Solid Freeform Fabrication 2025: Proceedings of the 36th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Review on Atomization of Metals

Forrest Orozco [1,2], Noah McCoy [1,2], Jianzhi Li [2,3], Monsuru Ramoni [2,3], Ahmed Bendaouia [2,3]

[1] College of Engineering and Computer Science, University of Texas Rio Grande Valley, United States.

[2] Institute for Advanced Manufacturing (IAM), University of Texas Rio Grande Valley, United States.
[3] Manufacturing and Industrial Engineering Department, University of Texas Rio Grande Valley, United States.

Abstract

The atomization of liquid metals is a critical technique for producing fine, high-quality metal powders used across various industries, including additive manufacturing (AM), powder metallurgy, and thermal spraying. The process allows for precise control over particle size, morphology, and chemical purity, properties that directly impact the performance of components made from these powders. This review explores the fundamental mechanisms of gas atomization and evaluates multiple atomization techniques, such as inert gas atomization, close-coupled and free fall nozzles, water atomization, and plasma-based methods. Emphasis is placed on the atomization behavior of key industrial metals: steel, titanium, magnesium, and copper. Each presents distinct challenges and requires tailored processing conditions. Issues such as oxidation, high melting points, and flowability are discussed alongside innovations in nozzle design, process control, and powder handling. By synthesizing current research and technological developments, this review provides an outlook on the future of gas atomization in advanced manufacturing systems.

Keywords: Atomization, Liquid Metal, Additive Manufacturing, AM, Nozzle, Metal Atomization

1. Introduction

The production of fine metal powders is a key process in modern manufacturing, enabling the development of advanced materials and components with superior properties. Among the various methods used to produce metal powders, gas atomization stands out as one of the most efficient and versatile techniques [8]. Gas atomization involves the disintegration of a molten metal stream into fine droplets by a high-velocity gas jet, which subsequently solidifies into spherical or near-spherical powders. The characteristics of the resulting powders, such as particle size, shape, and distribution, can be controlled by adjusting the atomization parameters, making this process particularly suitable for producing powders used in additive manufacturing, powder metallurgy, and thermal spraying [9],[10].

The demand for high-quality metal powders has grown significantly in recent years, driven by the rapid development of additive manufacturing technologies and the increasing need for complex, high-performance components [11]. In particular, the ability to produce uniform, fine powders with minimal contamination is critical for the successful implementation of these technologies in industries such as aerospace, automotive, and biomedical engineering [12]. Gas atomization, with its ability to produce powders with a high degree of sphericity and narrow particle size distribution, has become a preferred method for producing metal powders for these applications [13].

Steel, being one of the most widely used engineering materials, presents unique challenges when it comes to atomization. The high melting point and tendency to oxidize during the atomization process require the use of specialized techniques, such as inert gas atomization, to produce high-purity steel powders [14],[15]. The control over the atomization process, including the selection of the appropriate gas type, nozzle design, and operating parameters, is crucial to ensure the quality and consistency of the resulting steel powders

This paper aims to provide an overview of the gas atomization process. It explores the various types of gas atomization techniques, discussing their respective advantages and limitations, and examines the specific challenges associated with atomization. Furthermore, the paper reviews recent advancements in gas atomization technology, including innovations in nozzle design and process control, which have significantly improved the efficiency and quality of the atomization process. By providing insights into the current state and future potential of gas atomization, this study aims to contribute to the ongoing development of advanced manufacturing processes and the production of high-performance materials.

2. Atomization of Metal

The atomization of different materials can yield different results based on application, with this comes different methods and challenges. A review of some common materials frequently used in this process, such as Steel, Titanium, Magnesium and Copper.

Table 1: Material and Atomization methods

Material	**Preferred Atomization Method**	**Av. Droplet Size (µm)**	**Advantages**	**Disadvantages**	**Ref.**
Steel	Inert Gas Atomization (close-coupled)	20-100	High Sphericity, Low Oxidation	Requires inert Atmosphere, High Energy Cost	[5], [4]

Titanium	Plasma/Gas Atomization with Dealloying	14-45	High Purity, Great particle size control	Complex Set up, Expensive System	[17], [19]
Magnesium	Ultrasonic Inert Gas Atomization	30-150	Lightweight Alloy, Low energy requirement	Prone to oxidation, Reactive stability can be difficult	[18], [20]
Copper	Inert Gas Atomization (Multi-jet/High Pressure)	20-70	High Conductivity, Smooth particle morphology	Satellite formation, Prone to oxidation	[16], [20]

1.1 Atomization of Steel

The atomization of steel is a complex and critical process in metal powder production used in various industrial applications. Steel poses unique challenges during atomization due to its high melting point, tendency to oxidize, and the need for precise control over particle size distribution. The atomization process must ensure that the resulting steel powders possess the desired characteristics, such as high purity, controlled particle size, and minimal oxidation, to meet the stringent requirements of industries like automotive, aerospace, and construction. One of the renown studies to analyze the processing of powder particle sizes correlation was done by Lubanska [1] which yielded the equation:

$$\frac{d_m}{\delta} = K\left[\frac{v_m}{v_g We}\left(1+\frac{M}{A}\right)\right]^{0.5} \qquad \text{Eq. (1)}$$

where We = $\frac{\rho_g \Delta U^2 \delta}{\sigma}$
K = constant
v_g= kinematic viscosity of a gas
We = Weber number

Which was investigated on iron, aluminum and tin powder production.

1.2 Challenges in Steel Atomization

One of the primary challenges in the atomization of steel is the material's high melting point, which requires the use of advanced atomization techniques to achieve efficient disintegration of the molten metal. Inert gas atomization is often employed to prevent oxidation during the process. The use of inert gases like argon or nitrogen creates an oxygen-free environment, which is crucial for producing high-purity steel powders [1][2]. However, the cost of inert gases and the need for precise control over gas flow and temperature make this method more complex and expensive compared to other some other metals and atomization techniques [3].

