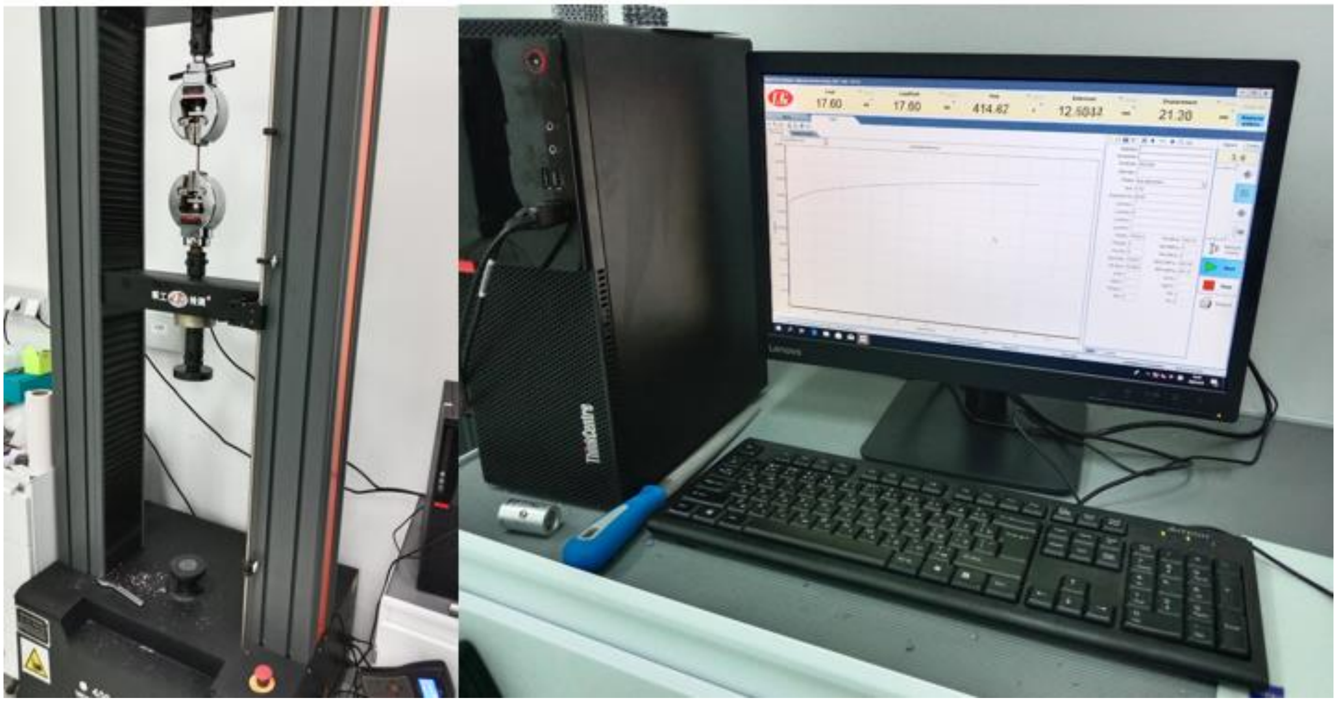


Figure 21. Standard tensile sample printed parts

The specimen is then subjected to a tensile load by the machine, which raises the gauge section's stress until it reaches its maximum tensile strength. (UTS). The specimen breaks and fractures at this point, and the highest weight it endured was noted. The machine also keeps track of the specimen's length variation throughout the test, which was then used to determine the material's elongation and other characteristics. A number of mechanical characteristics of the material, including its Young's modulus, yield strength, and ultimate tensile strength, were calculated using data obtained from a tensile test.

