

REVIEW ARTICLE

Gas atomization for metal powder production in additive manufacturing: A review

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Abstract

Gas atomization is a key technology for producing high-quality metal powders, widely adopted in additive manufacturing and other powder-based industries due to its versatility and productivity. Its complexity, such as intense gas–liquid momentum exchange, thermal gradients in solidification, and multiple influencing factors, poses significant challenges for process control. This comprehensive review explores the complexities of gas atomization technology in metal powder production, examining the underlying mechanisms, simulation techniques, flow field dynamics, and key influencing factors. It clarifies that primary atomization is characterized by liquid film atomization, driven by Kelvin–Helmholtz instabilities, and fountain atomization, triggered by Rayleigh–Taylor instabilities. Secondary atomization, on the other hand, is predominantly influenced by shear and inertial forces. The review emphasizes the key roles of physical gas and liquid properties, temperature, pressure, nozzle design, and solidification processes in determining the characteristics of the resulting metal powder. It concludes that a thorough understanding of these factors is essential for refining the atomization process and improving the quality of the metal powder produced. The review suggests that future research should focus on resolving discrepancies in atomization mechanisms, enhancing simulation methodologies, and investigating the effects of advanced nozzle designs on the production of metal powder.

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1. Introduction

Additive manufacturing, also known as 3D printing, is an advanced manufacturing technology that builds objects layer by layer. Compared to traditional subtractive machining methods, additive manufacturing can reduce material waste, increase production efficiency, and enable the fabrication of complex-shaped objects,¹ with wide applications in the aerospace, medical, and automotive fields.² Metal 3D printing technology is at the forefront and holds the most potential within the 3D printing industry. The cost elements of metal 3D printing manufacturing include materials, preparation, machine, build process, and post-processing.^{3–8} For example, machine costs

account for 74%, post-processing costs for 7%, material

costs for 11%, and the remaining 8% (Figure 1).⁶ Therefore,

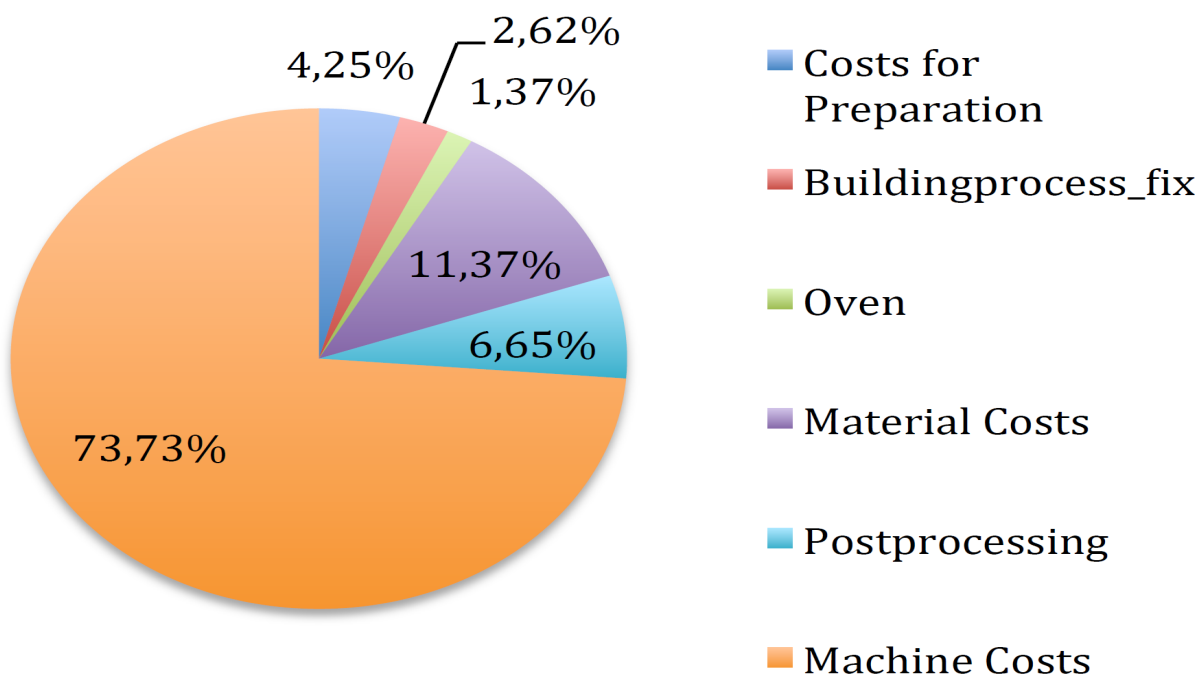


Figure 1. Cost breakdown structure for a batch size of 190 parts per build. Reprinted with permission from Lindermann *et al.*⁶ Copyright © 2012 University of Texas at Austin.

reducing material costs can effectively decrease the production costs of metal powder. The selection of metal powder should consider various factors, such as type, particle size, and shape. High-quality metal powder should have a relatively narrow size distribution, a spherical shape, and no defects to ensure stability and consistency during additive manufacturing.⁷⁻⁹

The preparation methods for metal powder mainly include water atomization, centrifugal atomization, ultrasonic atomization, plasma atomization, and gas atomization.⁹⁻¹² Water atomization utilizes high-pressure water jets to fragment molten metal into fine droplets (Figure 2a). This method offers a short process route, low cost, and environmental friendliness; however, the resulting powders typically exhibit poor sphericity, high oxygen content, and are unsuitable for highly reactive metals.¹³⁻¹⁶ Centrifugal atomization disperses molten metal by high-speed rotation of a rotating disk, forming tiny droplets that solidify under a cooling gas flow (Figure 2b). The produced powders have good sphericity, low oxidation

levels, controllable particle size, and high yield. However, it requires high equipment costs and generally yields coarser powders.^{17,18} Ultrasonic atomization involves applying ultrasonic vibrations to metal droplets, inducing Rayleigh instability and leading to the uncontrolled formation of small metal droplets (Figure 2c). These droplets solidify into powder during cooling.¹⁹ This method produces powders with good sphericity, uniform particle size distribution, low energy consumption, and low oxygen content, but its overall yield is limited.^{19,20-23} Plasma atomization involves feeding a metal wire into a plasma jet, where it melts and disintegrates into fine particles (Figure 2d). Metal powders produced by plasma atomization offer superior sphericity and finer particle sizes, but using wire as a raw material increases costs and restricts the range of processable alloys.^{12,24-26} Among these techniques, gas atomization stands out for its ability to produce highly spherical powders with narrow particle size distributions, high productivity, and controllable cost, making it the most widely adopted method for metal powder preparation in additive manufacturing.²⁷⁻²⁹

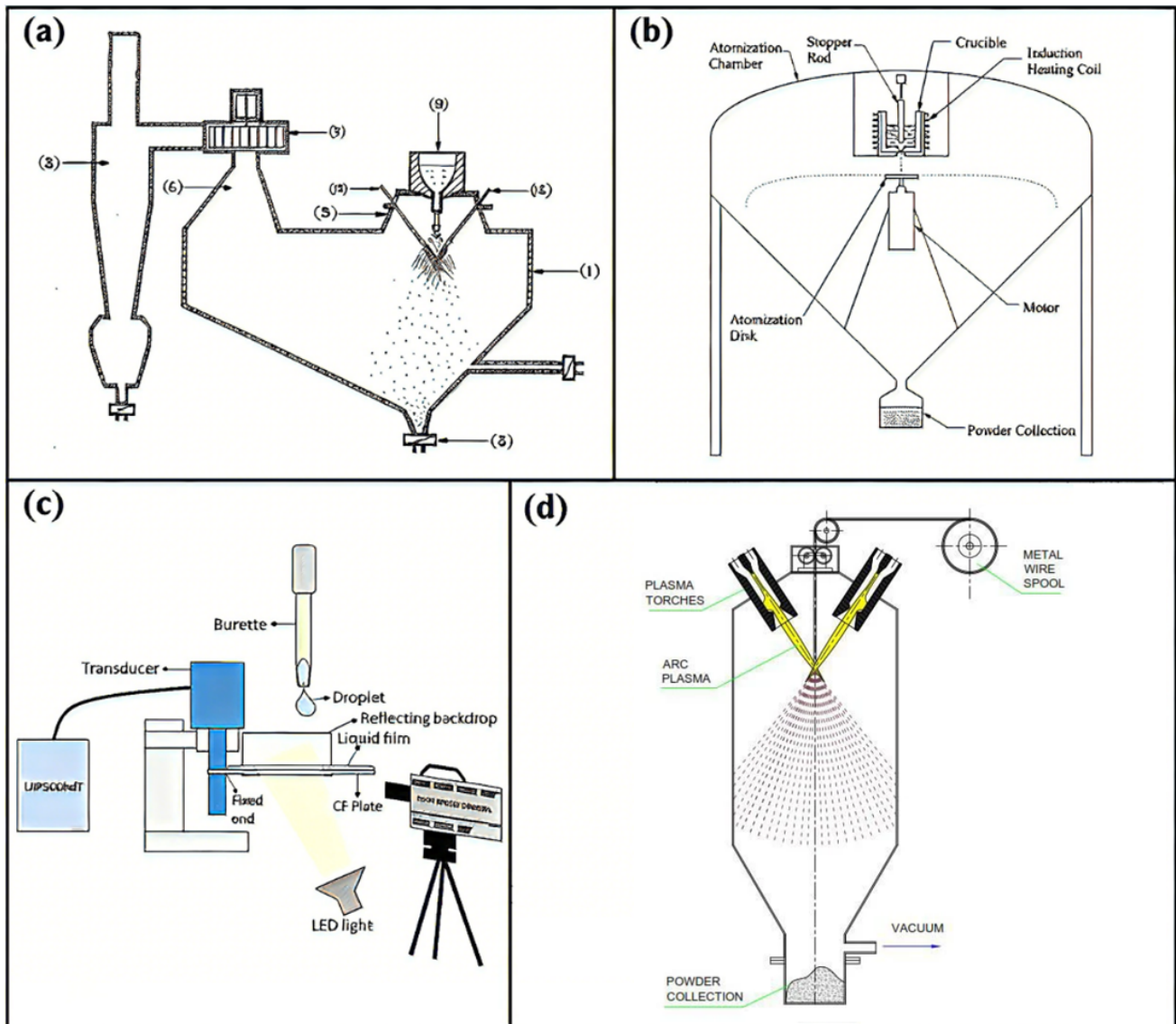


Figure 2. Schematic diagrams of preparation methods for metal powder. (a) Water atomization. Reprinted from Yenwiset *et al.*³⁰ (b) Centrifugal atomization with gas jet. Reprinted from Cegarra *et al.*³¹ (c) Ultrasonic atomization. Reprinted from Priyadarshi *et al.*¹⁹ (d) Plasma atomization. Reprinted from Baskoro *et al.*²⁴

Gas atomization, which originated in the 1920s, has become one of the most mainstream methods for producing metal powders.^{32,33} Common gas atomization nozzles include free-fall nozzles and close-coupled nozzles.^{27, 34-36} As shown in Figure 3a, a free-fall nozzle has a simple structural design and is less prone to clogging. To minimize the distance between the gas flow and the guide tube exit, a compact, close-coupled nozzle was developed. As shown in Figure 3b, the close-coupled system has been widely used due to its significant improvement in atomization efficiency.³⁷⁻³⁹ Gas atomization typically

involves three sequential stages, including primary atomization, secondary atomization, and cooling and solidification.⁴⁰⁻⁴² During atomization, the kinetic energy of the high-velocity gas stream is converted into the surface energy of molten metal droplets through intense gas-liquid interactions, forming fine metal droplets that subsequently solidify into spherical powders (Figure 3c). Gas atomization is a complex gas-liquid two-phase flow coupling process.⁴³⁻⁴⁶ Two recent reviews highlight emerging research directions: Ren *et al.*⁴⁷ comprehensively describe the full additive manufacturing powder lifecycle,

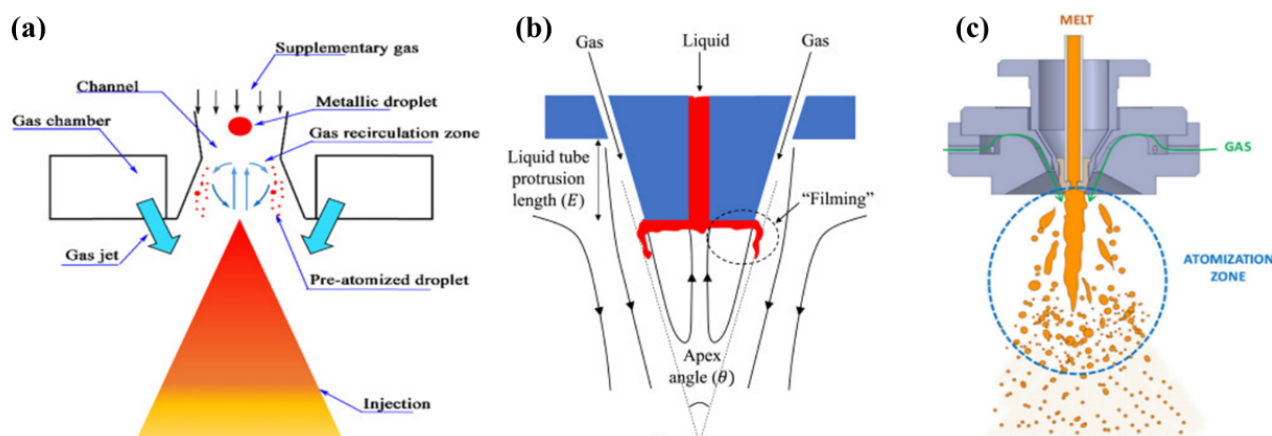


Figure 3. Schematic diagrams of (a) free-fall, (b) close-coupled gas atomizers, and (c) the atomization of a melt stream by the rapidly expanding gas. Reprinted with permission from (a) Zou and Xiao⁴⁶ Copyright © 2021 Elsevier, and (b) Cheng *et al.*³⁷ Copyright © 2024 Elsevier. (c) Reprinted from Urionabarretxea *et al.*⁴⁶

from atomization preparation and modification to reuse, while Xie *et al.*⁴⁸ review electromagnetic treatment as a novel route to enhance metal performance via microstructure control. These advances suggest that electromagnetic treatment can be integrated into powder processing, either during atomization (e.g., in-flight melt control) or as a post-treatment, to optimize powder characteristics and improve final part quality. However, the success of such integration depends critically on a thorough understanding of the factors that govern powder formation. The properties of the molten metal, atomizer design, and atomizing gas characteristics, all of which have been extensively studied, significantly influence powder morphology, size distribution, and overall quality. A systematic understanding and optimization of these parameters remain essential for improving the efficiency, controllability, and reproducibility of gas-atomized powder production.

In this review, we present a comprehensive and up-to-date overview of research on gas atomization. The structure of this paper is organized as follows: Following the general introduction in **Section 1**, **Section 2** outlines the fundamental mechanisms of gas atomization; **Section 3** summarizes the development of numerical and computational methods for modeling the atomization process; **Section 4** discusses the characteristics and morphology of the gas atomization flow field; **Section 5** reviews the influencing factors affecting atomization behavior and powder quality; and **Section 6** concludes this review and outlines future perspectives.

2. Mechanisms of gas atomization

2.1. Primary fragmentation

The gas atomization process is divided into primary and secondary fragmentation.^{49–52} Primary fragmentation comprises two types: fountain atomization and liquid film atomization. Fountain atomization is governed by Rayleigh–Taylor instability at the interface between two fluids of different densities.^{53–55} Under gravity, density differences cause wave crests to bulge. Disturbances from the undulating liquid surface create crests and troughs; gas passing through the troughs fragments the column. The resulting metal threads extend into ribbon-like structures along the gas flow direction. Liquid film atomization is driven by Kelvin–Helmholtz instability.^{53,56} Transverse shear forces in the recirculation zone act on the molten metal stream, inducing lateral flow. The velocity difference between melt and gas produces tangential shear at the interface, amplifying disturbances. As fluctuation amplitude increases, parts of the film spontaneously detach and, under surface tension, form fine droplets.