Oxidation is another significant challenge in steel atomization. During the atomization process, the molten steel is exposed to the surrounding environment, making it susceptible to oxidation, which can degrade the quality of the powders produced. To address this issue, researchers have developed various strategies, including the modification of liquid steel viscosity and surface tension, which helps in reducing the contact between the molten steel and the atomizing gas, thereby minimizing oxidation [4][11]. With a decrease in surface tension and viscosity yields smaller medium particle size. Additionally, advancements in nozzle design and gas dynamics have played a crucial role in enhancing the efficiency of inert gas atomization, further reducing the risk of oxidation, and improving the quality of the steel powders produced [12].

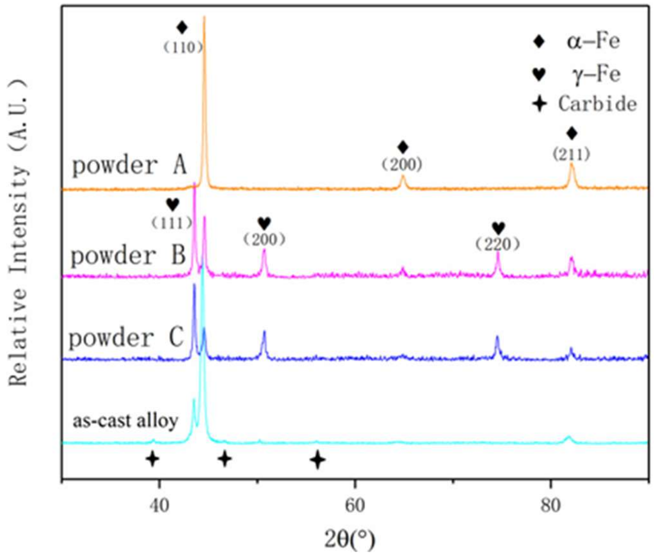

Figure 1: X-ray diffraction results of powders and as-cast alloy [5].

1.3 Techniques for Steel Atomization

Several techniques have been developed to optimize the atomization of steel. One such technique is close-coupled atomization, which involves the use of a nozzle positioned close to the molten metal stream, allowing for better control over the atomization process. This method has been shown to produce steel powders with a narrow particle size distribution and minimal contamination [8]. The proximity of the nozzle to the molten stream ensures that the gas jet effectively atomizes the molten steel, resulting in finer and more uniform particles [8]. Figure 1 shows XRD results of powders produced using gas atomization, which illustrates how particle size is closely linked to cooling rate. Powder A having gone through rapid cooling while Powder B and

C decrease in cooling time. Powder B is the target for the study and with its cooling rate has allowed the material to reach ideal size. The choice of atomizing gas temperature was studied using simulation for a close-coupled nozzle in vacuum, using stainless steel 316L as the material. Primary atomized droplets diameter showed a decrease with the increase in gas temperature (300k-600k) [41].

1.4 Morphology Characteristics and Applications

Morphology characteristics of gas-atomized steel powders typically include a spherical shape with smooth surfaces, though some satellite particles may form depending on atomization conditions [33]. The particle size distribution is usually narrow when inert gas is used, and finer particles are achieved under higher gas pressures. Higher gas pressure influences gas velocity, both are crucial to achieve desired powder size. Oxidation is minimized using inert atmospheres like argon or nitrogen, as well as when the nozzle is closer to the melt stream.[35]. Applications of atomized steel powders include structural components, automotive gears, sintered parts, and parts for additive manufacturing and metal injection molding (MIM). Due to their controlled particle size and relatively spherical morphology, these powders are especially used in high-strength sintered components and soft magnetic materials [25],[34]. Stainless-steel powders are commonly employed in binder jetting and laser powder bed fusion for corrosion-resistant parts [36].

Table 2: Material and Strategies

Material	**Challenges in Atomization**	**Mitigation Strategies**	**Morphology Characteristics**	**Applications**	**Ref.**
Titanium	Highly reactive with oxygen/nitrogen at high temp; Requires inert gas; Risk of contamination and embrittlement	Use high-purity argon/helium; Two-step dealloying (Ti-Cu → Mg)	Near-perfect sphericity; Some porosity and satellites; Can be optimized	Aerospace; Biomedical implants; Additive manufacturing (SLM, EBM)	[17], [18], [19], [20], [23]
Magnesium	High vapor pressure; Prone to oxidation/combustion in air	Argon atmosphere; Alloying with Ti or rare earths	Irregular/fragmented unless optimized; Difficult to control sphericity	Automotive/aerospace lightweight parts; Biodegradable implants	[18], [20], [21], [22]
Copper	Oxidation susceptibility; Satellite & coarse particle formation	High-pressure argon; Post-process sieving; Use of Cu-Ti metallic glasses	Spherical to mildly elongated; Satellite particles can affect flowability	Electronics; Thermal interfaces; Additive manufacturing; Metallic glasses	[16], [18], [20]

3. Methods of Atomization

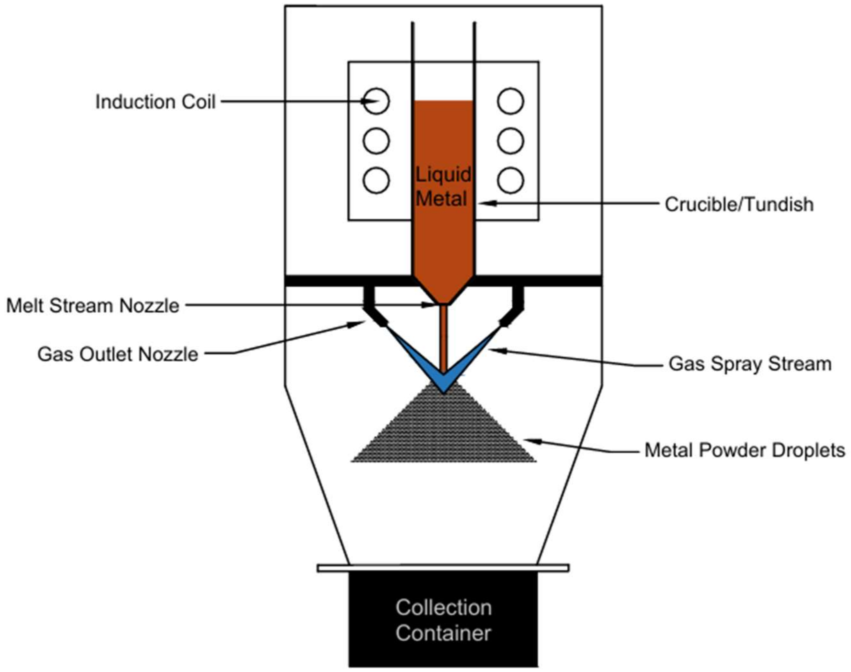

Figure 2: Gas Atomization Set up.