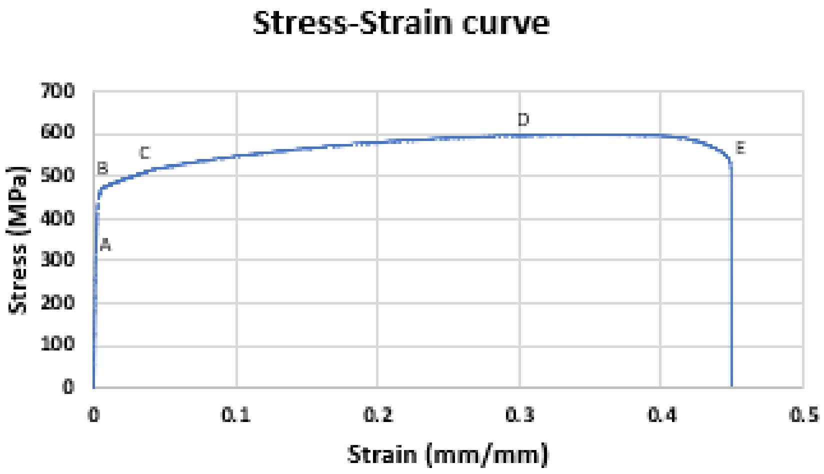


Figure 22. Stress-strain curve for SS 3116L standard tensile sample

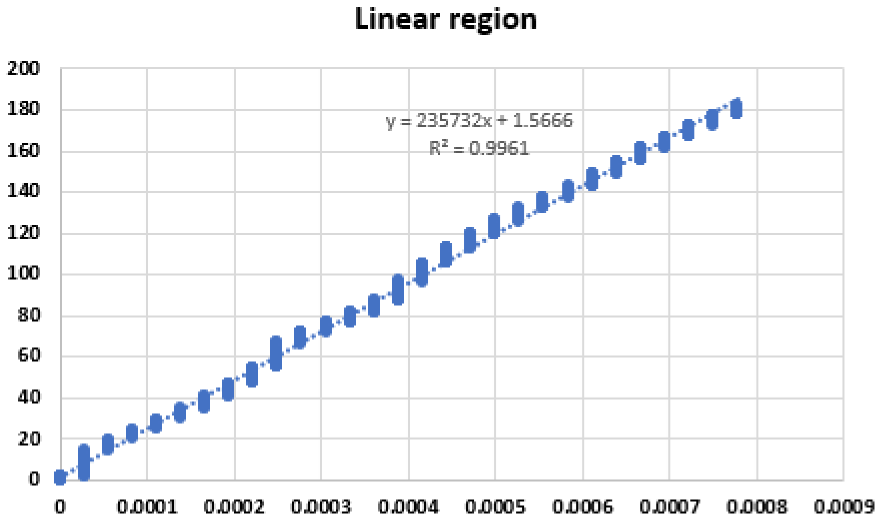


Figure 23. Linear region for SS 316L standard tensile sample

There is a linear relationship between stress and strain from point 0 to point A. In this area, stress and strain are directly proportional, and Hooke's law is applied up to point A. The stress at point A is known as the proportional limit, and the slope of the line OA represents Elastic modulus which was obtained as 235.7GPa from the graph.

Beyond point A, stress is not proportionate and strain is no longer related to stress linearly. The matching stress value at Point B, where the point of maximum yield is reached, is referred to as the yield strength (YS). The ideal plastic zone, sometimes referred to as the yielding region, is the area between points B and C.

The strain hardening zone runs between points C and D, and the ultimate tensile strength corresponds to the stress value at point D. The term "necking" refers to the decrease in the testing bar's cross-sectional area that results from stretching it past point D. Beyond point D, the curve begins to decline as a result of the bar's dramatically reduced load-bearing capability caused by the fall in cross-sectional area. The testing bar eventually fails at point E, and the stress at this point is referred to as the material's breaking strength.

4.4 Hardness test

The INNOVATEST falcon500 was utilized to perform a hardness test on the printed part of the stainless steel 316L. The Vickers hardness test was performed to evaluate the resilience of stainless steel 316L. It entails utilizing a diamond indenter to apply a known load to the material's surface and gauging the extent of the depression that results. Higher values denote harder materials according to the Vickers hardness scale, which is represented in HV (Vickers hardness) units. Below is the obtained results five experiments as seen in Table 14.

Table 15. Vickers hardness values

Exp no.	Vickers	Load	Dwelling time (sec)
1	200.99 HV/1	1kgf	10
2	201.87 HV/1	1kgf	10
3	204.07 HV/1	1kgf	10
4	207.32 HV/1	1kgf	10
5	198.98 HV/1	1kgf	10

Table 16. Mechanical properties

Grade	SS 316L	SS 316L Literature [93]
Yield strength, MPa	464	519.0
Tensile strength, MPa	597	633
Ductility	6.6	
%Elongation after fracture	48	32.45
Young’s modulus, GPa	235.7	207.2
Hardness maximum	207.32 HV/1	247 HV [94]