Initially, three primary fragmentation modes were identified: fiber breakup, bag breakup, and Rayleigh breakup.⁵⁰ Fiber breakup occurs when the initially broken liquid passes through the Mach disk, where the droplet–gas velocity difference is maximal, yielding a high Weber number; this mode dominates and promotes the formation of fine droplets. Further studies categorize primary fragmentation into four patterns: deformation, Rayleigh breakup, membranous (bag) breakup, and fiber-type breakup (Figure 4).^{57,58} Morphological analysis (aspect ratio and sphericity) shows that about 30% of the fragments exhibit fiber morphology.

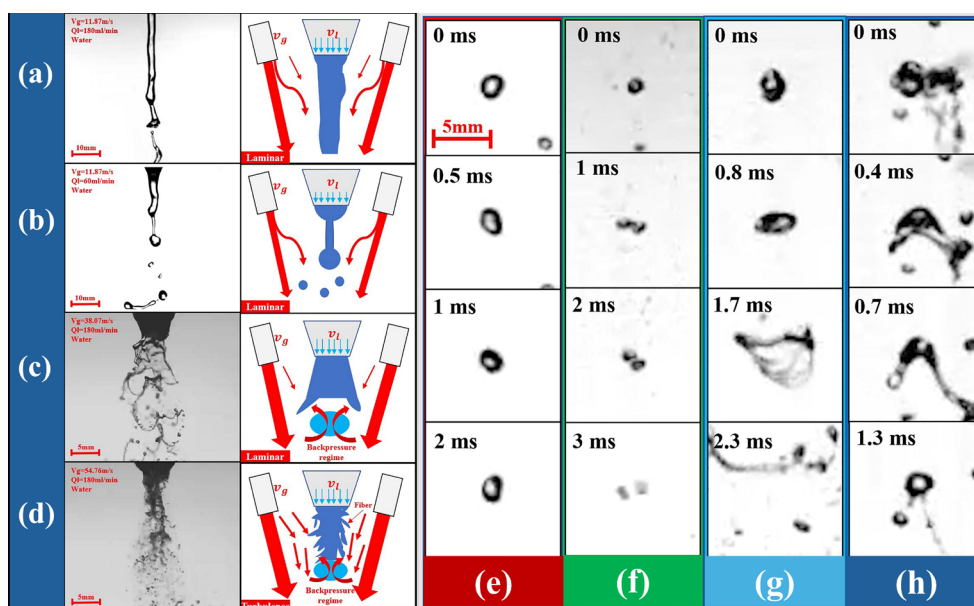


Figure 4. Four primary breakup modes: (a) deformation, (b) Rayleigh breakup, (c) membranous breakup, and (d) fiber-type breakup. Four secondary breakup modes: (e) deformation breakup, (f) vibration breakup, (g) bag breakup, and (h) sheet-thinning breakup.⁵⁸ Reprinted from Luo *et al.*⁵⁸

During primary atomization, recirculating gas at the liquid–melt interface forms an inverted mushroom-shaped structure (a miniature fountain). Strong gas recirculation also squeezes the melt flow, forcing part of the molten metal upward to form thin melt edges.⁵⁹ In the secondary fragmentation stage (droplet growth and aggregation), the gas Weber number always remains below 50; therefore, bag breakup and multimode breakup dominate.⁴⁹ For high-temperature alloy melts, fragmentation morphology alternates between umbrella and inverted mushroom shapes.⁵¹ Increasing gas–liquid interaction intensity induces chaotic flow, which becomes more pronounced with rising atomization pressure, thereby enhancing overall atomization efficiency.

2.2. Secondary fragmentation

Secondary fragmentation is driven by the combined effects of gas inertial forces and droplet surface tension.^{60–63} The Weber number (We), defined as the ratio of inertial forces to surface-tension forces, quantifies the relative importance of aerodynamic forces. Higher Weber numbers lead to more intense droplet breakup. Figure 5 shows the schematic of the metal liquid flow fragmentation model, including bag breakup, multimode breakup, and sheet stripping. Experimental studies have further refined these modes. Three distinct secondary fragmentation modes have been observed: normal necking, interference, and impact fragmentation.⁶⁴ Another classification identifies four patterns: deformation, vibrational, bag, and sheet-

thinning breakup.^{57,58} Among these, vibrational breakup dominates, accounting for about 68% of events and producing relatively uniform powder sizes. The remaining ~30% involve bag and multimode breakup, which contribute to a wider particle size distribution.

It should be noted that the boundaries between different fragmentation modes by Weber number vary across different literature studies. These variations arise from differences in experimental conditions, liquid properties, and diagnostic methods. The framework provided by Guildenbecher *et al.*⁶² remains the most comprehensive and frequently cited reference in the field. The atomization modes, as classified by Weber number from various sources, are summarized along with brief explanations:

- Vibrational/deformation ($We < 11$ – 12): Droplets oscillate and deform (e.g., oblate/prolate) without breaking; surface tension dominates, so the shape recovers; vibrational modes are periodic shape changes, and deformation modes are steady distortion.
- Bag breakup ($11 < We < 35$ or $12 < We < 20$): Droplets deform into a bag-like liquid film; the bag body breaks into smaller droplets while the bag rim fragments into larger ones.
- Multimode breakup ($20 < We < 80$, subdivided into bag/plume for $20 < We < 40$, and plume/shear for $40 < We < 80$): Similar to bag breakup but with an additional axial ligament, producing more large droplets.
- Shear breakup (sheet-thinning) ($80 < We < 350$ – 800):

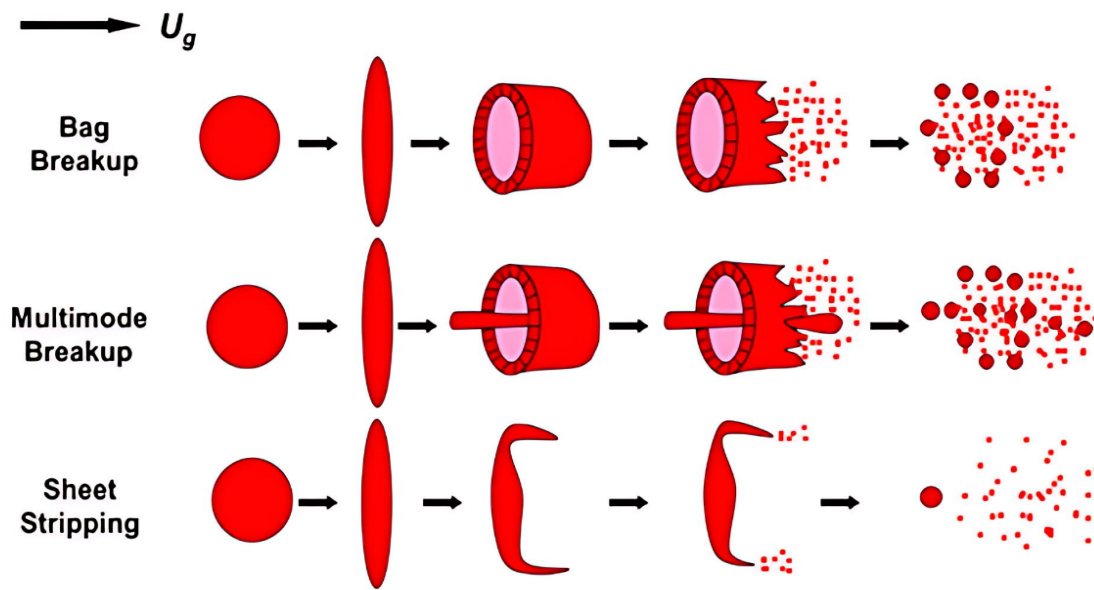


Figure 5. Schematic of secondary breakup modes of a molten metal droplet with increasing gas velocity, illustrating the transition from bag breakup to multimode breakup and finally to sheet stripping. Reprinted with permission from Li and Fritsching⁴⁹ Copyright © 2016 Elsevier.

Plate-like droplets are stripped from their edges downward, gradually reducing in size until only large droplets and numerous small droplets remain.

- Catastrophic breakup ($We > 350-800$): Aerodynamic forces completely overwhelm surface tension. The droplet disintegrates explosively into a fine spray immediately upon impact, with no oscillation or recovery, producing tiny fragments.

2.3. Droplet cooling and solidification

Solidification plays a critical role in shaping metal powders, as once droplets solidify, their morphology becomes fixed. Surface tension drives droplets toward a spherical shape, but the time available for this transformation is limited by the solidification time; thus, the solidification rate directly affects powder sphericity.⁶⁵⁻⁷¹ Droplet size influences the solidification rate because smaller droplets have a higher surface-area-to-volume ratio, enabling more efficient heat exchange and faster cooling. Consequently, smaller droplets exhibit faster cooling rates than larger ones.

During solidification, temperature decreases from the droplet surface toward the center. High undercooling induces transient nucleation and rapid surface solidification. The windward side cools faster than the leeward side, creating an overall temperature gradient from windward to leeward within the droplet (Figure 6).⁶⁶ The resulting rapid-solidification structure shows minimal element segregation, a typical feature of rapidly

solidified powders.^{67,68} The cooling rate is controlled by the convective heat transfer coefficient during solidification and by the ratio of the inertial force to the viscosity (i.e., the Reynolds number).⁶⁵

As solidification proceeds, latent heat is continuously released, significantly reducing the cooling rate. As particle temperature decreases, the heat transfer rate between the particle and the gas phase also decreases, further lowering the cooling rate. Small particles cool faster than large particles because of their higher heat transfer rate in the gas flow field.^{70,71} Atomized droplets undergo segregation solidification into twin-crystal spherical segments. For a Cu–Sn alloy system, the critical morphological transition from cellular to dendritic structures occurs when the powder diameter lies in the range of 44.1–86.0 μm .⁶⁹ The cellular-to-dendritic transition is strongly influenced by alloy chemistry, constitutional supercooling, and solidification conditions. To explain this alloy-specific behavior, the Kurz–Fisher (KF) criterion⁷² relates the critical growth velocity to the planar stability limit and alloy-dependent parameters, such as the solute partition coefficient, liquidus slope, and solute diffusivity. Building on Flemings⁷³ work, constitutional supercooling drives this morphological shift. However, recent evidence indicates that the KF criterion is not universal; its predictions deviate for certain partition coefficients, reinforcing alloy specificity. Gianoglio *et al.*⁶⁵ demonstrates that in gas atomization, varying particle size and thus cooling rate

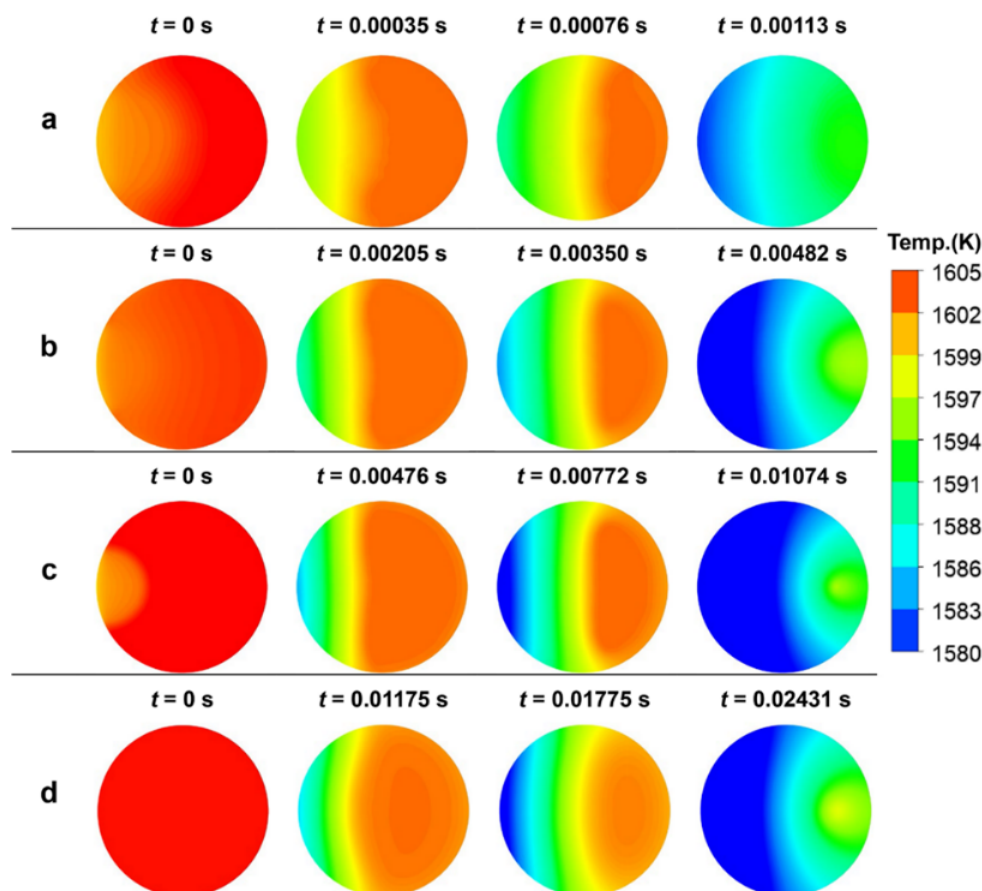


Figure 6. Computational temperature field maps at different time points for secondary droplets of Fe-Co-Ni-Cr-Mo-B-Si high-entropy alloy with varying diameters: (a) 25 μm, (b) 55 μm, (c) 95 μm, and (d) 155 μm. Reprinted with permission from Liu *et al.*⁶⁶ Copyright © 2024 Elsevier.

results in distinct solidification microstructures across different alloys.

2.4. Formation of defective powder

Defective powders produced during gas atomization are generally classified into four categories: hollow, satellite, dumbbell-shaped, and irregular powders (Figures 7 and 8). Each type originates from distinct gas–liquid interaction and solidification behaviors.^{42,66,74–79}

Hollow powders form when gas becomes trapped inside molten droplets during rupture and closure, and surface tension fails to expel the bubbles before solidification. Such entrapment can arise from Kelvin–Helmholtz instability during primary atomization, as well as from the rupture and closure of film droplets in secondary atomization.⁷⁶

Satellite powders result from collisions between droplets or particles of different sizes and solidification states. Owing to different aerodynamic resistances, smaller

solidified particles move faster and adhere to larger, still-liquid, or semi-liquid particles.^{74,75,77,79} Collisions between fine droplets and spherical powders are particularly prone to satellite formation.⁴² In general, droplet–powder or droplet–droplet collisions hinder the production of spherical powders.