Table 2: Atomization methods and energy consumption

Method	**Approx. Energy Consum.**	**Characteristics**	**Advantages**	**Disadvantages**	**Ref.**
Plasma Atomization	200–400 kWh/kg	High-temperature arc plasma used to melt wire or powder feed	High purity spherical particles	High energy cost, Low throughput	[17]
Gas Atomization	15–50 kWh/kg	High-pressure inert gas disintegrates molten metal stream	Fine powders, Inert atmosphere	Moderate oxidation risk, Gas cost	[20], [30]
Water Atomization	5–15 kWh/kg	High-velocity water jets used	Low cost, High throughput	Irregular shapes, Oxidation	[27], [31]
		to fragment melt			

1.1 Gas Atomization

Gas atomization is a widely used technique for producing fine metal powders by breaking a molten metal stream using high-velocity inert gas jets. The method is suitable for a wide range of metals and alloys, including stainless steel, aluminum, titanium, and copper. The process begins with the melting of the feedstock material in a controlled environment, most commonly by induction heating. Typically, under an inert gas atmosphere such as argon or nitrogen. The molten stream is then disrupted by one or more high-pressure gas jets, causing it to fragment into droplets, which rapidly solidify into powder particles.

One of the main advantages of gas atomization is the production of spherical powders with a narrow particle size distribution, which is highly beneficial for powder flowability and packing density—essential characteristics for applications such as additive manufacturing and powder metallurgy. Additionally, gas atomization allows for good control of particle size by adjusting parameters like gas pressure, melt superheat, and nozzle design. However, the process can be energy intensive and relatively costly due to the need for inert gases and complex system designs [13],[20],[30].

Copper powders generated via gas atomization are typically spherical to mildly elongated, with smooth surfaces and low internal porosity. However, the formation of satellite particles can impair flowability, advanced nozzle designs and higher atomization gas pressures help suppress this effect [16][20].

1.2 Issues and Challenges in Gas Atomization

Despite its ability to produce high-quality powders, gas atomization presents several challenges. The process is energy-intensive, particularly when using high-purity inert gases like argon. Maintaining an oxygen-free environment is critical to prevent oxidation, especially for reactive metals like titanium and magnesium. Moreover, nozzle clogging, inconsistent gas flow, and turbulence can affect the uniformity of droplet formation. Achieving consistent powder morphology often requires precise control.

1.3 Equipment Required for Gas Atomization

Gas atomization systems generally consist of a melting furnace (induction or resistance type), a tundish or crucible for controlled pouring, a gas delivery system with pressurized inert gases (typically argon or nitrogen), and a specially designed atomization chamber. The nozzle design (e.g., close-coupled or swirl-type) is central to determining droplet size and distribution. Ancillary equipment includes powder collection systems, sieves, and gas purification units.

2.1 Applications for Atomized Powders

The powders produced through atomization have a wide range of applications. In the automotive and aerospace industries, these powders are used in additive manufacturing to produce complex, lightweight components with superior mechanical properties [13]. The ability to produce steel powders with controlled particle size and high purity is critical in these industries, where material performance and reliability are of utmost importance. Additionally, steel powders are also used in powder metallurgy to manufacture high-density components with enhanced strength and durability [14].

In the construction industry, atomized steel powders are used in thermal spraying processes to apply protective coatings to structural components. These coatings provide resistance to wear, corrosion, and high temperatures, thereby extending the lifespan of the components [15]. The versatility and performance of steel powders make them valuable in various industrial sectors, driving ongoing research and development in steel atomization techniques.

2.2 Parameters of atomization

1. Particle Size and Distribution

Particle size distribution (PSD) is one of the most critical parameters for steel powders used in additive manufacturing (AM) and powder metallurgy (PM). Controlling the particle size ensures optimal powder flowability, packing density, and layer thickness during printing or sintering processes.

- Additive Manufacturing: In laser-based AM processes such as selective laser melting (SLM) and electron beam melting (EBM), smaller, spherical particles in the range of 15–45 µm are ideal. A narrow PSD is preferred as it ensures uniform powder layers, which is essential for producing highly accurate and finely detailed components. Larger or irregularly shaped particles can cause uneven layer deposition, leading to defects in the final component.

- Powder Metallurgy (PM): For applications like pressing and sintering, the particle size distribution influences the packing density of the powder, which affects the density and mechanical properties of the final part. Finer powders provide better surface finish, while coarser powders may lead to porosity in the final product

2. Particle Shape and Morphology

The sphericity and surface morphology of steel powders are critical design parameters, particularly for AM and thermal spraying applications. High sphericity ensures good powder flowability, which is crucial for powder-based processes such as SLM, EBM, and binder jetting. The following are the key aspects of particle morphology:

- Sphericity: Spherical powders allow for smooth flow through powder hoppers and consistent layer deposition in AM machines. High-sphericity particles also reduce the likelihood of clogging in the powder delivery systems, thereby improving process reliability and productivity.

- Surface Roughness: Powders with smoother surfaces tend to have better flowability and packing density. Rough surfaces can lead to agglomeration, affecting the uniformity of the powder bed in AM or PM applications.