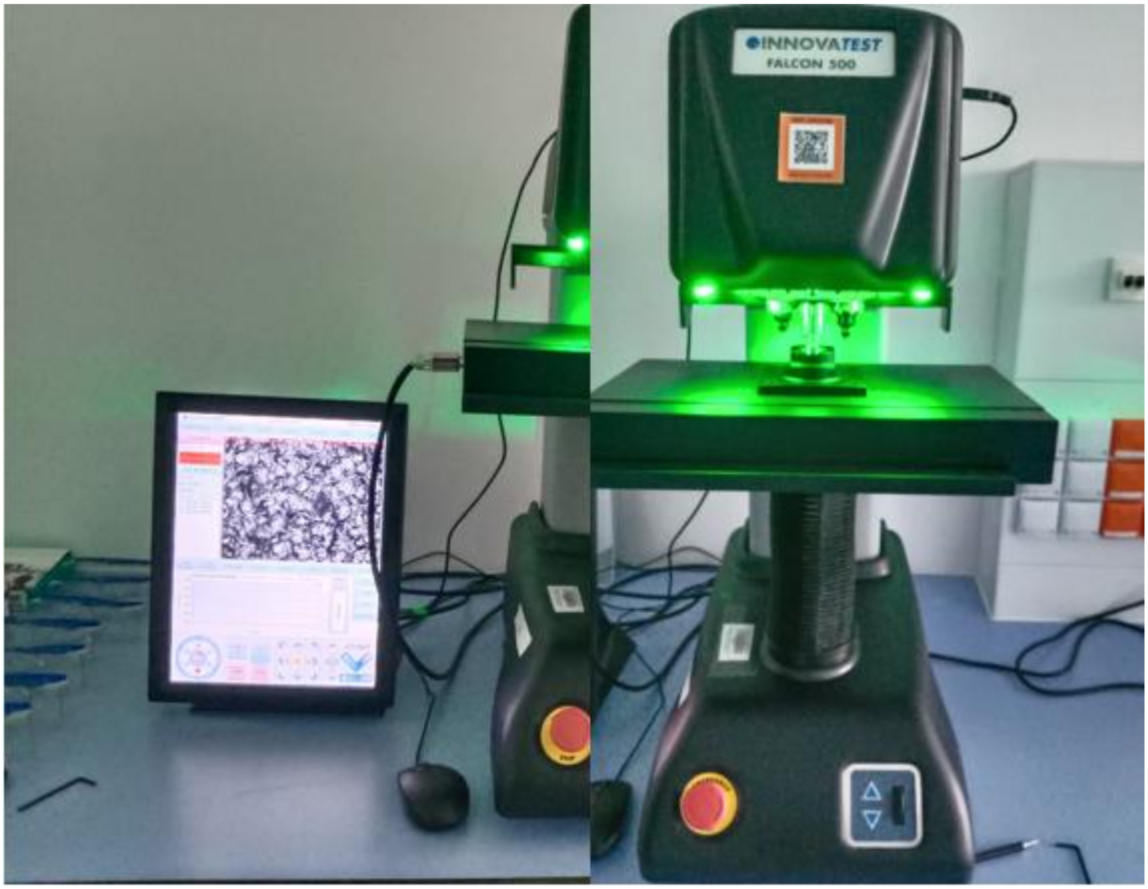


Figure 24. INNOVATEST falcon 500 hardness tester

The Vickers hardness test findings shows that the SLM printed sample that was put through routine tensile testing demonstrates outstanding resistance to indentation, scratching, and deformation. These results demonstrates that the sample satisfies the required standards for strength. A common technique for determining a material’s hardness is the Vickers hardness test.

5.0 Conclusion

Overall, Stainless steel 316L metal powder was fabricated and bench marked with commercially produced Stainless steel 316L. Characterization was done to ensure the effectiveness and quality of the powders. The fabricated powder was used to 3D print, and the printed part was tested for hardness and tensile strength. Generally, the following points were observed in the process:

- The production process of stainless steel 316L via ultrasonic atomization was significantly impacted by the process parameters, specifically the current of 130A, amplitude of 80%, and feeder speed rate of 50%, which resulted in increased productivity rates.
- The outcomes revealed that the ultrasonic fabricated powder has a better morphology than powder that was manufactured commercially.
- The generated powder's particle size distribution was 61.8µm microns after being sieved with a mesh size of 63µm, indicating that it had superior flow and was appropriate for the SLM manufacturing process.
- The characterization results indicate that the commercially produced powder is a lower grade powder since it did not display the same level of quality as the ultrasonic atomized stainless steel powder.
- Both powders have rheological characteristics that are advantageous for additive manufacturing methods, this indicates that they have characteristics that make them simple to handle and work with when printing.
- The rheological characteristics of the fabricated powder enabled the production of high-quality metal components with superior mechanical qualities as observed in the printed standard tensile sample due to its ability to spread and level on the printing bed which is crucial for achieving a consistent layer thickness and print without clogging or deformation
- Tensile and hardness tests on the printed standard samples revealed that its mechanical characteristics fell within the allowed range, proving that the material is appropriate for the intended application. Manufacturers and designers that want to confidently incorporate the material into their goods or projects might benefit from this information. The successful conclusion of the testing procedure also emphasizes the significance of quality control systems and the requirement for accurate and dependable testing methods in the field of materials science.

5.1 Future work

Futher study of stainless steel 316L fabrication using ultrasonic atomizer is required to enhance its mechanical and corrosion resistant qualities given the rising demand for high-performance materials across a variety of industrial sectors.

- Exploring the usage of different manipulator angles while fabricating is advised in order to promote more spherical and uniform size of powder.
- The fabricated powder should also be analyzed to make sure it has a nearly perfect spherical shape.
- Experiments with printing of the powder can be carried out to further test the final product's mechanical qualities after the powder has been examined and optimized.

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