Dumbbell-shaped powders are produced when two molten droplets with low superheat coalesce; the increased viscosity of the undercooled melt prevents their separation before solidification. Irregular powders arise from multiple mechanisms involving rapid cooling and insufficient spheroidization time. When droplets cool drastically, there is insufficient time for surface tension to reshape them into spheres. Insufficient drag force may also deform droplets rather than separate them.⁷⁶ Collisions between flake-like droplets and fine spherical powders tend to produce flaky powder with torn surfaces.³⁵ Additionally, when two melting rods join, the overlapping joint melts instantaneously under surface tension, forming irregular

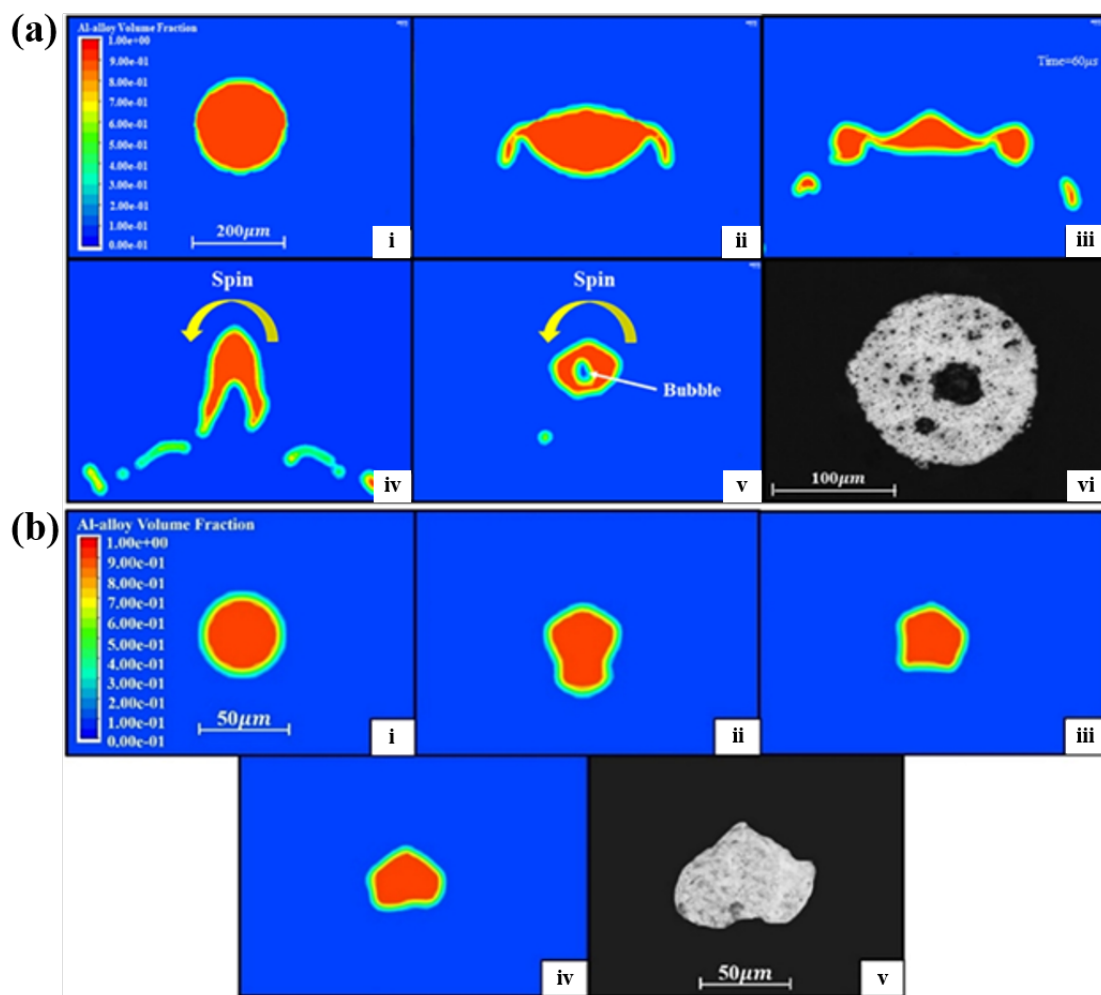


Figure 7. Evolution of hollow powders in (a) secondary breakup from the initial droplet (i) to bubble formation in the droplet (v), and (vi) is the hollow powder in an optical microscope. (b) Evolution of irregular droplet from the initial droplet (i) to solidification of droplet (iv), and (v) is the irregular powder in an optical microscope. Reprinted from Luo *et al.*⁷⁸

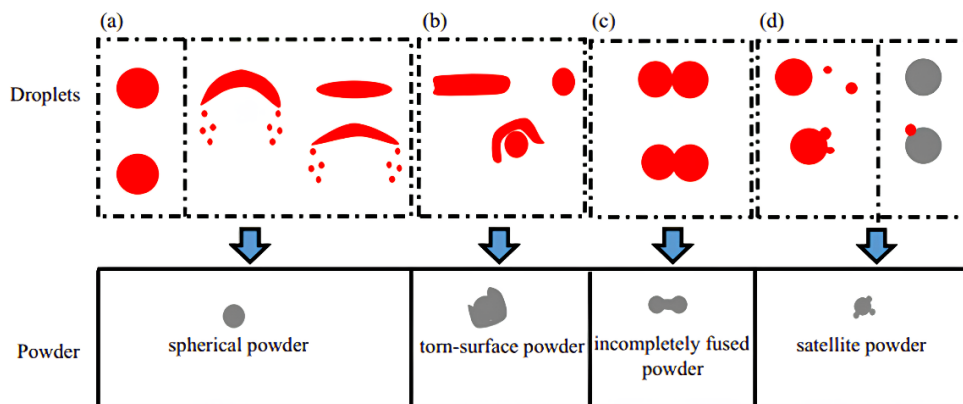


Figure 8. The relationship between powder morphology and the simulated droplet shape. (a) Spherical powder by direct solidification of spherical droplets in the primary or secondary atomization. (b) Torn-surface powder formed by sheet droplets colliding with the spherical powder. (c) Incompletely fused powder due to the low superheat of bonded droplets. (d) Satellite powder formed by fine droplets colliding with larger-sized droplets or solidified powder. Reprinted with permission from Wang *et al.*⁴² Copyright © 2021 Editorial Office of Chinese Physics B.

melt that solidifies into coarse irregular powder under rapid cooling.⁶⁶

Reducing the diameter of primary atomization droplets can prevent gas encapsulation (reducing hollow powders) and decrease droplet–particle collisions (reducing satellite powders)^{11,79–81} Extending droplet cooling time provides sufficient opportunity for gas bubbles to escape and for droplets to become spherical, thereby effectively reducing satellite and irregular powders. Understanding these formation mechanisms is crucial for optimizing powder morphology and mechanical properties.^{82–86}

3. Experimental and numerical approaches

3.1. Gas atomization platform

Gas atomization includes three distinct platforms:^{87–91} vacuum induction melting gas atomization (VIGA), electrode induction melting gas atomization (EIGA), and free-fall systems. VIGA melts feedstock in a ceramic crucible and atomizes via a close-coupled nozzle. It provides high fine-powder yields, broad alloy compatibility, and high efficiency, but risks ceramic inclusions and yields more satellites, with particle sizes skewed toward the finer range. EIGA employs crucible-free electrode induction melting of a pre-alloyed rod; the melt falls freely before atomization. This eliminates contamination, producing ultra-clean powders with narrow size distribution, high sphericity, and few satellites, ideal for reactive and high-melting alloys (>1,700 °C). However, EIGA requires more expensive electrodes and precise melt-rate control. Compared with VIGA, EIGA powders are finer and cleaner, whereas VIGA powders offer better cohesiveness. Free-fall atomization, in which the melt descends by gravity before gas impact, is used in EIGA and in traditional crucible-based small-scale systems. It prevents melt buildup at nozzles in close-coupled designs, but suffers from lower efficiency, producing coarser powders (median ~100 µm) with usable yields of 20%–60% depending on conditions.

Extensive research has been conducted on gas atomization equipment for metal powder production, enabling the rational design of powder characteristics for specific additive manufacturing and powder metallurgy applications. A typical setup (Figure 9) uses a heating coil and melting crucible to melt the metal, which is then poured into a melting chamber connected to the atomization chamber's guide tube. Under pressure and gravity, the molten metal flows through the guide tube and interacts with atomizing gas, forming small droplets that cool and solidify into powder. Screens or filters remove impurities, and the powder is characterized by sphericity and size distribution. Such experiments are designed to investigate how critical process parameters,

such as gas pressure, melt superheat, and nozzle geometry, influence droplet breakup dynamics, cooling histories, and final powder attributes, thereby offering a scientific basis for optimizing the atomization process. Ultimately, this knowledge is of significant practical importance, as it guides the production of high-quality powders with consistent morphology, narrow size distribution, and low defect content, which are essential prerequisites for reliable and reproducible performance in downstream manufacturing processes.

3.2. Numerical approach

Due to high gas consumption, vacuum conditions, and high-temperature melt, experimental observation of the gas atomization process is challenging.^{46,92,93} Therefore, numerical simulation has become essential for visualization. For primary atomization, the volume of fluid (VOF) method is widely used to capture immiscible fluid interfaces, where the gas–liquid coupling is primarily realized through shared pressure and velocity fields at the interface, with momentum exchange governed by surface tension forces and viscous shear. However, this coupling mechanism suffers from issues such as spurious parasitic currents arising from inaccurate surface tension gradient discretization, numerical diffusion that smears the sharp interface, and severe grid-resolution dependence, which together compromise the fidelity of ligament and sheet formation. The method is often coupled with various turbulence models (e.g., k – ϵ , k – ω , Reynolds stress model, and large eddy simulation [LES]), offering higher accuracy at higher computational cost.^{94–100} For secondary atomization, the discrete particle method (DPM) is commonly employed, which neglects particle volume to reduce computational cost but may cause mass non-conservation; nonetheless, it reasonably predicts the particle size distribution.¹⁰¹

Other approaches include the Reynolds-averaged Navier–Stokes (RANS) method, as well as the Euler–Lagrange method with two-way coupling, which accounts for momentum, heat, and mass transfer between the continuous gas and discrete droplet phases through drag, lift, turbulent dispersion, and evaporation models. This coupling faces persistent difficulties in convergence stability, the appropriate selection of exchange coefficients in dense spray regions, and the accurate modeling of droplet-induced turbulence modulation, while the inherent scale disparity between large gas eddies and fine droplets further exacerbates computational expense and sub-grid closure uncertainties. Commonly used commercial software includes ANSYS Fluent and OpenFOAM.^{102–108} Some studies have also simplified simulations using logarithmic stability rate, similarity theory, and pre-exponential factors.

Regarding the initial conditions for droplet diameter in DPM, as reported by Luo *et al.*,¹⁰⁹ the initial droplet diameter follows the Rosin–Rammler distribution, and the initial particle size can be explicitly determined from a given mass fraction, mean diameter, and spread parameter. During atomization, droplet breakup is described by either the Kelvin–Helmholtz–Rayleigh–Taylor model³³ or the Taylor analogy breakup (TAB) model:¹¹⁰ the former is applicable to high Weber number regimes ($80 < We < 800$),

capturing droplet breakup through Kelvin–Helmholtz wave and Rayleigh–Taylor instability mechanisms; the latter is suitable for low Weber number conditions ($12 < We < 40$ – 100), determining breakup timing by tracking droplet oscillation and distortion. For convenience, all types of models involved in gas atomization are summarized in Table 1, along with their key features, advantages, and limitations. The governing equations employed in the VOF–computational fluid dynamics (CFD)–DPM approach are listed in Table 2.

Table 1. Types of models involved in simulating the gas atomization process

Model	Key features	Advantages	Limitations
Eulerian interface tracking (VOF)	Track gas–melt interface dynamics and droplet formation during primary breakup	Ideal for simulating primary breakup and droplet formation; good for primary droplets $> 100 \mu\text{m}$	Computationally costly to resolve small droplets ($< 10 \mu\text{m}$); only resolve droplets above $\sim 100 \mu\text{m}$
Lagrangian particle tracking (DPM)	Track discrete particles/droplets and model secondary breakup via breakup models (KH, KH–RT, TAB)	Ideal for secondary breakup of large droplets and particle temperature variation; suitable for dispersed phase volume fraction $< 10\%$	Results depend heavily on input conditions (droplet size, position, velocity, temperature); require empirical breakup models
Coupled VOF–DPM	VOF tracks primary atomization, extracts droplet information; DPM simulates secondary atomization	Combine advantages of Eulerian and Lagrangian methods; enable multi-scale atomization modeling	Transition criterion from VOF to DPM requires correct identification; coupling errors require optimization
Coupled VOF–DPM–LES	VOF–DPM–LES with KH–RT breakup model and adaptive mesh refinement	Cross-scale simulation of atomization mechanisms; LES captures large-scale turbulent structures with higher accuracy than RANS	Higher computational cost than RANS; model constants require calibration for specific conditions
Full-scale modeling (FSM) ¹⁰²	Resolve dynamics of droplets/particles of all sizes through adaptive mesh refinement/coarsening	Capture detailed physics without empirical closure models	Impractical for engineering processes due to extreme computational cost; computational domain typically limited to less than $10\times$ nozzle diameter
Turbulence: RANS	Solve time-averaged Navier–Stokes equations with turbulence closure models (e.g., k – ϵ , k – ω SST)	Lower computational cost than LES; widely used in industry	Cannot resolve turbulent fluctuations and vortical structures; rely on empirical closure models
Turbulence: LES	Resolve large-scale turbulent structures; sub-grid modeling for small scales	More accurate than RANS for capturing unsteady features, vortical flow structures, and spray dynamics	Higher computational cost than RANS; still require sub-grid modeling
Breakup: KH–RT	Combine KH (shear-driven) and RT (acceleration-driven) instabilities	Widely used for RANS and LES spray simulations; captures both primary and secondary breakup mechanisms	Model predictions highly dependent on empirical constants; droplet size may be severely underestimated if constants are not calibrated
Breakup: TAB	Taylor analogy breakup model—spring-mass-damper analogy for droplet deformation	Suitable for secondary breakup prediction; insensitive to droplet drag coefficient	Deformation parameter reaches maximum rapidly at high gas velocities
Simplified engineering models ^{111,112}	Empirical/Semi-empirical correlations for rapid prediction	Extremely low computational cost; suitable for preliminary design and parameter screening	Limited physical basis; prediction accuracy constrained by empirical correlations

Abbreviations: DPM: Discrete particle model; KH: Kelvin–Helmholtz; LES: Large eddy simulation; RANS: Reynolds-averaged Navier–Stokes; RT: Rayleigh–Taylor; SST: Shear stress transport; TAB: Taylor analogy breakup; VOF: Volume of fluid.

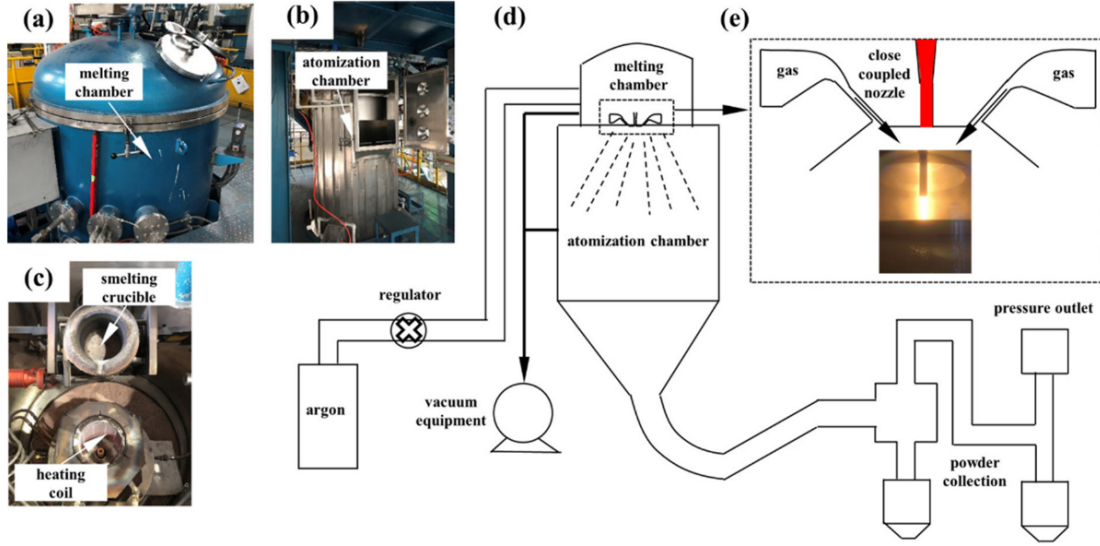


Figure 9. Schematic of the gas atomization setup for metal powder production and corresponding principle diagrams: (a) melting chamber, (b) atomization chamber, (c) heating coil and melting crucible, (d) atomizing gas interacts violently with the molten metal, and (e) atomization nozzle. Reprinted with permission from Zhang *et al.*⁷⁹ Copyright © 2022 Elsevier.

Table 2. Governing equations in VOF–CFD–DPM modeling of gas atomization

Items	Governing equations
Fluid governing equations	Continuity: $\partial \rho / \partial t + \nabla \cdot u = 0$ (1)
	Momentum: $\rho (\partial u / \partial t + u \cdot \nabla u) = -\nabla p + \rho g + \mu \nabla^2 u + f$ (2)
	Energy: $\partial (\rho h) / \partial t + \rho u \cdot \nabla h = \nabla \cdot (k_f \nabla T) + \Phi + Q$ (3)
	VOF phase: $\partial \alpha / \partial t + \nabla \cdot (\alpha u) = 0$ (4)
	where t is time, h is the specific enthalpy, k_f is the thermal conductivity, T is the temperature, Φ is the viscous dissipation term, Q is the heat transferred from the liquid phase to the gas phase, α is the volume fraction of the gas phase, u is the velocity of the molten metal, ρ is the density of the fluid, g is the gravity, p is the pressure, μ is the dynamic viscosity, and f is gas–liquid interface term, the resistance caused by the surface tension at the interface.
Turbulence: SST $k - \omega$	$\partial (\rho k) / \partial t + \partial (\rho u k) / \partial x_j = \partial (\Gamma_k \partial k / \partial x_j) / \partial x_j + G_k - Y_k$ (5)
	$\partial (\rho \omega) / \partial t + \partial (\rho u \omega) / \partial x_j = \partial (\Gamma_\omega \partial \omega / \partial x_j) / \partial x_j + G_\omega - Y_\omega + D_\omega$ (6)
	where k is the turbulent kinetic energy, ω is the specific turbulence dissipation, G_k represents the generation of turbulent kinetic energy due to mean velocity gradients, G_ω represents the generation of ω , Γ_k and Γ_ω represent the effective diffusivity of k and ω , respectively, Y_k and Y_ω represent the dissipation of k and ω , respectively, and D_ω represents the cross-diffusion term due to turbulence.
DPM	$m_i dv_i / dt = f_{d,i} + m_i (\rho_p - \rho) g / \rho_p + f_{vm,i} + f_{pgf,i}$ (7) where m_i and v_i are the mass and velocity of particle i. The terms on the right side are the drag force, buoyancy force, virtual mass force, and pressure gradient force, respectively, acting on particle i.
Initial droplet diameter & breakup model	$Y = \exp \left[- \left(d_{init} / \bar{d}_{init} \right)^n \right]$ (8) where Y is the mass fraction of droplets smaller than a given diameter d_{init}, $\bar{d}_{init}$ is the mean diameter, and n is the spread parameter with a specific value of 0.35. The droplet diameter will gradually decrease based on the droplet breakup model using the KH–RT model and the TAB model.