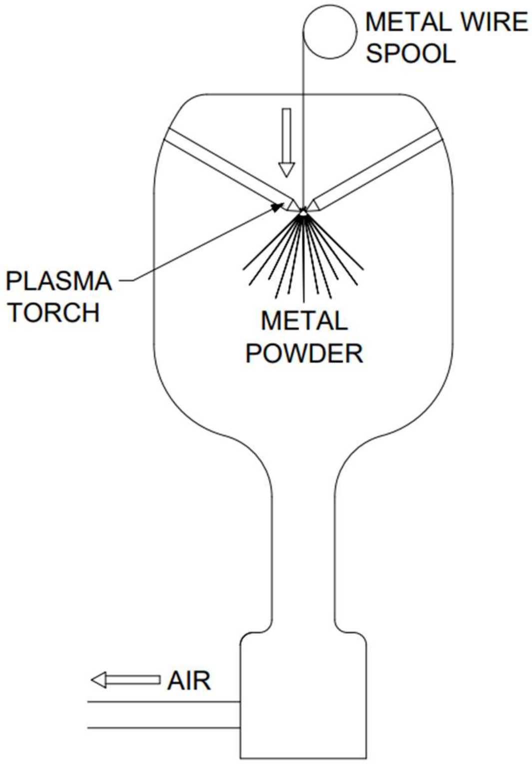

Figure 3: Plasma Atomization Set up

Table 3: Plasma and Water Atomization Information

Aspect	**Plasma Atomization**	**Water Atomization**
Feedstock Type	Wire, Rod, or Powder	Molten metal from furnace
Temperature Range	Above 10,000°C (for plasma arc)	Depends on melt temp (e.g., steel: ~1500°C)
Cooling Method	Rapid cooling via inert gas in controlled chamber	Rapid cooling via water jets
Challenges	High energy use, expensive, oxidation risk, limited material flexibility, PSD control	Irregular shape, oxidation risk, broader PSD, post-processing needed
Applications	Additive manufacturing, aerospace, medical implants	Press-and-sinter metallurgy, non-AM bulk powder uses
Required Equipment	Plasma torch, feed system, cooling/collection chamber, control systems	Melting furnace, tundish, water nozzles, drying & sieving units
Ref.	[7], [9], [14], [15]	[27], [31]

3. Oxidation Control

Inert gas atomization using argon or nitrogen is commonly used to minimize oxidation during the atomization of steel powders. Plasma atomization also allows for effective control of oxidation due to the inert environment created by the plasma torch. This is crucial for applications like stainless steel and high-alloy steels, where oxidation can significantly impact the corrosion resistance and strength of the final component. As well for gas atomization using a controlled environment with an inert gas.

4. Development of Key Components

The successful use of atomized steel powders in AM and PM processes relies on the development of specific components designed to handle, process, and optimize the powders. Some of these key components include:

- **Powder Feeders and Hoppers:** In AM systems, powder hoppers are designed to deliver the steel powder uniformly and consistently to the build platform. The design of these hoppers must accommodate powders with different flow properties, and advanced systems may include vibration mechanisms or gas-assisted feeding to ensure even distribution [9].

- **Powder Spreaders:** For processes such as SLM and binder jetting, powder spreaders are critical components. These spreaders ensure that a uniform layer of powder is deposited across the build surface. Poorly designed spreaders can lead to uneven powder distribution, resulting in defects or irregular layer thicknesses.

- **Recycling and Sieving Systems:** In AM, unused powder is often recycled for future builds. Sieving systems are used to ensure that the recycled powder meets the necessary size and quality specifications. These systems must be capable of filtering out agglomerated or oversized particles, as well as removing contaminants introduced during the build process.

- **Cooling and Collection Systems:** In plasma and gas atomization processes, cooling chambers and cyclone separators are used to solidify and collect the fine steel powders. The design of these systems affects the particle size distribution and quality of the final powders, and advanced cooling systems are designed to minimize oxidation and preserve powder purity.

2.3 Nozzle Design for Liquid Metal Atomization

Nozzle design plays a critical role in the efficiency and effectiveness of liquid metal atomization. The design of the nozzle determines the interaction between the molten metal stream and the atomizing gas, which in turn influences the size, distribution, and quality of the metal powders produced. Advances in nozzle design have led to significant improvements in the atomization process, enabling the production of finer and more uniform powders with better control over particle size distribution.

The primary function of the nozzle in gas atomization is to direct the atomizing gas at high velocity towards the molten metal stream, causing it to break up into fine droplets that solidify into powders. The design and positioning of the nozzle are crucial in achieving efficient atomization. A well-designed nozzle can enhance the gas-metal interaction, leading to better efficiency, reduced energy consumption, and improved powder quality [9][10]. Conversely, poor nozzle design can result in large, irregularly shaped particles, inconsistent powder quality, and increased material waste [7].