Abbreviations: CFD: Computational fluid dynamics; DPM: Discrete particle model; KH: Kelvin–Helmholtz; RT: Rayleigh–Taylor; SST: Shear stress transport; TAB: Taylor analogy breakup; VOF: Volume of fluid.

4. Gas atomization flow field characteristics

The characteristics of the gas atomization flow field are crucial for revealing the interactions and degree of confusion between the atomizing gas and metal droplets throughout the atomization process. Based on fluid types, the flow field characteristics are categorized into gas and liquid. The gas-phase flow field reflects the behavior and dynamics of the atomizing gas, and the liquid-phase flow field describes the motion, deformation, and breakup of the molten metal stream. Analyzing these flow field characteristics provides valuable insight into atomization efficiency and the mechanisms governing droplet formation and solidification.

4.1. Gas flow field characteristic

As illustrated in Figure 10, the gas flow field within an atomization chamber exhibits several distinct yet interrelated structures. The following description reveals common observations from multiple studies:^{42,79,92,98,101,113-118}

- (i) Initial expansion and supersonic flow. When the atomizing gas exits the nozzle into the lower-pressure chamber, it expands, forming a cluster of expansion waves. This process converts dynamic pressure into kinetic energy, accelerating the flow to supersonic speed while reducing its dynamic pressure.¹¹⁹ The compressible gas undergoes one-dimensional isentropic acceleration and decompression within the nozzle passage, creating a pressure difference that generates a chain-like Prandtl–Meyer wave at the nozzle exit.^{120,121} This supersonic transition occurs once the nozzle pressure ratio exceeds the critical value, choking the flow at the throat. The Prandtl–Meyer fan arises because the supersonic jet must turn around the nozzle lip through a series of discrete Mach waves, each corresponding to a specific pressure reduction and a corresponding increase in Mach number. The expansion waves remain stationary due to the continuous high-pressure supply, ensuring a steady underexpanded jet structure.
- (ii) Recirculation zone formation. The supersonic gas converges near the bottom of the chamber. Most of the flow continues downstream, but a small portion moves upward. This upward stream is deflected sideways near the guide tube, then merges with the downward supersonic flow, forming a low-velocity recirculation zone.^{42,98,113} At the melt tube corner, the airflow separates, creating a vertical recirculation zone bounded by an acoustic wave line; within this zone, upstream and downstream flows are separated by a turbulent layer.^{92,114-117} An extensive recirculation zone is typically present in atomization equipment. Due to

nozzle geometry constraints, the gas jet converges at a certain angle, and as the airflow deflects, a recirculation structure develops above the jet convergence point. The recirculation zone is sustained by entrainment of ambient gas into the high-speed jet, creating a low-pressure zone that draws fluid back upstream. The acoustic wave line acts as a sonic barrier isolating the recirculation region from the supersonic core. Within the turbulent layer, strong velocity gradients enhance mixing and momentum exchange across the shear interface, stabilizing the vortex structure.

- (iii) Shock waves and stagnation point. The expansion waves accelerate the gas, which then collides with the outer wall of the melt delivery tube and reflects from the free boundary, generating internal shock waves. A recirculation zone forms at the bottom of the melt delivery tube, separated from the surrounding high-speed gas by a sonic line, with a stagnation point (zero velocity) at its conical vertex.^{119,122} The atomizing gas expands through a series of Prandtl–Meyer waves composed of recompression shock waves. Below the feed pipe, an inverted conical recirculation zone exists, separated from the high-speed gas by a Mach line; approximately 26 mm below the feed pipe, the gas velocity drops to zero, forming another stagnation point. As the gas moves, the Prandtl–Meyer waves alternate continuously between compression and expansion.¹²⁰ The interface between upward and downward gas motions always contains a stagnation point where local velocity is zero. This compression–expansion alternation arises from the underexpanded jet, where exit pressure exceeds ambient pressure, forcing the flow to adjust through repeated shock-diamond structures. At each stagnation point, kinetic energy fully converts to pressure energy, causing local temperature and pressure rising. These stagnation points partition the flow field into distinct aerodynamic zones, directly influencing where the molten metal jet experiences primary breakup and thus affecting the final powder size distribution.

4.2. Liquid flow field characteristics

Based on the molten metal mass flow rate, two distinct primary atomization regimes are observed: liquid film flow and fountain-like flow (Figure 11).^{46,58,78,93,95,105,123-125} At low mass flow rates (e.g., 0.0075 kg/s), the molten metal cannot directly penetrate the recirculation zone. Near the bottom of the guide tube, the downward motion almost ceases, and the liquid spreads radially as a thin film. Over time, this film grows until it encounters the high-speed gas stream, whereupon ligament-like or filamentous rupture and fragmentation occur at the film's leading edge.

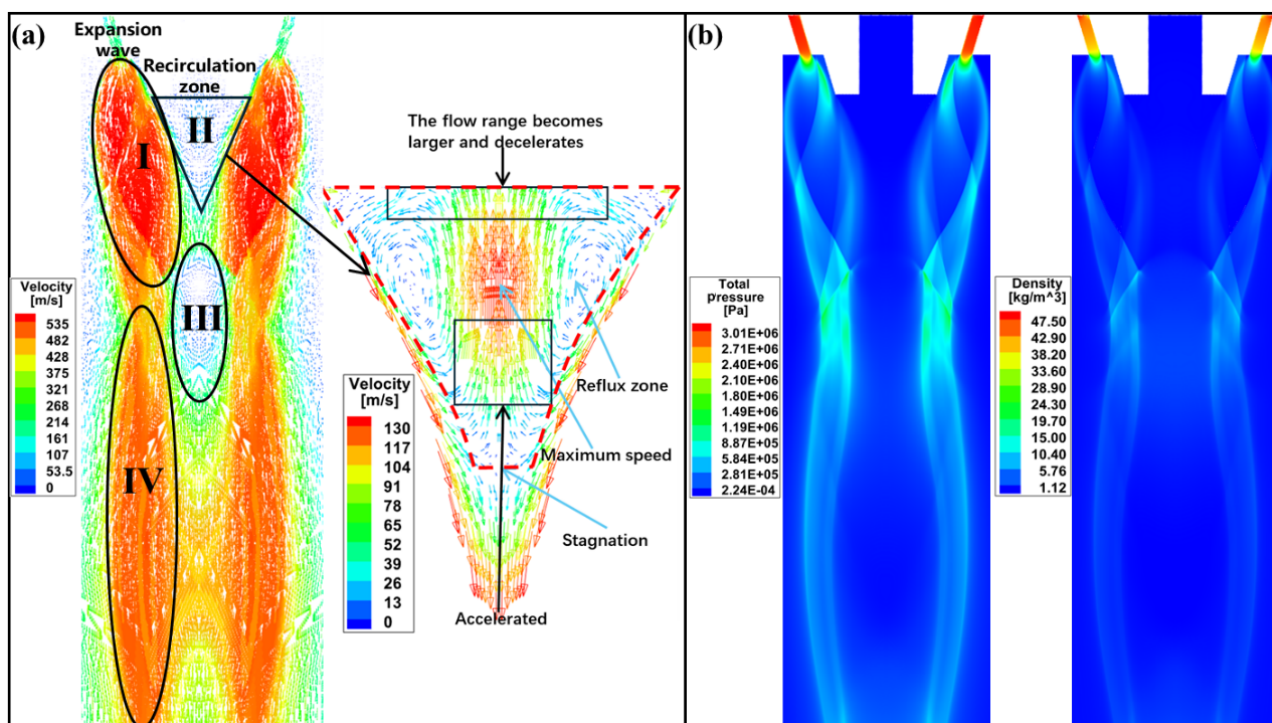


Figure 10. Characteristics of gas flow. (a) Velocity distribution of gas flow and the illustration of the recirculation zone, and (b) pressure and density distribution when the atomization pressure is 3.0 MPa.¹⁰⁰ Reprinted with permission from Zhang *et al.*¹⁰⁰ Copyright © 2026 Elsevier.

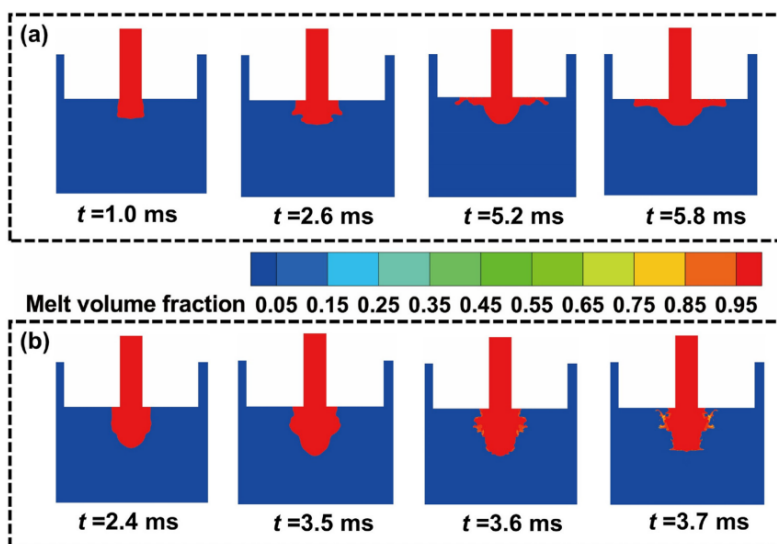


Figure 11. Breakup pattern of primary atomization under different liquid metal mass flow rates: (a) 0.0075 kg/s showing the typical liquid film breakup, (b) 0.0100 kg/s indicating a typical fountain breakup.¹²⁵ Reprinted from Wang *et al.*¹²⁵

This film-type breakup is governed by the competition between surface tension, which resists deformation, and the aerodynamic shear force exerted by the high-speed gas. When the local Weber number exceeds a critical

threshold, the interface becomes unstable, and capillary waves amplify into ligaments. The reduced melt flow rate yields insufficient momentum to overcome the adverse pressure gradient of the recirculation zone, forcing the

liquid to spread radially and form a thin film that is easily destabilized by the gas flow. Similar behavior is observed under specific conditions: at a liquid flow rate of 180 mL/min and a gas velocity of 38.07 m/s, the liquid fails to bypass the back-pressure region and cannot form a stable film due to high flow resistance and a broad film area that promotes easy rupture.⁶⁷ In aluminum melts, a toroidal liquid film forms at the bottom of the delivery tube, developing into a stable umbrella-shaped annular film. As atomization proceeds, the film thickness decreases. When it reaches a critical value, asymmetric wrinkled deformation appears, and the wrinkled tips evolve into a serrated pattern.^{46,78,95}

At higher mass flow rates (e.g., 0.01 kg/s), the melt no longer spreads radially but maintains an almost intact liquid column, exhibiting a typical “fountain” rupture pattern.^{105,123,124} Under the influence of gravity and the high-speed gas jet, the liquid spreads and converges at the bottom into a hemispherical shape. Thin sheets form around the hemisphere, pointing upward, giving an overall fountain-like appearance. Subsequently, the high-speed gas stream induces wrinkles on the fountain surface, which then transform into a serrated pattern. This transition to fountain-mode breakup is driven by the increased liquid

inertia, which overcomes the recirculation-induced back-pressure, allowing the melt to penetrate deeper into the gas field. The hemispherical liquid accumulation at the stagnation point experiences intense aerodynamic pressure, promoting sheet formation and subsequent perforation. Unlike the film regime where gravitational spreading dominates, the fountain mode exhibits enhanced surface instability because the larger liquid volume provides greater interfacial area for aerodynamic wave growth, facilitating finer droplet formation. At a mass flow rate of 0.05 kg/s, the liquid core continues to flow slowly downward while also extending radially. At 0.075 kg/s, the tip of the liquid core remains an almost intact column, and droplets are continuously stripped off by the gas impact, again demonstrating the fountain rupture mode (Figure 12).⁹³ For a liquid flow rate of 180 mL/min and a gas velocity of 54.76 m/s, the liquid surface becomes covered with many fibrous structures, indicating a transition toward finer disintegration,⁵⁸ where the enhanced aerodynamic shear and increased relative velocity between the gas and liquid phases promote capillary wave amplification, leading to ligament formation and subsequent droplet detachment from the liquid surface.

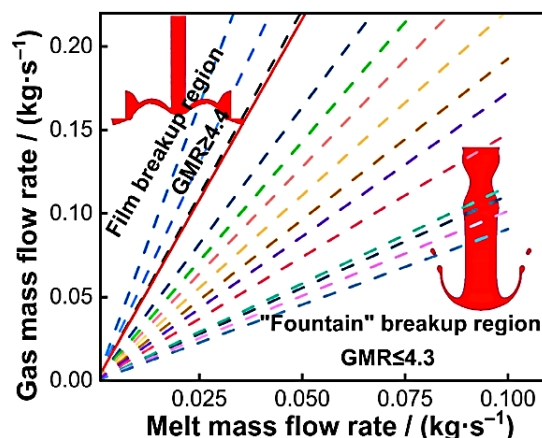


Figure 12. Influence of gas-to-melt ratio (GMR) on primary atomization breakup mode: with the two dividing lines (GMR = 4.3 and 4.4), the upper left corner represents liquid film breakup, and the lower right corner represents fountain breakup mode. Reprinted from Liu *et al.*⁹³

5. Influence factors on gas atomization

Gas atomization is governed by a complex interplay of parameters that determine final powder quality. Among these, the gas-to-melt ratio (GMR) is the most critical factor; higher GMR yields finer powders by enhancing kinetic energy transfer. Gas pressure, temperature, and type also influence breakup efficiency. Higher pressure and

temperature reduce droplet size, while helium produces finer powders than argon due to its higher velocity and thermal conductivity. Melt superheat and mass flow rate further affect viscosity and atomization stability, and nozzle geometry dictates atomization efficiency. Ultimately, powder characteristics such as particle size, sphericity, and microstructure result from the intricate

balance of these processing parameters. These powder attributes, in turn, directly govern the performance of downstream additive manufacturing processes. For example, Slotwinski *et al.*¹²⁶ developed ultrasonic porosity monitoring for powder bed fusion, while Brika *et al.*¹²⁷ linked Ti-6Al-4V powder morphology and flowability to laser powder bed fusion manufacturability. These

studies demonstrate that powder quality, such as porosity, particle shape, and size distribution, is critical for process control and final part properties. Table 3 summarizes the key influencing factors, their typical variation ranges, the effects on powder characteristics, and the underlying physical mechanisms, providing a concise overview before the detailed discussions.

Table 3. Overview of influencing factors on gas atomization

Factor category	Parameters	Typical variation	Effect on powder characteristics	Underlying mechanisms
Gas parameters	Pressure	Increasing	Decrease d_{50} ; increase fine powder yield	Higher gas kinetic energy improves melt disintegration; excessive pressure may cause turbulence and gas entrapment, leading to internal porosity.
	Temperature	Increasing (e.g., 25 °C to 400 °C)	Decrease d_{50} ; increase sphericity; decrease satellite formation	Higher temperatures increase gas velocity (to supersonic levels) and reduce melt viscosity, improving atomization efficiency.
	Type	Helium (He) > N ₂ > Argon (Ar) (velocity)	He produces the finest powders; Ar is cost-effective and inert	Helium's higher thermal conductivity and velocity yield rapid solidification, but its high cost limits industrial use.
Melt properties & conditions	Melt superheat (ΔT)	Increasing (e.g., 150 °C to 300 °C)	Decrease d_{50} ; decrease viscosity & surface tension	Enhanced fluidity allows finer breakup; excessive superheat increases the risk of hollow powder formation (gas bubble entrapment).
	Melt mass flow rate ($\dot{m}$)/nozzle diameter	Increasing	Increase d_{50} ; decrease fine powder fraction	For a given gas flow rate, higher melt throughput reduces GMR, lowering atomization efficiency.
	Gas-to-melt ratio (GMR)	Increasing	Decrease d_{50} ; increase sphericity	GMR is the most critical combined parameter; higher GMR improves energy transfer from gas to melt.
Atomizer design	Atomizer configuration	Close-coupled (confined) vs. free-fall	Confined: finer powders, higher efficiency, prone to melt buildup. Free-fall: coarser powders ($d_{50} \sim 100 \mu\text{m}$), simpler setup.	Confined nozzles achieve higher gas velocities at the impact point; free-fall nozzles allow longer melt pre-fragmentation time.
	Nozzle geometry (e.g., jet angle)	Optimized vs. suboptimal	Optimized design minimizes coarse particle generation and promotes a uniform size distribution.	Determines the gas-melt impact angle and turbulence intensity; influences droplet trajectory and solidification time.
Cooling & solidification	Cooling rate (indirect, determined by particle size)	Smaller particles; higher cooling rates (10^4 – 10^7 K/s)	Decrease secondary dendrite arm spacing; decrease micro-segregation	Cooling rate is inversely correlated with particle diameter; finer microstructures improve mechanical properties.
Environmental factors	Chamber atmosphere/vacuum level	High vacuum/inert gas purity	Decrease oxygen/nitrogen pick-up; decrease oxide film formation	Essential for reactive alloys (e.g., Ti, Ni-based superalloys); EIGA excels due to crucible-free melting, preventing ceramic inclusions.

Abbreviation: EIGA: Electrode induction melting gas atomization.

5.1. Properties of gas and liquid

Physical properties of both gas and liquid, such as viscosity, surface tension, and density, significantly influence the particle size and morphology of metal powders produced by gas atomization. Surface tension promotes droplet breakup, while viscosity resists melt flow and reduces the gas shear, thereby hindering fragmentation. However, under typical atomization conditions, the high shearing force largely overcomes the opposing effects of viscosity and surface tension. Additionally, reducing gases help suppress oxidation, remove entrapped bubbles, and minimize the formation of hollow particles. The specific type of atomizing gas also plays a role due to its distinct properties. Their effects are briefly reviewed in this section.

The effect of liquid viscosity on gas atomization has been systematically investigated.^{128–133} Decreasing viscosity generally reduces the median particle size and yields a finer powder fraction (Figure 13). This reduction lowers the Ohnesorge number, promoting capillary wave growth and ligament thinning to produce finer primary droplets, but also intensifies the Rayleigh–Plateau instability, generating satellites via ligament necking. However, this effect is not cumulative, potentially due to interactions among multiple factors, such as metal flow rate. Moreover, compared to other influencing parameters, viscosity appears to play a relatively minor role.^{128,131} When viscosity is decoupled and considered in isolation, lower viscosity still promotes the formation of finer particles, altering the particle size distribution relative to reference atomization conditions.^{102,134,135}

Conversely, higher viscosity adversely affects atomization. Higher viscosity suppresses capillary waves, delaying breakup and coarsening particles, while excessive viscous dissipation reduces energy for surface creation, leading to irregular shapes. As viscosity increases, the melt flow rate within the delivery tube decreases, heat dissipation from the melt increases, and fragmentation resistance rises. Insufficiently fragmented melt may suspend at the top of the delivery tube, leading to nozzle clogging.¹³⁶ An optimal viscosity range exists: at 5.24 mPa·s and 5.45 mPa·s, the resulting powder has a particle size of 27.4–32.5 μm , good sphericity, and a smooth surface. In contrast, at a lower viscosity of 5.01 mPa·s, a large number of irregular particles (e.g., rod-like and elliptical shapes) appear, which are detrimental to powder flowability.

The choice of atomizing gas significantly influences the density, morphology, and yield of metal powders.^{137,138} For example, in a study on a tin-based alloy system,¹³⁸ hot argon gas atomization produces powder with the highest density (7.84 g/cm³) and the most spherical shape, whereas hot oxygen gas atomization yields the lowest density (6.83

g/cm³), the largest endothermic area (60.42 area units), and the most elongated, irregular morphology (Figure 14). This contrasting behavior arises because oxygen, being surface-active, lowers surface tension and promotes capillary-wave growth, yet it simultaneously forms a solid oxide film that dampens breakup instabilities and stabilizes irregular droplets before spheroidization. However, it should be noted that powder density is strongly alloy-dependent, and this value should not be generalized to other alloy systems. Temperature also plays a role: for hot argon and nitrogen atomization, a melting pot temperature of 800 °C produces a higher yield of 0–25 μm powder than 700 °C. In contrast, hot oxygen atomization shows the opposite temperature dependence. This inverse trend is attributed to competing mechanisms: at higher temperatures, accelerated oxygen adsorption reduces surface tension for finer droplets, but rapid oxide-film formation stiffens droplet surfaces, suppressing capillary-wave breakup and thus reducing fine-powder yield. Using hydrogen as a reducing gas during atomization inhibits surface oxidation of the molten droplets and effectively removes trapped bubbles before solidification, thereby reducing the total pore volume of the powder.^{135,139,140} Hydrogen also promotes droplet spheroidization by preserving a clean, oxide-free surface, which allows surface-tension-driven relaxation to proceed without dynamic instability damping. The low cost and abundance of hydrogen further promote its industrial application. The purity of the atomizing gas significantly affects powder impurity content and flowability.¹⁴¹ Using normal-purity (99.9%) argon leads to high nitrogen and oxygen levels in the powder, forming the Ti₆O phase, whereas the spherical morphology remains unchanged. High oxygen and nitrogen concentrations reduce powder flowability, necessitating the use of high-purity (99.999%) argon to improve quality.

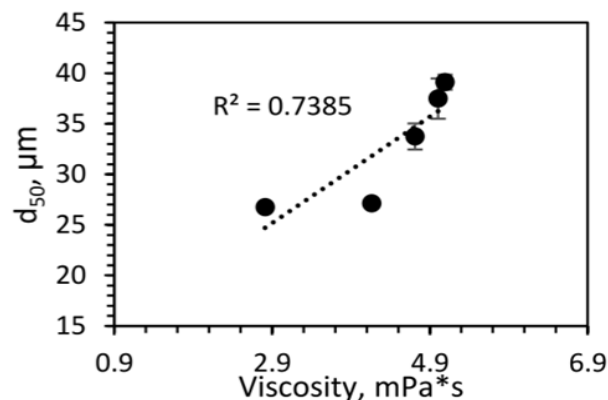


Figure 13. The effect of viscosity on the median particle size. Reprinted from Korobeinikov *et al.*¹³⁰

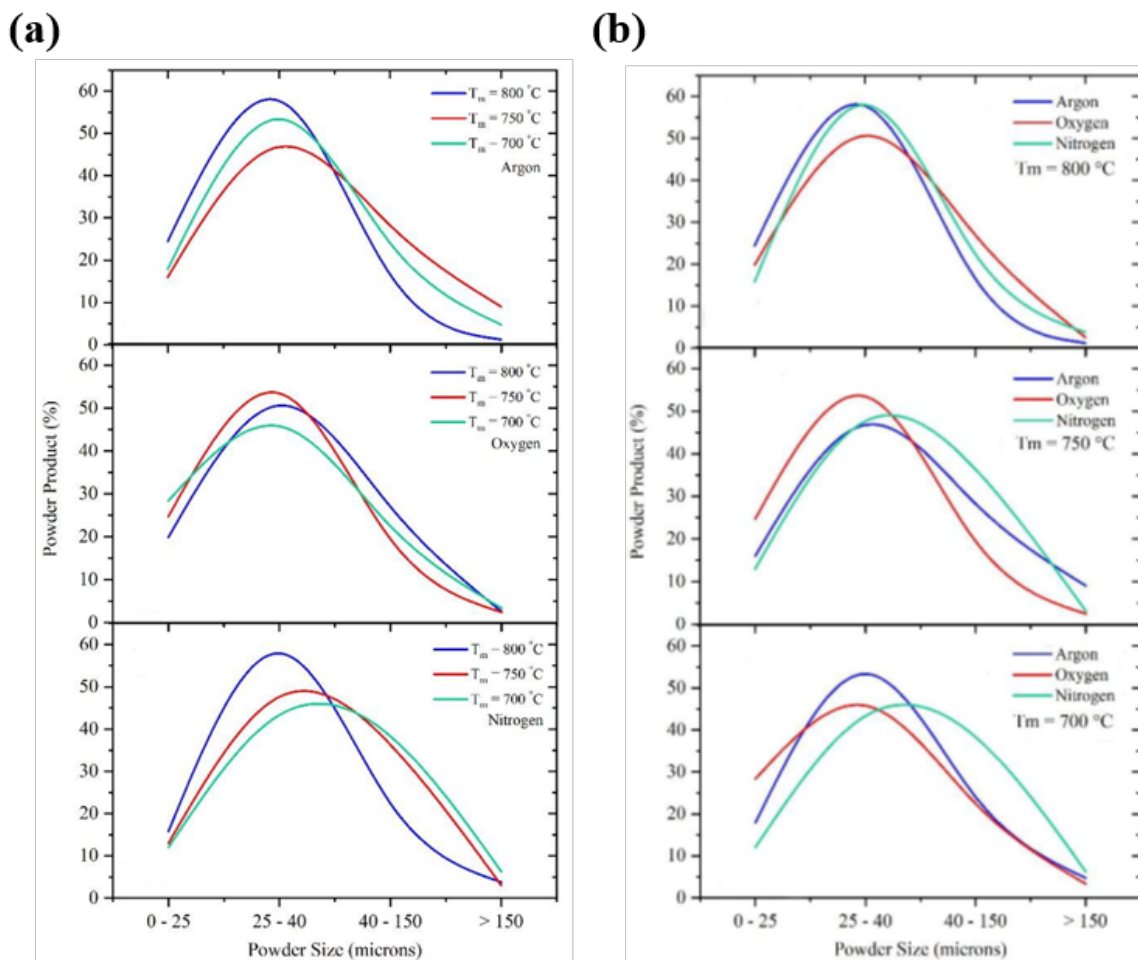


Figure 14. Powder size distribution curves generated by (a) various melting pot temperatures with the same hot gas atomization and (b) various hot gas atomization with the same melting pot temperature. Reprinted with permission from Basyir *et al.*¹³⁸ Copyright © 2022 Sains Malaysiana.

Lower surface tension consistently reduces the median particle size and promotes the formation of finer powder fractions during gas atomization^{27,101,102,133-135,142,143}. This occurs because lower surface tension weakens the restoring force that stabilizes the liquid ligament against capillary perturbations, thereby shortening the dominant Rayleigh-Plateau wavelength and producing finer droplets. However, the reduced surface tension also accelerates ligament thinning, promoting faster necking and enhancing satellite generation via secondary droplet shedding during ligament rupture. Quantitative analysis shows that as the surface tension of the melt decreases, the resulting powder becomes significantly finer. When surface tension is decoupled and considered in isolation, it can alter the particle size distribution relative to reference atomization conditions, confirming that surface tension is a key control parameter for tailoring powder characteristics.^{102,134,135}

5.2. Temperature

Increasing the superheat of the metal melt reduces both viscosity and surface tension, making droplets easier to fragment and yielding finer powder with better sphericity. Raising the atomization gas temperature lowers the cooling rate, allowing more complete droplet spheroidization and also reducing particle size. Both temperature increases contribute to the formation of finer, more spherical powders. However, the overall thermal effect on the flow field is a complex coupling process, and understanding it is important for optimizing metal powder production.

Higher melt superheat generally leads to finer particles during gas atomization.^{76,102,132} However, the effect of furnace temperature depends on the atomizing gas: for hot oxygen atomization, a lower furnace temperature (700 °C) produces more powder below 25 µm than at

800 °C, whereas for hot argon and nitrogen atomization, the opposite trend is observed (800 °C yields more fine powder).¹³⁸ This inverse behavior arises because oxygen adsorption, promoted at higher temperatures, lowers surface tension for finer droplets but accelerates oxide film formation that dampens capillary breakup. The film stabilizes ligaments against Rayleigh–Plateau instabilities, reducing fine-particle generation and increasing the production of irregular fragments. When decoupled from other factors, increased overheating alters the particle size distribution relative to reference conditions (Figure 15).¹⁰²

Raising the atomization gas temperature (e.g., from 300 K [26.85 °C] to 600 K [326.85 °C]) increases the gas ejection velocity outside the annular liquid film while leaving the internal recirculation zone velocity unchanged, thereby enhancing the gas velocity difference and improving both primary and secondary atomization efficiency (Figure 16).⁶³ Higher temperatures also enlarge the secondary atomization dispersion angle, reducing droplet collisions. Above 400 K (126.85 °C), GMR decreases slightly, while kinetic energy increases, further improving atomization.⁹³ However, excessively

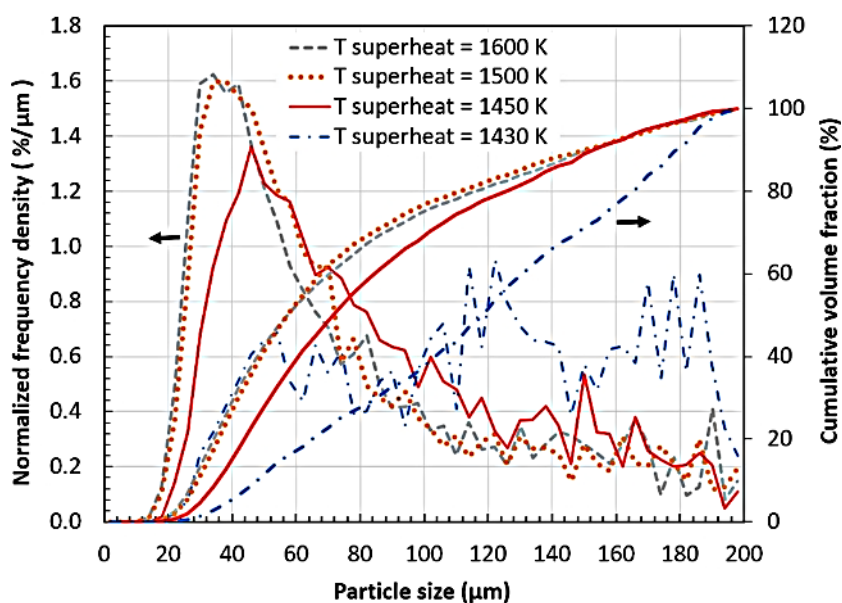


Figure 15. Comparison of particle size distribution after secondary breakup at different melt superheat temperatures of 1,600, 1,500, 1,450, and 1,430 K. Reprinted from Hua *et al.*¹⁰²

high temperatures may induce severe Kelvin–Helmholtz instabilities and gas–liquid interactions, leading to hollow powder formation. Elevated gas temperatures also reduce the cooling rate of in-flight droplets, allowing more time for surface-tension-driven spheroidization, which suppresses irregular shapes. When the viscosity drops excessively, ligaments rupture prematurely, generating satellites via enhanced Rayleigh–Plateau fragmentation. Conversely, elevated gas temperatures allow droplets more time to accelerate and spheroidize under surface tension, reducing irregular particles.^{78,144} Some studies have reported that gas temperature has a negligible effect on particle roundness or final shape for certain alloys.^{142,145–147}

5.3. Atomization pressure

Increasing atomization pressure generally reduces

powder particle size and increases fine powder yield, but excessive pressure may impede melt flow, reduce fragmentation efficiency, and increase satellite powder formation. However, conflicting views on the effect of atomization pressure on secondary breakup arise from differences in the systems used across studies. Atomizer geometry plays a primary role in close-coupled (confined) nozzles. Increasing pressure enhances gas velocity and recirculation-zone stagnation pressure, promoting finer droplets. However, excessive pressure induces shock waves and flow instabilities that can suppress breakup. In free-fall systems such as EIGA, pressure promotes shear breakup of finer droplets, but an overpressure that is too low can lead to nozzle clogging. The wake-closure phenomenon, highly sensitive to nozzle and melt-tube geometry, can cause variations in median powder size of up to 42% across