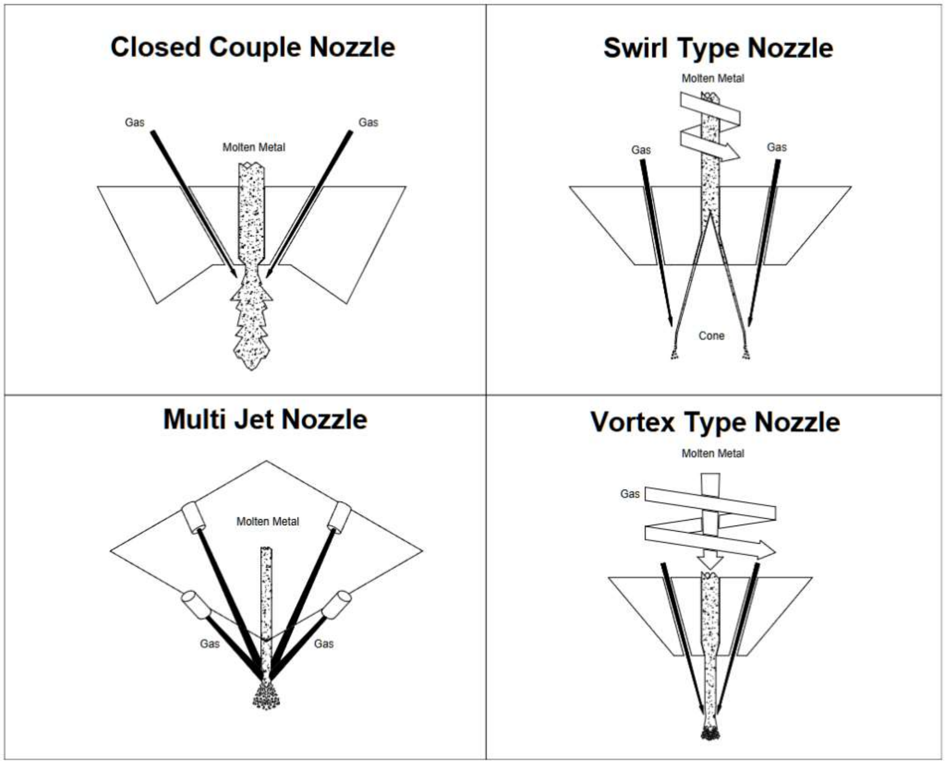

Figure 4: Nozzle Configurations.

2.4 Types of Nozzle Configurations

Several nozzle configurations have been developed and optimized for liquid metal atomization, each offering distinct advantages depending on the application requirements.

1. Close-Coupled Nozzles: Close-coupled nozzles are positioned very close to the molten metal stream, allowing the atomizing gas to interact with the metal immediately as it exits the delivery tube. This design is particularly effective in producing fine powders with a narrow particle size distribution, as the proximity of the nozzle ensures that the gas jet breaks up the molten metal efficiently [11]. The close-coupled design also reduces the amount of superheat required in the molten metal, thereby minimizing oxidation and energy consumption [12].

2. Swirl-Type Nozzles: Swirl-type nozzles impart a swirling motion to the atomizing gas, which enhances the breakup of the molten metal stream. The swirling action creates a more uniform distribution of droplets, resulting in powders with consistent particle size and shape. This design is especially useful for materials that require high sphericity and uniformity in their powder form [14][9].

3. Multi-Jet Nozzles: Multi-jet nozzles utilize multiple gas jets arranged around the molten metal stream, providing a more uniform and controlled atomization process. This design allows for the adjustment of gas flow rates and angles to optimize the atomization process for different materials and powder characteristics [10]. Multi-jet nozzles are commonly used in the production of high-purity powders where precise control over particle size distribution is essential [13].

4. Vortex Nozzles: Vortex nozzles generate a vortex or spiral flow of the atomizing gas, which enhances the breakup of the molten metal into fine droplets. The vortex flow creates a highly turbulent environment, which promotes rapid cooling and solidification of the droplets, leading to the formation of fine, uniform powders [15]. This design is particularly effective in producing ultra-fine powders for applications requiring high surface area and reactivity [8].

Table 3: Nozzle Configuration methods

Method	Feed Material Form	Best Atomizing Gas	Advantage	Disadvantage	Ref.
Close Coupled	Molten Steam	Argon or Nitrogen	Good droplet breakup, Scalable Reduced oxidation	Nozzle wear, Sensitive to gas pressure variation	[4],[5]
Swirl-Type	Allow Wire	Argon or Helium	Enhanced control over atomization cone, High sphericity	Complex design Potential clogging with viscous melts	[17], [19]. [26]
Multi-Jet	Molten Stream	Argon	Uniform spray pattern, Effective cooling, Consistent particles shape	Satellite formation, High gas consumption	[16], [20], [28]
Vortex	Molten Stream	Argon	Improved atomization efficiency, Suitable for reactive metals	Flow instability, Tuning sensitive performance	[24], [29]

2.5 Melt Stream Nozzle

Nozzle geometry for the melt stream for gas atomization is of key interest for optimizing powder production. Inner diameter can be used to configure the atomization process to produce particles within a range that is desired. As the melt stream nozzle diameter was decreased, a range of 1 mm – 4 mm, it was observed that narrower particle size distribution occurred as well as a reduction is satellite particles which improves surface quality of the particles [42]. The angle at which the nozzle converges or diverges also plays a role. Based on the converging or diverging angle the static pressure can be observed to reach an ideal set up for the material, Zinc was used in this study [43] to find aspirating atomization conditions.

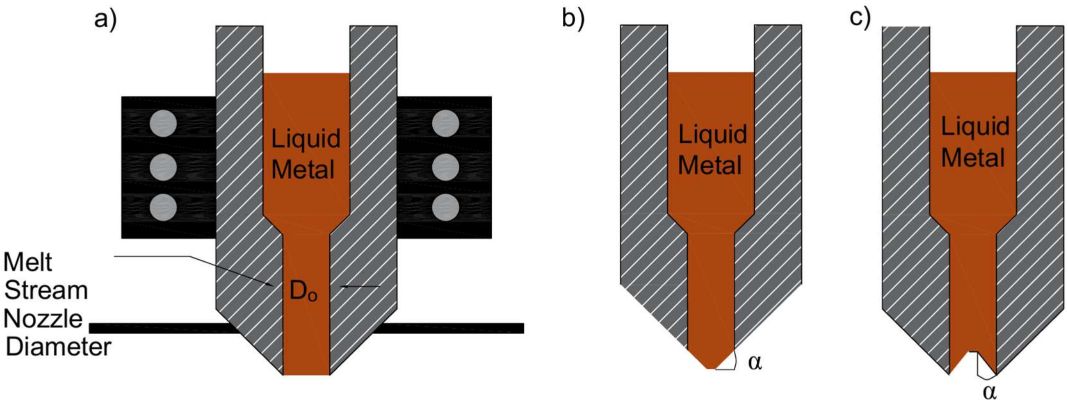

Figure 5: (a) Illustration of Melt Delivery tube: (b) Converging angle; (c) Diverging angle

2.6 Impact of Nozzle Design on Powder Quality

The quality of metal powders produced through atomization can be influenced by the nozzle's design. Key powder characteristics, such as particle size, shape, distribution, and purity, are all affected by the interaction between the atomizing gas and the molten metal stream, which is governed by the nozzle design [8]. For instance, close-coupled nozzles are known to produce powders with a high degree of sphericity and narrow size distribution, making them ideal for additive manufacturing applications where uniformity and flowability are critical [13]. On the other hand, swirl-type and vortex nozzles are preferred for producing powders that require high surface area and reactivity, such as those used in catalysis and chemical processes [14].