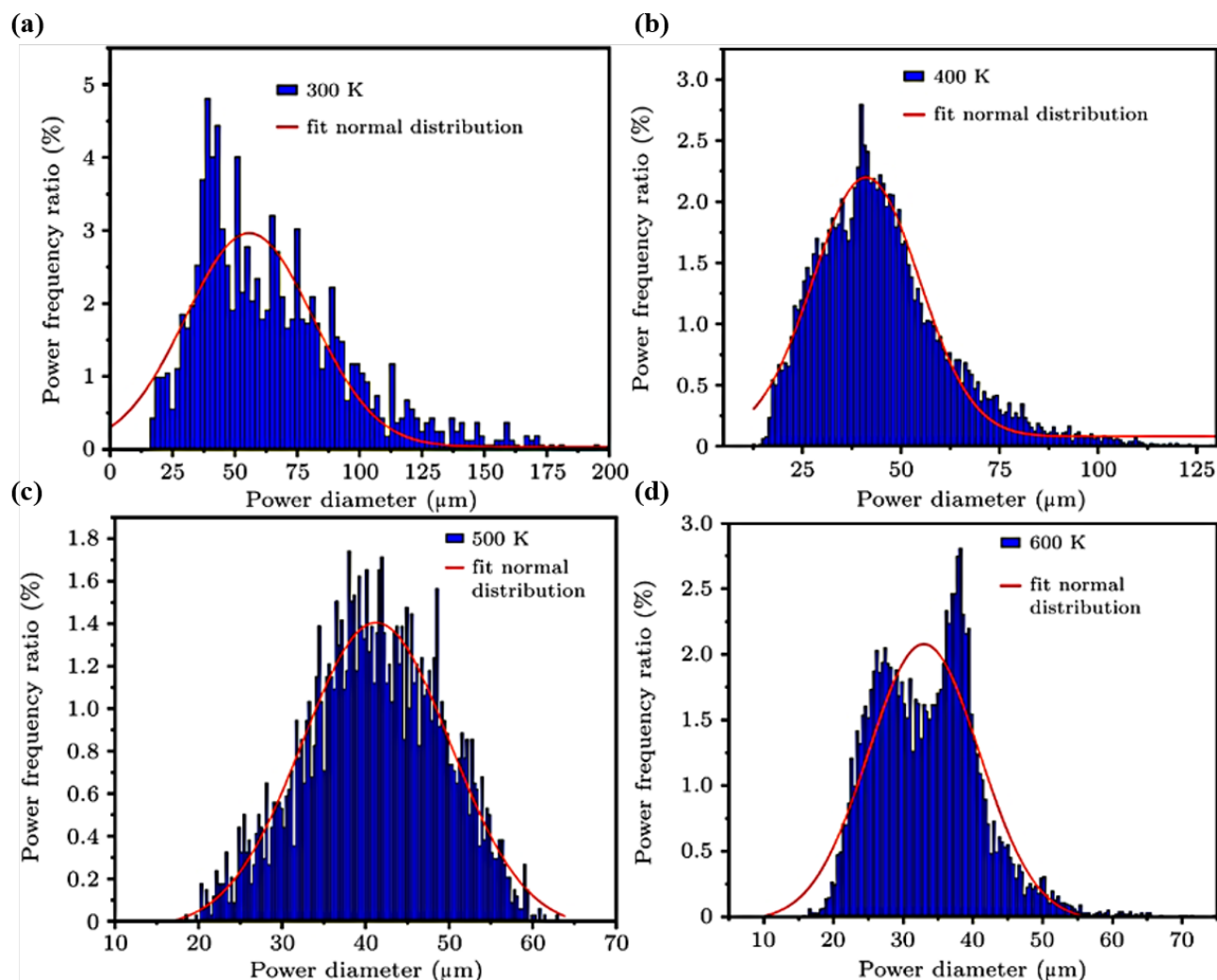


Figure 16. Particle diameter distribution after secondary atomization at different gas temperatures: (a) 300 K (26.85 °C), (b) 400 K (126.85 °C), (c) 500 K (226.85 °C), (d) 600 K (326.85 °C).⁶³ Reprinted with permission from Wang *et al.*⁶³ Copyright © 2021 Editorial Office of Chinese Physics B.

a narrow pressure range. Gas species further complicates comparisons: helium produces finer powders than argon at equivalent pressures due to higher velocity. Melt properties and measurement methodologies add additional variability. The most plausible interpretation is that pressure effects follow a non-monotonic trend: moderate increases improve atomization efficiency, while excessive pressure introduces destabilizing shockwave interactions, increased risk of nozzle clogging, and flow perturbations that counteract the benefits. This is further evidenced by findings that both high and low atomization pressures result in broad particle size distributions, and that GMR, not pressure alone, governs particle size. **Sections 5.3.1 and 5.3.2** detail the effects of atomization pressure on flow fields and powder characteristics.^{46,51,64,70,93,95,101,116,117,125,139,140,148-165}

5.3.1. Impact on flow field

Higher pressure increases the gas mass flow rate, widens the velocity range, extends the ultrasonic jet, raises the Mach number near the nozzle exit, and improves flow field uniformity.^{46,103,117} Pressure correlates positively with flow velocity, with 2.0 MPa as a critical node.^{156,162} Pressure differentials induce expansion wave systems at the nozzle exit.⁹⁵ As pressure increases, the recirculation zone evolves stepwise: a second zone appears at 5 MPa, a third above 7 MPa (Figure 17a). Low pressure (1 MPa) causes flow separation and droplet backflow. This backflow recirculates fragmented droplets into the high-shear breakup zone, promoting secondary fragmentation while also increasing collision-induced coalescence, broadening

the size distribution. At intermediate pressures (3–5 MPa), the recirculation zone stabilizes and enhances ligament stretching via Kelvin–Helmholtz instabilities, reducing median size. GMR increases with pressure and is negatively correlated with median particle size (Figure 17b). Pressure drives gas-liquid relative velocity while fundamental breakup mechanisms remain unchanged.^{51,70,150,152,153} Insufficient pressure hinders melt outflow; excessive

pressure causes overly strong negative pressure and unstable fragmentation.^{51,64,143,156} Above 3.0 MPa, Kelvin–Helmholtz waves are fully developed, leading to irregular particle shapes (Figure 18).⁹³ At these high pressures, the amplified shear instability promotes rapid ligament rupture, generating numerous fine droplets and enhancing satellite formation through uncontrolled ligament fragmentation and droplet shedding. Flow disorder can be beneficial for fragmentation⁵¹ or detrimental to stable necking.^{64,156}

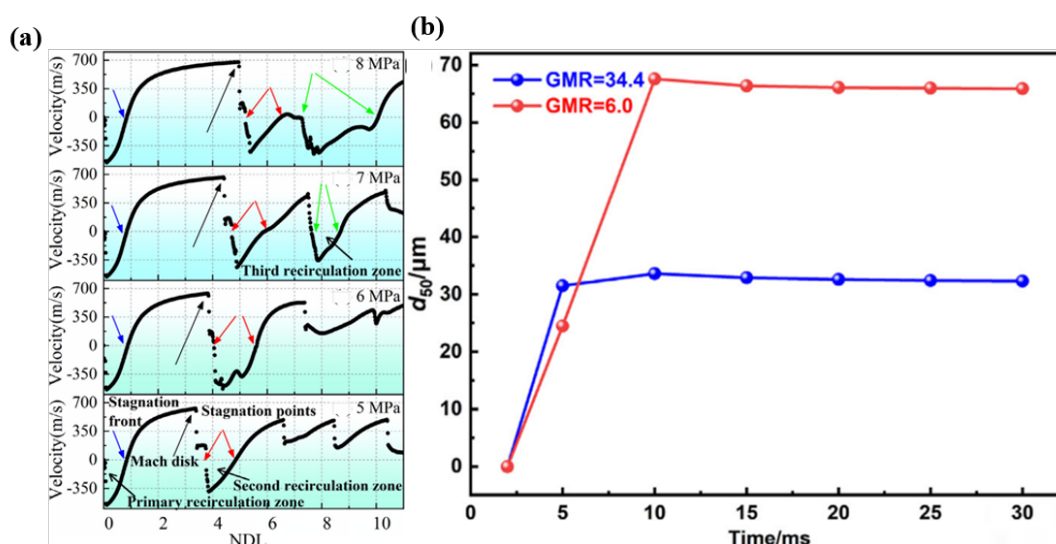


Figure 17. Effects of atomization pressure and gas-to-melt ratio (GMR). (a) The variation pattern of air velocity on the central axis at different atomization pressures. Reprinted with permission from Shi *et al.*¹¹⁶ Copyright © 2022 Elsevier Ltd on behalf of the editorial office of Journal of Materials Science & Technology. (b) The median particle size at different GMRs. Reprinted from Wang *et al.*¹²⁵ Abbreviation: NDL: Nozzle diameter length.

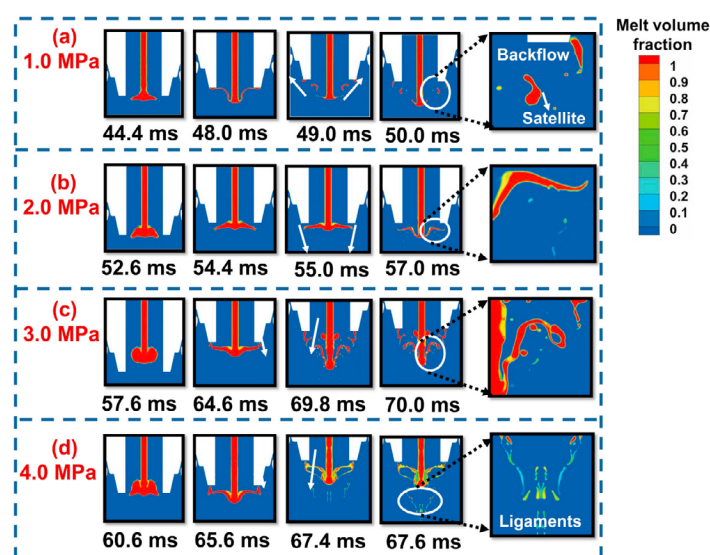


Figure 18. Comparison of melt flow morphology under different atomization pressures: (a) 1.0 MPa; (b) 2.0 MPa; (c) 3.0 MPa; (d) 4.0 MPa. Reprinted from Liu *et al.*⁹³

5.3.2. Influence on powder size and shape

Within an appropriate range, increasing pressure reduces particle size, narrows distribution, and improves uniformity (Figure 19).^{51,70,95,101,116,148,150,151,154,155,165} Higher pressure promotes more complete fragmentation, smaller particles, and faster solidification.^{49,153,155} This is because increased gas momentum intensifies the shear-driven Kelvin–Helmholtz instability, shortening the breakup length and reducing the droplet diameter before solidification. At low pressure, increasing pressure reduces both particle size and standard deviation;^{51,101} at elevated pressure, it decreases the mass median diameter and distribution width.^{157,160} Low-pressure argon yields lower porosity but larger, irregular particles.^{139,140} Moderate pressure helps transform flakes into regular rods.⁶⁴ Excessive pressure deteriorates quality: flowability decreases, and satellite powder content increases.¹⁰¹ At pressures above the optimal window, excessive turbulent kinetic energy destabilizes the liquid jet, producing multiple breakup nodes and enhancing the Rayleigh–Plateau instability that generates satellites, especially in the 5–50 μm range. A reasonable pressure window for secondary atomization is 1–3 MPa, where increasing pressure continuously reduces median particle size without negative effects.¹²⁵

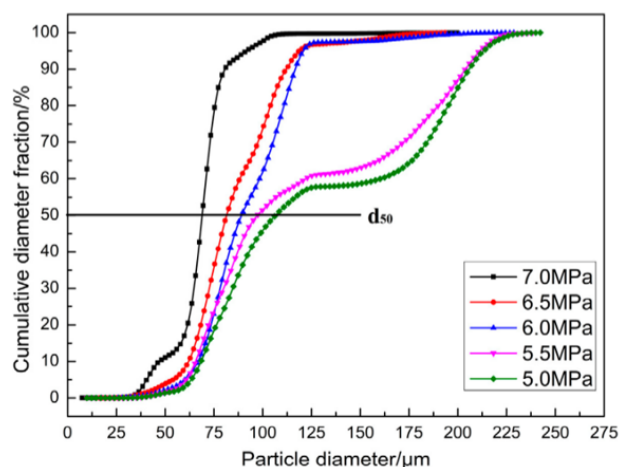


Figure 19. Cumulative size distribution by mass under five different pressures varying from 5.0 MPa to 7.0 MPa. Reprinted from Guo *et al.*⁹⁵

5.4. Tube and nozzle structure

Different delivery tube and gas nozzle structures yield distinct flow field morphologies; hence, their structures are of great significance to the entire gas atomization process.

5.4.1. Delivery tube structure

Research on delivery tube structures focuses on inner

diameter and extension length. These parameters interact with suction pressure (determined by atomization pressure) to influence melt flow, atomization, and powder quality. Low atomization pressure creates positive suction pressure; narrow tubes slow melt flow, promoting liquid film breakup for finer powder but risking clogging, while wide tubes accelerate flow, causing fountain-like breakup. High atomization pressure creates negative suction pressure, aiding melt outflow. This suction pressure transition alters the local gas velocity gradient and shear stress at the tube tip, directly modulating the Kelvin–Helmholtz instability growth rate that governs primary ligament thinning. Increasing tube length reduces the suction pressure acting area—under positive pressure, this accelerates melt flow; under negative pressure, it slows flow—improving the gas-liquid velocity ratio for finer droplets, but excessive length causes premature secondary atomization, harming fragmentation.^{77,97,101,160,166–170} Longer tubes delay the onset of primary breakup, allowing ligaments to stretch further; however, excessive elongation promotes Rayleigh–Plateau instability on the stretched ligaments, generating satellite droplets via necking and rupture before the main droplet formation is complete.