By optimizing nozzle design, manufacturers can achieve greater control over the atomization process, leading to improved powder quality and reduced production costs. As the demand for high-performance metal powders continues to grow, the importance of advanced nozzle design in liquid metal atomization will only increase, driving further research and innovation in this field.

2.7 Use of Computational Fluid Dynamics (CFD)

Recent research has focused on optimizing nozzle design through computational fluid dynamics (CFD) simulations, which allow for detailed analysis of gas flow patterns, metal stream behavior, and droplet formation [10]. These simulations have enabled the development of nozzles with improved gas dynamics, resulting in more efficient atomization processes and higher quality powders [7]. Additionally, advances in additive manufacturing have facilitated the production of complex nozzle geometries that were previously difficult or impossible to fabricate using traditional methods [11]. These innovations have opened new possibilities for tailoring nozzle designs to specific materials and applications, further enhancing the capabilities of liquid metal atomization.

CFD has emerged as a crucial tool in understanding the complex multiphase interactions that occur during gas atomization. By simulating the primary and secondary breakup of molten metal streams, CFD offers predictive insight into powder particle size, morphology, and distribution. The simulation of these processes can help visualize the breakup of molten jets into ligaments and droplets under varying operational parameters, including gas velocity, melt temperature, orifice size, and nozzle geometry [14][15]. It has become particularly valuable for optimizing process parameters such as nozzle design, gas type, and feedstock flow conditions.

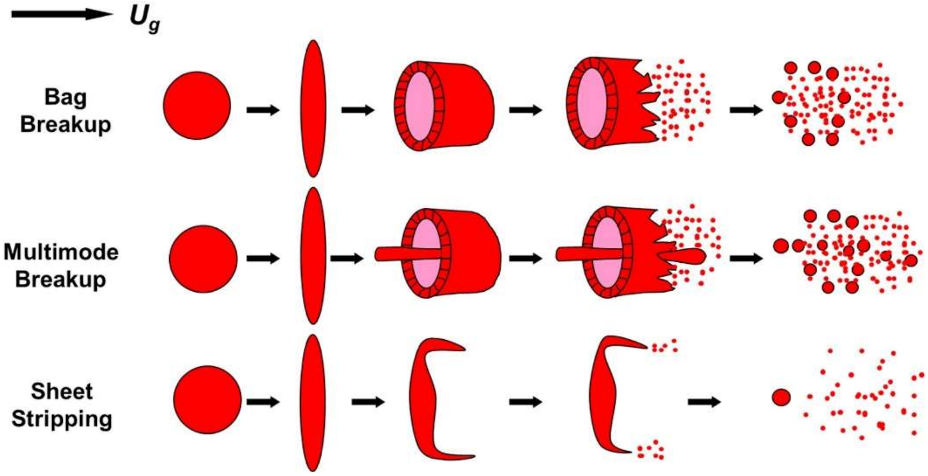

Figure 6: Typical modes of droplet breakup [37].

A widely employed modeling approach involves coupling the Volume of Fluid (VOF) method for capturing gas–liquid interfaces with Lagrangian particle tracking for simulating droplet behavior post-fragmentation. Li and Fritsching [37] demonstrated this hybrid Eulerian-Lagrangian approach in simulating the Pressure Swirl Gas Atomization (PSGA) process. Their model incorporated both the primary breakup of the molten metal sheet and secondary droplet disintegration under the influence of gas jets, leading to improved accuracy in predicting droplet velocity and size distribution. Notably, they highlighted how incorporating droplet solidification and drag into the model enabled closer alignment with experimental measurements.

The comparison of three nozzle geometries (annular-slit, swirling gas, and inner gas jet) using VOF and Reynolds Stress Models (RSM) to capture turbulent atomization behavior [38]. Their findings revealed that inner gas jet designs enhanced primary breakup efficiency, contributing to finer powder generation. They also demonstrated that geometric factors significantly influence atomization energy transfer and droplet dispersion patterns.

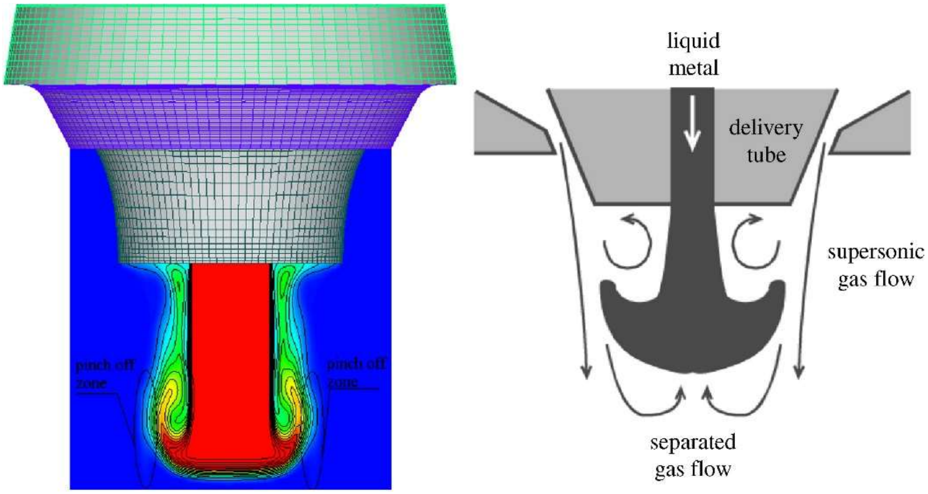

Figure 7: Illustration of the gas–melt interaction. [38].

Hsiao and Chiang [39] developed a CFD framework to assess how gas pressure influences molten metal fragmentation and atomization efficiency. Their simulations, which aligned closely with experimental data, revealed that increasing gas pressure significantly decreases the median droplet size and enhances the turbulent kinetic energy field. Furthermore, they demonstrated how standoff distance optimization can reduce energy losses and improve particle uniformity in close-coupled systems.