Smaller inner diameters increase melt flow resistance, especially below 1 mm, where resistance reaches 100 kPa, improving fine powder yield and surface quality (Figure 20).^{77,168} The increased resistance reduces melt flow velocity, enhancing the gas-to-melt momentum ratio, which promotes capillary wave growth and shortens the primary breakup length, yielding finer droplets. Nozzle diameter and atomization pressure have an inverse effect on gas-to-liquid mass flow ratio; small-diameter nozzles achieve higher powder yields.^{167,169} Larger melt nozzle diameters increase splash diameter and droplet diameter.^{160,166} Powder particle size increases with delivery tube diameter.^{76,170} Increasing guide tube protrusion length reduces particle size up to a certain point, but at 12 mm, particle size suddenly increases.¹⁰¹ The non-monotonic particle-size trend with protrusion reflects competing gas-flow effects. Increasing protrusion from 1 to 4 mm progressively lengthens the recirculation zone, with peak suction at 2–3 mm promoting secondary breakup and finer powders. Beyond 4 mm, flow distortion reduces suction, resulting in coarser powders. This distortion creates an unstable wake where droplet recirculation promotes coalescence, broadening the distribution and increasing satellite formation. Protrusion also modifies GMR. Shorter protrusions reduce melt flow via recirculation, raising GMR and refining the powder. This trend is general in close-coupled systems, but optimal protrusion values remain configuration-specific. Using VOF–LES, delivery tube tip particle trajectories and nozzle clogging mechanisms during primary atomization have

been elucidated; selecting an appropriate coupling length prevents clogging and stabilizes atomization.⁹⁷

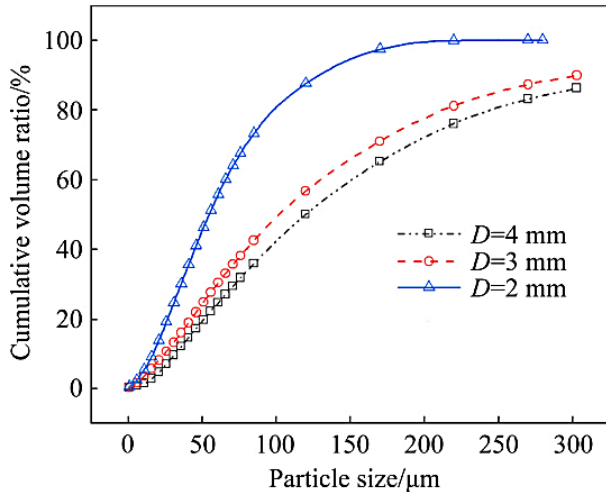


Figure 20. Particle size distribution of gas atomized powder prepared with nozzles of different inner diameters. Reprinted from Liu *et al.*⁷⁷

5.4.2. Gas nozzle structure

Nozzle shape governs the morphology of the gas flow field, directly affecting atomization efficiency and powder quality. Key nozzle types include De Laval (accelerates gas to supersonic speeds, enhancing kinetic energy and gas-liquid velocity ratio), dual nozzles (reduce external circulation zone height, decrease satellite powder, and increase gas velocity and recirculation range, lowering melt velocity for finer droplets), and swirling nozzles (create swirl that increases gas kinetic energy but may stabilize melt core and hinder atomization). The intensified shear layer from supersonic flow promotes Kelvin–Helmholtz instability, accelerating ligament stretching and droplet detachment, while strong recirculation in dual nozzles encourages secondary breakup but may increase satellite generation via droplet–droplet collisions. Increasing nozzle intersection angle and slot diameter expands atomization range, reduces droplet collisions, and promotes primary atomization^{46,78,99,101,103,105,125,141,157,171–178}

(a) Laval nozzle design

The convergent section is critical for accelerating gas from subsonic to sonic velocity; the design must ensure uniform flow at the throat. Both excessively large and small expansion angles cause adverse effects: too small leads to a long expansion distance and energy loss; too large reduces gas velocity (Figure 21).^{171,172}

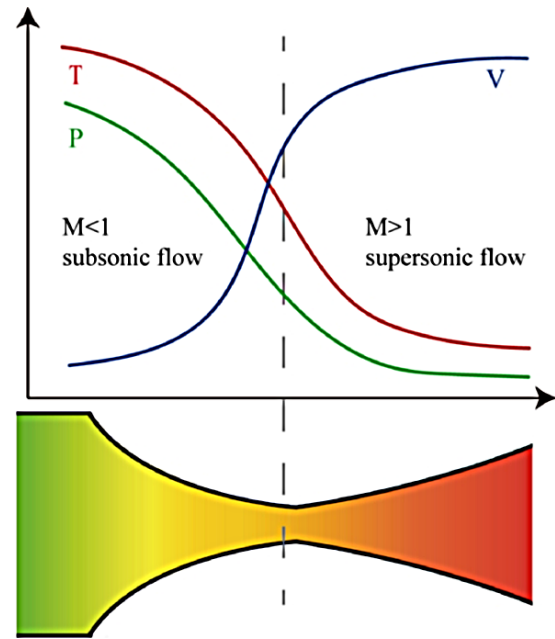


Figure 21. Schematic of De-Laval dynamics theory. Reprinted with permission from Chen *et al.*¹⁷² Copyright © 2024 Elsevier.

(b) Dual nozzles

The pressure difference between the primary and secondary nozzles significantly affects the gas flow field, melt atomization, and powder characteristics (size, sphericity, satellite particles). Increasing secondary pressure refines droplets, shortens spheroidization time, and improves sphericity (Figure 22a).¹⁷⁶ Annular-slot nozzles produce smaller particles than annular-hole nozzles due to different gas flow distribution.¹⁷⁴ A dual-atomizer system (two-stage atomization) further improves powder quality by first breaking liquid columns into uniform droplets, then refining them.⁷⁸ This two-stage approach decouples primary and secondary breakup: the first stage controls initial droplet size via Rayleigh–Plateau instability, while the second stage uses high-velocity gas to shear droplets further. The secondary shear intensifies the Kelvin–Helmholtz instability, producing fine droplets and generating satellites from ligament remnants.

(c) Swirl vs. internal-mixing nozzles

Increasing the outlet slit size of swirl nozzles increases the swirl number, intensifies jet asymmetry, and produces finer particles.¹⁰³ However, swirl nozzles can stabilize the melt core and hinder atomization (Figure 22b).¹⁰³ Internal-mixing nozzles reduce horizontal melt movement, enhancing powder production (Figure 22c).¹⁰⁵ The swirl-induced radial velocity component enhances gas–liquid shear, promoting the Kelvin–Helmholtz instability for

finer primary droplets, yet the centrifugal force stabilizes the core jet, delaying breakup and potentially increasing the formation of irregular ligaments that fragment into satellites.

Increasing semi-cone angle reduces median particle size; 30° is suitable for Laval nozzles (Figure 23).¹⁰¹ A

larger gas slot diameter decreases the median size but increases the dispersion of the size distribution. A larger nozzle intersection angle shortens the distance to the axis, intensifies gas-liquid interaction, promotes droplet formation,^{99,173} and increases the spray scattering angle and the axial velocity; the annular velocity peak occurs farther from the delivery tube.¹⁷⁸ Droplet mass median diameter

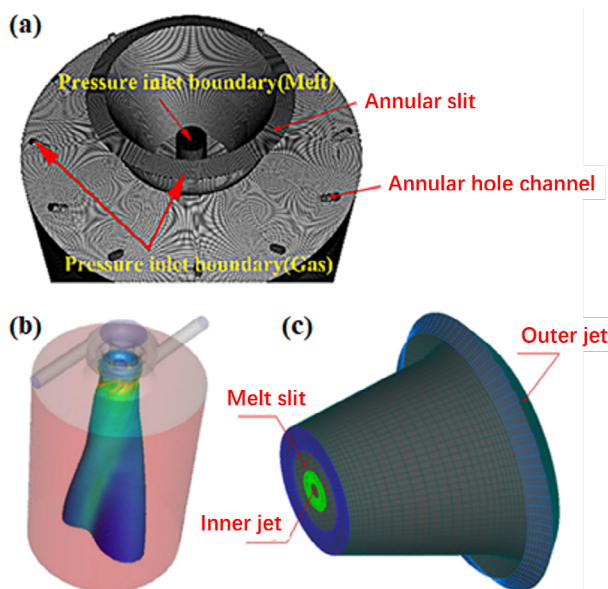


Figure 22. Schematic diagrams of nozzle design: (a) dual nozzles, (b) swirling atomization nozzle, and (c) an internal spray atomization nozzle. Reprinted with permission from (a) Wang *et al.*¹⁷⁶ Copyright © 2023 Elsevier; (b) Qaddah *et al.*¹⁰³ Copyright © 2022 Elsevier; and (c) Hua *et al.*¹⁰²

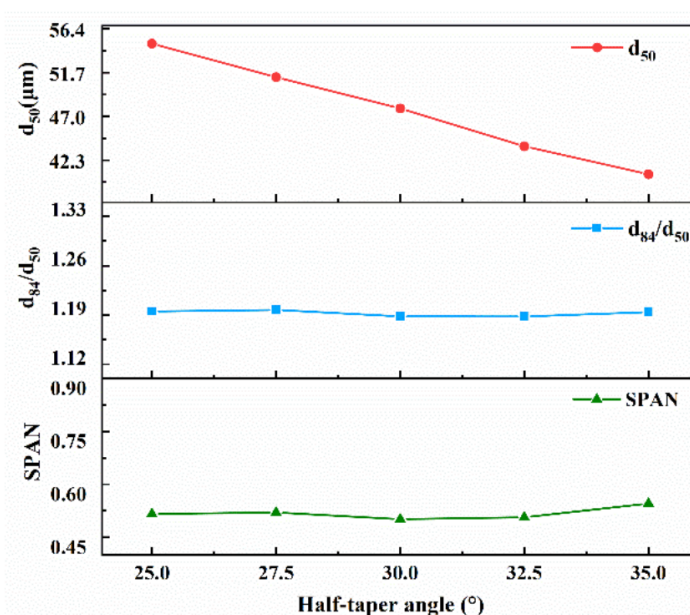


Figure 23. Schematic diagram of the Kelvin–Helmholtz Rayleigh–transport fracture model simulation showing the impact of the semi-cone angle on d_{50} , d_{84}/d_{50} , and SPAN ($\frac{d_{90}-d_{10}}{d_{50}}$). Reprinted from Xu *et al.*¹⁰¹

decreases with a smaller nozzle apex angle,¹⁵⁷ whereas a smaller spray cone angle increases collision probability and standard deviation, reducing efficiency.^{125,175} Nozzle throat area significantly affects gas flow, with throat width critically influencing flow characteristics.^{46,177} Orifice protrusion length changes gas distribution, adjusting recirculation zone position and powder yield.¹⁴¹ Larger cone angles create stronger shear layers that enhance liquid sheet breakup and capillary wave growth. However, excessive angles cause non-uniform velocity profiles, leading to irregular fragmentation and increased satellite formation due to uncontrolled ligament rupture.

6. Conclusion and future perspective

6.1. Conclusion

The gas atomization process for preparing metal powder consists of three stages: primary atomization, secondary atomization, and solidification. Based on a review of research by various scientists and scholars on atomization mechanisms, simulation methods, flow field characteristics, and influencing factors, the following conclusions are drawn:

- (i) The atomization behavior of molten metal in gas atomization is investigated and reviewed. Primary atomization typically involves two main processes: liquid film atomization, driven by the Kelvin–Helmholtz instability, which arises from the velocity difference between the high-speed gas and the slower liquid surface; and fountain atomization, governed by the Rayleigh–Taylor instability, which develops when the accelerating gas exerts a pressure gradient opposing the liquid inertia, causing surface perturbations to grow into ligaments and droplets. The transition between these modes is primarily controlled by the competition between aerodynamic forces and surface tension, characterized by the Weber number and the liquid inertia relative to the recirculation-zone back-pressure. Secondary atomization, by contrast, is mainly governed by shear and inertial forces, with the resulting droplet morphology, such as bag, stripping, or catastrophic breakup, being closely associated with the Weber number regime. Extending solidification time, achieved through lower cooling rates or higher gas temperatures, allows more time for surface tension to restore droplets to a spherical shape, thereby improving powder sphericity and reducing the formation of irregular particles.
- (ii) The gas flow field exhibits necklace-like expansion wave clusters arising from periodic compression-expansion cycles in the underexpanded supersonic jet, recirculation zones sustained by entrainment-induced

pressure deficits, and stagnation points where kinetic energy fully converts to pressure energy. Depending on the metal mass flow rate, the liquid flow field can be characterized as either a film-like metal liquid flow governed by the inability of low-inertia melt to overcome the recirculation-zone back-pressure, spreading radially into a thin film that breaks via aerodynamic shear or a fountain-like metal liquid flow, where higher melt inertia penetrates the recirculation zone and accumulates into a hemispherical shape, with surface instabilities evolving into ligaments and droplets. These flow field characteristics enable visualization of transient breakup morphologies such as ligament formation, sheet perforation, and droplet shedding that cannot be directly observed in experimental studies of gas atomization due to the opaque, high-temperature, and short-timescale nature of the process.

- (iii) Multiple factors influence particle size and sphericity, but with differing control. GMR is the dominant parameter for median particle size (d_{50}), as it governs kinetic energy transfer; higher GMR enhances aerodynamic shear, promoting primary and secondary breakup and reducing particle size. Atomizer geometry ranks second: close-coupled designs outperform free-fall configurations due to shorter gas-liquid interaction distance and higher gas velocities. Gas properties (e.g., pressure, temperature, species) and melt superheat are secondary refinements. Higher pressure increases gas density and velocity; higher temperature reduces density but increases sonic velocity. Helium outperforms argon due to higher thermal conductivity, though it accelerates cooling. Sphericity is controlled primarily by superheat and GMR. Sufficient superheat lowers viscosity and surface tension, enabling spheroidization; insufficient superheat freezes irregular shapes. Excessive GMR promotes satellite formation by stripping droplets and re-entraining them into the recirculation zone. Satellite formation is minimized by optimizing delivery tube protrusion and avoiding excessive gas velocities. Internal porosity results from gas entrapment during primary breakup; high pressure forces gas into the melt, while insufficient degassing leaves dissolved gases that expand during solidification, forming pores.

6.2. Future perspective

Although extensive studies have been conducted, the following future development trends are recommended:

- (i) Atomization mechanisms: Despite extensive research on gas atomization mechanisms, several fundamental disputes persist. A widely accepted theory remains

elusive. One priority is clarifying the respective roles of primary and secondary atomization in determining the final particle size distribution. The transition between breakup regimes, film-like versus fountain-like behavior, is poorly defined under intermediate conditions. Furthermore, the mechanisms underlying the formation of defect powders (irregular shapes, satellites, internal porosity) are not fully understood, limiting the optimization of sphericity and tap density. Future studies should combine high-speed visualization with coupled breakup-solidification models to link breakup dynamics to final powder quality, enabling targeted morphology control through rational parameter selection.

- (ii) Turbulence modeling and simulation methods: No consensus exists on turbulence model selection for gas atomization, yet this choice critically affects simulation accuracy. The VOF–DPM hybrid approach shows promise, transitioning from VOF to DPM once droplets detach from the liquid core, thereby reducing coupling errors between the two models. A major challenge is the high computational cost of this method, which limits the scope of parametric studies. Future efforts should accelerate computations through adaptive mesh refinement, GPU acceleration, or reduced-order models. Optimizing the VOF–DPM coupling strategy can improve efficiency while maintaining breakup-prediction accuracy, enabling a more systematic exploration of atomization conditions and nozzle configurations.
- (iii) Nozzle design: Future nozzle design should focus on geometry optimization via multiphysics simulations to resolve complex gas–melt interactions. Critical challenges include understanding the 4–8 mm protrusion transition range, where the wake-closure alters recirculation and causes non-monotonic particle size variations; developing real-time diagnostic tools (e.g., high-speed imaging, phase Doppler) for model validation; exploring adaptive nozzles that self-adjust to varying melt conditions; and investigating nozzle-material effects to prevent clogging and erosion for high-temperature alloys. Recommendations include multi-objective optimization integrating breakup efficiency with wear resistance, coupled with in-situ validation experiments to accelerate nozzle design cycle.