Zhang et al. [40] modeled the atomization of nickel-based superalloys using a transient multiphase CFD simulation that incorporated thermal and surface tension effects. Their analysis showed how melt properties and gas velocity vectors interact to shape the ligament and droplet formation stages. Notably, the simulation captured both hydrodynamic and thermal behavior, emphasizing the complex interplay between heat transfer, viscosity, and brea0kup dynamics.

Together, these studies demonstrate the evolution of CFD techniques toward multiscale and multiphase frameworks capable of capturing both large-scale gas dynamics and fine interfacial phenomena. This progress paves the way for more predictive and optimized atomization systems across a wide range of metal alloy feedstocks.

4. Conclusion

Liquid metal gas atomization is vital in producing high-quality metal powders, essential for advanced manufacturing applications, including additive manufacturing, powder metallurgy, and thermal spraying. This paper has provided an in-depth examination of the various aspects of gas atomization, particularly focusing on the atomization of steel, a material of immense industrial significance.

The atomization of steel presents unique challenges due to its high melting point and susceptibility to oxidation. However, through advanced techniques such as inert gas atomization and innovations in nozzle design, these challenges can be effectively managed. Close-coupled, swirl-type, and multi-jet nozzles have been shown to significantly enhance the efficiency of the atomization process, leading to the production of powders with superior properties, including narrow particle size distribution, high sphericity, and minimal contamination.

Furthermore, recent advancements in computational fluid dynamics (CFD) simulations and additive manufacturing have opened new avenues for optimizing nozzle design, allowing for greater control over the atomization process and the quality of the resulting powders. These developments underscore the critical role that nozzle design plays in the success of liquid metal atomization processes.

As the demand for high-performance metal powders continues to grow across various industries, ongoing research, and innovation in gas atomization technology, particularly in the areas of nozzle design and process control, will be essential. By improving the efficiency and consistency of the atomization process, manufacturers can meet the increasing requirements for high-quality powders, driving further advancements in manufacturing and material science. The future of liquid metal gas atomization looks promising, with continuous improvements in technology likely to yield even better results in terms of powder quality, production efficiency, and process sustainability.

Acknowledgement

The authors would like to acknowledge funding provided by the U.S. Department of Energy NNSA MSIPP Program under Award No. DE-NA0004003. The opinions expressed in this paper are solely those of the authors, and do not necessarily represent those of the DOE/NNSA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Morakotjinda, M., Fakpan, K., & Yotkaew, T. (2010). Gas atomization of low melting-point metal powders. *Chiang Mai Journal of Science*

[2] Dubberstein, T., & Heller, H. P. (2013). Effect of surface tension on gas atomization of a CrMnNi steel alloy. *Steel Research International*

[3] Heck, U., Fritsching, U., & Bauckhage, K. (2000). Gas flow effects on twin-fluid atomization of liquid metals. *Atomization and Sprays*.

[4] Supriadi, S., Susimah, T. I., Akbar, M. H. S., & others. (2020). Designs and evaluations of a gas atomizer to fabricate stainless steel metal powder for metal injection molding.

[5] Qi, H., Zhou, X., Li, J., Hu, Y., & Xu, L. (2021). Performance testing and rapid solidification behavior of stainless-steel powders prepared by gas atomization. *Materials*

[6] Prashanth, W. S., Thotarath, S. L., Sarkar, S., & others. (2021). Experimental investigation on the effect of melt delivery tube position on liquid metal atomization. *Advanced Powder Technology*

[7] Ünal, R. (2006). The influence of the pressure formation at the tip of the melt delivery tube on tin powder size and gas/melt ratio in gas atomization method. *Journal of Materials Processing Technology*

[8] Anderson, I. E., & Terpstra, R. L. (2002). Progress toward gas atomization processing with increased uniformity and control.

[9] Kaiser, R., Li, C., Yang, S., & Lee, D. (2018). A numerical simulation study of the path-resolved breakup behaviors of molten metal in high-pressure gas atomization: Emphasis on the role of shock waves. *Advanced Powder Technology*.

[10] Mates, S. P., & Settles, G. S. (2005). A study of liquid metal atomization using close-coupled nozzles, Part 1: Gas dynamic behavior. *Atomization and Sprays*

[11] Korobeinikov, I., Perminov, A., Dubberstein, T., & Volkova, O. (2021). Modification of liquid steel viscosity and surface tension for inert gas atomization of metal powder. *Metals*

[12] Wang, P., Li, J., Wang, X., Du, B. R., Shen, S. Y., & Ge, X. Y. (2021). Impact mechanism of gas temperature in metal powder production via gas atomization. *Chinese Physics B*

[13] Kassym, K., & Perveen, A. (2020). Atomization processes of metal powders for 3D printing. *Materials Today: Proceedings*.

[14] Li, X., & Fritsching, U. (2017). Process modeling pressure-swirl-gas-atomization for metal powder production. *Journal of Materials Processing Technology*

[15] Chang, L., Xin, L., Shi, S., Huang, Y., & Li, X. (2021). Numerical investigation on flow process of liquid metals in melt delivery nozzle during gas atomization process for fine metal powder production. *Journal of The Chinese Society of Metals*

[16] Barreto, E. S., Liang, H., Phani, P. S., Hasan, R., & Pauly, S. (2022). Properties of gas-atomized Cu-Ti-based metallic glass powders for additive manufacturing. Materials Characterization, 186, 111852.

[17] Sun, P., Fang, Z. Z., Zhang, Y., Xia, Y., & Zhang, T. (2017). Review of the methods for production of spherical Ti and Ti alloy powder. JOM, 69(10), 1853–1860.

[18] Ciftcli, J., Choma, T., Morończyk, B., Kalicki, B., Puchalski, F. and Żrodowski, Ł., 2025. Alloy Development from Sustainable Materials–Close-Loop of Materials Using Ultrasonic Atomization. *Journal of the Japan Society of Powder and Powder Metallurgy*, *72*(Supplement), pp.S729-S735.

[19] Qian, J., Wang, T., Wang, X., Ding, Y., Zhang, W., Wang, F., ... & Yu, Y. (2022). A method for the preparation of spherical titanium powder for additive manufacturing. Powder Technology, 410, 117901.

[20] Mandal, S., Sutradhar, A., & Ghosh, R. N. (2022). Experimental and numerical investigations on molten metal atomization techniques. Advanced Powder Technology, 33(8), 103658.

[21] Kanaginahal, G., Kumar, K. A., Harisha, S. K., & Nayak, M. M. (2023). Automobile applications of mechanically alloyed magnesium and titanium materials. In A. M. Rane, & K. J. (Eds.), Nanocomposite Materials for Engineering Applications (pp. 231–243). Springer.

[22] Kanakannavar, S. H., Ramesh, B. M., & Kumar, K. P. (2024). Mechanical alloying of magnesium and titanium alloys. In A. J. M. F. Sarwar (Ed.), Sustainable Materials and Green Processing for Energy Conversion (pp. 210–232). IGI Global.

[23] Qian, J., Ding, Y., Wang, T., & Yu, Y. (2023). Preparation of spherical porous Ti6Al4V powder by copper-assisted spheroidization. JOM, 75(5), 1867–1877.

[24] Wang, Z., Fan, W., Shi, H., Shi, P. and Don, R., 2022, March. Study of atomization characteristics of air atomizing nozzles for additive manufacturing. In *Journal of Physics: Conference Series* (Vol. 2228, No. 1, p. 012032). IOP Publishing.

[25] Liu, Y., Niu, S., Li, F., Zhu, Y. and He, Y., 2011. Preparation of amorphous Fe-based magnetic powder by water atomization. *Powder technology*, *213*(1-3), pp.36-40.

[26] Lüscher, P., Bochsler, J., Weiss, D., Huber, M., Löffel, K., Nieulande, R. and Duda, T., 2019. Numerical and experimental investigation of pressure-swirl nozzles produced by additive manufacturing. *ILASS-Europe 2019*, pp.2-4.

[27] Riabov, D., Hryha, E., Rashidi, M., Bengtsson, S. and Nyborg, L., 2020. Effect of atomization on surface oxide composition in 316L stainless steel powders for additive manufacturing. *Surface and Interface Analysis*, *52*(11), pp.694-706.

[28] Sames, W.J., List, F.A., Pannala, S., Dehoff, R.R. and Babu, S.S., 2016. The metallurgy and processing science of metal additive manufacturing. International materials reviews, 61(5), pp.315-360.

[29] Luo, A.A., 2004. Recent magnesium alloy development for elevated temperature applications. International materials reviews, 49(1), pp.13-30.

[30] Srivatsan, T.S., & Sudarshan, T.S. (Eds.). (2015). Additive Manufacturing: Innovations, Advances, and Applications (1st ed.). CRC Press.

[31] Persson, F., Eliasson, A. and Jönsson, P.G., 2014. Oxidation of water atomized metal powders. *steel research international*, *85*(12), pp.1629-1638

[32] Chen, G., Zhao, S.Y., Tan, P., Wang, J., Xiang, C.S. and Tang, H.P., 2018. A comparative study of Ti-6Al-4V powders for additive manufacturing by gas atomization, plasma rotating electrode process and plasma atomization. Powder technology, 333, pp.38-46.

[33] Jandaghi, M.R., Pouraliakbar, H., Iannucci, L., Fallah, V. and Pavese, M., 2023. Comparative assessment of gas and water atomized powders for additive manufacturing of 316 L stainless steel:

Microstructure, mechanical properties, and corrosion resistance. *Materials Characterization*, *204*, p.113204.

[34] Upadhyaya, G.S., 2006. German RM, Powder metallurgy and particulate materials processing, Metal powder industries federation, Princeton, USA, 2005, pp. 522, isbn 0-9762057-1-8. *Science of Sintering*, *38*(1), pp.95-95.

[35] Gao, M.Z., Ludwig, B. and Palmer, T.A., 2021. Impact of atomization gas on characteristics of austenitic stainless steel powder feedstocks for additive manufacturing. *Powder Technology*, *383*, pp.30-42.

[36] Mirzababaei, S. and Pasebani, S., 2019. A review on binder jet additive manufacturing of 316L stainless steel. *Journal of Manufacturing and Materials Processing*, *3*(3), p.82.

[37] Li, X. G., & Fritsching, U. (2017). Process modeling pressure-swirl-gas-atomization for metal powder production. Journal of Materials Processing Technology, 239, 1–17.

[38] Zeoli, N., Tabbara, H., & Gu, S. (2011). CFD modeling of primary breakup during metal powder atomization. Chemical Engineering Science, 66(17), 6498–6504.

[39] Beckers, D., Ellendt, N., Fritsching, U. and Uhlenwinkel, V., 2020. Impact of process flow conditions on particle morphology in metal powder production via gas atomization. *Advanced Powder Technology*, *31*(1), pp.300-311.

[40] Zhao, W., Cao, F., Ning, Z., Zhang, G., Li, Z. and Sun, J., 2012. A computational fluid dynamics (CFD) investigation of the flow field and the primary atomization of the close coupled atomizer. *Computers & chemical engineering*, *40*, pp.58-66.

[41] Wang, P., Li, J., Wang, X., Du, B.R., Shen, S.Y., Ge, X.Y. and Wang, M.H., 2021. Impact mechanism of gas temperature in metal powder production via gas atomization. *Chinese Physics B*, *30*(5), p.054702.

[42] Li, X.G., Zhu, Q., Shu, S., Fan, J.Z. and Zhang, S.M., 2019. Fine spherical powder production during gas atomization of pressurized melts through melt nozzles with a small inner diameter. *Powder Technology*, *356*, pp.759-768.

[43] Le, T. and Henein, H., 1996. Effect of nozzle geometry and position on gas atomization. *International Journal of Powder Metallurgy*, *32*, pp.353-364.