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Conflict of interest

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References

1. Yang Y, Song X, Li X, *et al.* Recent progress in biomimetic additive manufacturing technology: from materials to functional structures. *Adv Mater.* 2018;30(36):1706539. doi: 10.1002/adma.201706539
2. Atzeni E, Salmi A. Economics of additive manufacturing for end-usable metal parts. *Int J Adv Manuf Technol.* 2012;62:1147–1155. doi: 10.1007/s00170-011-3878-1
3. Baumers M, Dickens P, Tuck C, Hague R. The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technol Forecast Soc Change.* 2016;102:193–201. doi: 10.1016/j.techfore.2015.02.015
4. Duda T, Raghavan L. 3D metal printing technology. *IFAC-PapersOnLine.* 2016;49(29):103–110. doi: 10.1016/j.ifacol.2016.11.111
5. Jiménez M, Romero L, Domínguez I, Espinosa MdM, Domínguez M, García-Alcaraz JL. Additive manufacturing technologies: an overview about 3D printing methods and future prospects. *Complexity.* 2019;2019(1):9656938. doi: 10.1155/2019/9656938
6. Lindermann C, Jahnke U, Moi M, Koch R. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In: *2012 International Solid Freeform Fabrication Symposium.* 2012:177–188. doi: 10.26153/tsw/15341
7. Strondl A, Lyckfeldt O, Brodin H, Ackelid U. Characterization and control of powder properties for additive manufacturing. *JOM.* 2015;67(3):549–554. doi: 10.1007/s11837-015-1304-0

8. Weller C, Kleer R, Piller F. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *Int J Prod Econ*. 2015;164:43-56.
doi: 10.1016/j.ijpe.2015.02.020
9. Kassym K, Perveen A. Atomization processes of metal powders for 3D printing. *Mater Today Proc*. 2020;26:1727-1733.
doi: 10.1016/j.matpr.2020.02.364
10. Sajbura A, Sokolowski P. Ultrasonic Atomization as a Novel Route for the Metal Powder Development. *Proc Int Therm Spray Conf*. 2023;84536:735-741.
doi: 10.31399/asm.cp.itsc2023p0735
11. Soong S, Lai W, Kay Lup A. Atomization of metal and alloy powders: processes, parameters, and properties. *AIChE J*. 2023;69(11):e18217.
doi: 10.1002/aic.18217
12. Sun P, Fang Z, Zhang Y, Xia Y. Review of the methods for production of spherical Ti and Ti alloy powder. *JOM*. 2017;69(10):1853-1860.
doi: 10.1007/s11837-017-2513-5
13. Heaney D. Powders for metal injection molding (MIM). In: *Handbook of Metal Injection Molding*. 2nd ed. Elsevier; 2019:45-56.
doi: 10.1016/B978-0-08-102152-1.00004-0
14. Hoeges S, Zwiren A, Schade C. Additive manufacturing using water atomized steel powders. *Metal Powder Rep*. 2017;72(2):111-117.
doi: 10.1016/j.mprp.2017.01.004
15. Klar E. Atomization. In: *Metals Handbook*. American Society for Metals; 1984:25-51.
16. Liu Y, Niu S, Li F, Zhu Y, He Y. Preparation of amorphous Fe-based magnetic powder by water atomization. *Powder Technol*. 2011;213(1-3):36-40.
doi: 10.1016/j.powtec.2011.06.026
17. Phairete P, Plookphol T, Wisutmethangoon S. Design and Development of a Centrifugal Atomizer for Producing Zinc Metal Powder. *IJAPM*. 2012:77-82.
doi: 10.7763/ijapm.2012.v2.58
18. Zdujić M, Uskoković D. Production of atomized metal and alloy powders by the rotating electrode process. *Sov Powder Metall Met Ceram*. 1990;29(9):673-683.
doi: 10.1007/BF00795571
19. Priyadarshi A, Shahrani S, Choma T, et al. New insights into the mechanism of ultrasonic atomization for the production of metal powders in additive manufacturing. *Addit Manuf*. 2024;83:104033.
doi: 10.1016/j.addma.2024.104033
20. Bittner B, Kissel T. Ultrasonic atomization for spray drying: a versatile technique for the preparation of protein loaded biodegradable microspheres. *J Microencapsul*. 1999;16(3):325-341.
doi: 10.1080/026520499289059
21. Dalmoro A, Barba A, Lamberti G, d'Amore M. Intensifying the microencapsulation process: ultrasonic atomization as an innovative approach. *Eur J Pharm Biopharm*. 2012;80(3):471-477.
doi: 10.1016/j.ejpb.2012.01.006
22. Naidu H, Kahraman O, Feng H. Novel applications of ultrasonic atomization in the manufacturing of fine chemicals, pharmaceuticals, and medical devices. *Ultrason Sonochem*. 2022;86:105984.
doi: 10.1016/j.ultsonch.2022.105984
23. Park K, Yeo Y. Microencapsulation using ultrasonic atomizers. US Patent 6767637B2. Published July 27, 2004.
24. Baskoro AS, Supriadi S, Dharmanto. Review on Plasma Atomizer Technology for Metal Powder. *MATEC Web of Conferences*. 2019;269:05004.
doi: 10.1051/mateconf/201926905004
25. Baskoro A, Supriadi S, Dharmanto. Review on plasma atomizer technology for metal powder. *MATEC Web Conf*. 2019;269:05004.
doi: 10.1051/mateconf/201926905004
26. Grenier S, Allaire F. Plasma atomization gives unique spherical powders. *Metal Powder Rep*. 1997;52(11):34-37.
doi: 10.1016/S0026-0657(97)87150-0
27. Goudar D, Srivastava V, Rudrakshi G. Effect of atomization parameters on size and morphology of Al-17Si alloy powder produced by free fall atomizer. *Eng J*. 2017;21(1):155-168.
doi: 10.4186/ej.2017.21.1.155
28. Kourmatzis A, Lowe A, Masri A. Combined effervescent and airblast atomization of a liquid jet. *Exp Therm Fluid Sci*. 2016;75:66-76.
doi: 10.1016/j.expthermflusci.2016.02.002
29. Motaman S, Mullis AM, Cochrane RF, Borman DJ. Numerical and experimental investigations of the effect of melt delivery nozzle design on the open-to closed-wake transition in closed-coupled gas atomization. *Metall Mater Trans B*. 2015;46(4):1990-2004.
doi: 10.1007/s11663-015-0346-6
30. Yenwiset S, Yenwiset T. Design and construction of water atomizer for making metal powder. *J Met Mater Miner*. 2011;21(1):75-81.
31. Cegarra SA, Pijuan J, Riera MD. Cooling rate modeling and evaluation during centrifugal atomization process. *J Manuf Mater Process*. 2023;7(3):112.

- doi: 10.3390/jmmp7030112
32. Gibbons DW, Govender P, van der Merwe AF. Metal powder feedstock evaluation and management for powder bed fusion: a review of literature, standards, and practical guidelines. *Prog Addit Manuf.* 2024;9(4):805-833.
doi: 10.1007/s40964-023-00484-x
33. Kanaginahal GM, Kiran MC, Shahapurkar K, Mahale RS, Kakkamari P. Automobile Applications of Mechanically Alloyed Magnesium and Titanium Material. In: *Mechanically Alloyed Novel Materials: Processing, Applications, and Properties.* 2024;220:379-406.
doi: 10.1007/978-981-97-6504-1_16
34. Anderson IE, Achelis L. Two fluid atomization fundamentals. In: *Metal Sprays and Spray Deposition.* Cham, Switzerland: Springer; 2017:49-88.
doi: 10.1007/978-3-319-52689-8_3
35. Le T, Henein H. Effect of nozzle geometry and position on gas atomization. *Int J Powder Metall.* 1996;32(4):353-364.
doi: 10.1016/S0026-0657(97)86585-X
36. Zou H, Xiao Z. Pre-breakup mechanism of free-fall nozzle in electrode induction melting gas atomization. *Mater Today Commun.* 2021;29:102778.
doi: 10.1016/j.mtcomm.2021.102778
37. Cheng T, Leibovici R, Kong B, Hout R. Experimental investigation of primary breakup in close-coupled gas atomization. *Int J Multiphase Flow.* 2024;181:105009.
doi: 10.1016/j.ijmultiphaseflow.2024.105009
38. Lagutkin S, Achelis L, Sheikhaliev S, Uhlenwinkel V, Srivastava V. Atomization process for metal powder. *Mater Sci Eng A.* 2004;383(1):1-6.
doi: 10.1016/j.msea.2004.02.059
39. Mullis A, Adkins N, Aslam Z, McCarthy I, Cochrane RF. Close-coupled gas atomization: high-frame-rate analysis of spray-cone geometry. *Int J Powder Metall.* 2008;44(1):55-64
40. Si C, Tang X, Zhang X, Wang J, Wu W. Characteristics of 7055Al alloy powders manufactured by gas-solid two-phase atomization: a comparison with gas atomization process. *Mater Des.* 2017;118:66-74.
doi: 10.1016/j.matdes.2017.01.028
41. Ünal A. Production of rapidly solidified aluminium alloy powders by gas atomisation and their applications. *Powder Metall.* 1990;33(1):53-64.
doi: 10.1179/pom.1990.33.1.53
42. Wang P, Li J, Wang X, et al. Close-coupled nozzle atomization integral simulation and powder preparation using vacuum induction gas atomization technology. *Chin Phys B.* 2021;30(2):027502.
doi: 10.1088/1674-1056/abc167
43. Jiang X, Siamas G, Jagus K, Karayiannis TG. Physical modelling and advanced simulations of gas-liquid two-phase jet flows in atomization and sprays. *Prog Energy Combust Sci.* 2010;36(2):131-167.
doi: 10.1016/j.pecs.2009.09.002
44. Rahman M, Heidrick T, Fleck B. A critical review of advanced experimental techniques to measure two-phase gas/liquid flow. *Open Fuels Energy Sci J.* 2009;2(1):54-70.
doi: 10.2174/1876973X00902010054
45. Wu H, Zhang F, Zhang Z, Hou L. Atomization and droplet dynamics of a gas-liquid two-phase jet under different mass loading ratios. *Int J Multiphase Flow.* 2022;151:104043.
doi: 10.1016/j.ijmultiphaseflow.2022.104043
46. Urionabarrenetxea E, Martín JM, Avello A, Rivas A. Simulation and validation of the gas flow in close-coupled gas atomisation process: influence of the inlet gas pressure and the throat width of the supersonic gas nozzle. *Powder Technol.* 2022;407:117688.
doi: 10.1016/j.powtec.2022.117688
47. Ren P, Ouyang Y, Mu J, et al. Metal powder atomization preparation, modification, and reuse for additive manufacturing: a review. *Prog Mater Sci.* 2025;152:101449.
doi: 10.1016/j.pmatsci.2025.101449
48. Xie L, Sun H, Wen Y, Hua L, Zhang L. Electromagnetic treatment enhancing performance of metal materials: a review. *Prog Mater Sci.* 2025;153:101488.
doi: 10.1016/j.pmatsci.2025.101488
49. Li X, Fritsching U. Process modeling pressure-swirl-gas-atomization for metal powder production. *J Mater Process Technol.* 2017;239:1-17.
doi: 10.1016/j.jmatprotec.2016.08.009
50. Qaddah B, Chapelle P, Bellot JP, et al. Primary and secondary breakup of molten Ti64 in an EIGA atomizer for metal powder production. *Powder Technol.* 2024;438:119665.
doi: 10.1016/j.powtec.2024.119665
51. Qing Y, Guo K, Liu C, et al. Impact of atomization pressure on the particle size of nickel-based superalloy powders by numerical simulation. *Materials.* 2022;15(9):3020.
doi: 10.3390/ma15093020
52. Zeoli N, Tabbara H, Gu S. Three-dimensional simulation of primary break-up in a close-coupled atomizer. *Appl Phys A.* 2012;108:783-792.
doi: 10.1007/s00339-012-6966-7
53. Beale J, Reitz R. Modeling spray atomization with the Kelvin-Helmholtz/Rayleigh-Taylor hybrid model. *Atom Sprays.* 1999;9(6):623-650.
doi: 10.1615/AtomizSpr.v9.i6.40

54. Rayleigh. Investigation of the character of the equilibrium of an incompressible heavy fluid of variable density. *Proc Lond Math Soc.* 1882;1(1):170-177.
doi: 10.1112/plms/s1-14.1.170
55. Sharp DH. *An overview of Rayleigh–Taylor instability.* Los Alamos, NM: Los Alamos National Laboratory; 1983.
56. Lee HG, Kim J. Two-dimensional Kelvin–Helmholtz instabilities of multi-component fluids. *Eur J Mech B Fluids.* 2015;49:77-88.
doi: 10.1016/j.euromechflu.2014.08.001
57. Luo S, Ouyang Y, Lai S, *et al.* 3D numerical modeling of gas atomization process for powder preparation based on similarity theory. *Powder Technol.* 2024;433:119244.
doi: 10.1016/j.powtec.2023.119244
58. Luo S, Ouyang Y, Wei Q, *et al.* Understanding the breakup behaviors of liquid jet in gas atomization for powder production. *Mater Des.* 2023;227:111793.
doi: 10.1016/j.matdes.2023.111793
59. Tong M, Browne DJ. Direct numerical simulation of melt–gas hydrodynamic interactions during the early stage of atomisation of liquid intermetallic. *J Mater Process Technol.* 2008;202(1-3):419-427.
doi: 10.1016/j.jmatprotec.2007.10.012
60. Abdollahi S. Secondary atomization and solidification of metal melt in gas atomization [doctoral dissertation]. Politecnico di Torino. Accessed May 20, 2026. <https://webthesis.biblio.polito.it/id/eprint/29856>
61. Ejim C, Rahman M, Amirfazli A, Fleck BA. Effects of liquid viscosity and surface tension on atomization in two-phase, gas/liquid fluid coker nozzles. *Fuel.* 2010;89(8):1872-1882.
doi: 10.1016/j.fuel.2010.03.005
62. Guildenbecher D, López-Rivera C, Sojka P. Secondary atomization. *Exp Fluids.* 2009;46(3):371-402.
doi: 10.1007/s00348-008-0593-2
63. Wang P, Li J, Wang X, *et al.* Impact mechanism of gas temperature in metal powder production via gas atomization. *Chin Phys B.* 2021;30(5):054702.
doi: 10.1088/1674-1056/abd75e
64. Wei M, Chen S, Liang J, Liu C. Effect of atomization pressure on the breakup of TA15 titanium alloy powder prepared by EIGA method for laser 3D printing. *Vacuum.* 2017;143:185-194.
doi: 10.1016/j.vacuum.2017.06.014
65. Gianoglio D, Ciftci N, Armstrong S, Uhlenwinkel V, Battezzati L. On the cooling rate-microstructure relationship in molten metal gas atomization. *Metall Mater Trans A.* 2021;52(9):3750-3758.
doi: 10.1007/s11661-021-06325-2
66. Liu L, Zhang J, Zhang Q, Zhai C, Zheng H. Computational insights into gas atomization of FeCoNiCrMoBSi high-entropy alloy: from droplet formation to rapid solidification. *Int J Heat Mass Transf.* 2024;228:125628.
doi: 10.1016/j.ijheatmasstransfer.2024.125628
67. Park S, Gokcekaya O, Ozasa R, *et al.* Microstructure evolution of gas-atomized β -solidifying γ -TiAl alloy powder during subsequent heat treatment. *Crystals.* 2023;13(12):1629.
doi: 10.3390/cryst13121629
68. Qi H, Zhou X, Li J, Hu Y, Xu L. Performance testing and rapid solidification behavior of stainless steel powders prepared by gas atomization. *Materials.* 2021;14(18):5188.
doi: 10.3390/ma14185188
69. Shi L, Zou J, Chen J, *et al.* Study on segregation solidification and homogenization behavior of Cu–16Sn–0.3 Ti alloy powders. *J Mater Res Technol.* 2023;23:5547-5558.
doi: 10.1016/j.jmrt.2023.02.186
70. Wang G, Deng Y, Adjeikyeremeh F, *et al.* Numerical analysis of droplet breakup, cooling, and solidification during gas atomisation. *Powder Metall.* 2023;66(5):493-508.
doi: 10.1080/00325899.2023.2213002
71. Zeoli N, Gu S. Computational validation of an isentropic plug nozzle design for gas atomisation. *Comput Mater Sci.* 2008;42(2):245-258.
doi: 10.1016/j.commatsci.2007.07.013
72. Kurz W, Fisher D. Dendrite growth at the limit of stability: tip radius and spacing. *Acta Metall.* 1981;29:11-20.
doi: 10.1016/0001-6160(81)90082-1
73. Flemings M. Solidification processing. *Metall Trans.* 1974;5(10):2121-2134.
doi: 10.1007/BF02643923
74. Achelis L, Uhlenwinkel V. Characterisation of metal powders generated by a pressure-gas-atomiser. *Mater Sci Eng A.* 2008;477(1-2):15-20.
doi: 10.1016/j.msea.2007.07.095
75. Cech R, Turnbull D. Microscopic observation of the solidification of Cu–Ni alloy droplets. *JOM.* 1951;3(3):242-243.
doi: 10.1007/BF03397300
76. Gao C, Xiao Z, Zou H, *et al.* Characterization of spherical AlSi10Mg powder produced by double-nozzle gas atomization using different parameters. *Trans Nonferrous Met Soc China.* 2019;29(2):374-384.
doi: 10.1016/S1003-6326(19)64947-2
77. Liu C, Li X, Shu S, Huang Y, Li X, Zhu Q. Numerical investigation on flow process of liquid metals in melt delivery nozzle during gas atomization process for fine metal powder production. *T Nonferr Metal Soc.* 2021;31(10):3192-3204.

- doi: 10.1016/S1003-6326(21)65725-4
78. Luo S, Wang H, Gao Z, Wu Y, Wang H. Interaction between high-velocity gas and liquid in gas atomization revealed by a new coupled simulation model. *Mater Des.* 2021;212:110264. doi: 10.1016/j.matdes.2021.110264
79. Zhang L, Xu W, Li Z, Zheng L, Liu Y, Zhang G. Mechanism of rapidly solidified satellites formation in gas atomized powders: simulation and characterization. *Powder Technol.* 2023;418:118162. doi: 10.1016/j.powtec.2022.118162
80. Abdelsayed M, Trautner E, Berchtenbreiter J, Klein M. Primary atomization of shear-thinning liquid jets: a direct numerical simulation study. *Sci Rep.* 2024;14(1):23896. doi: 10.1038/s41598-024-75553-4
81. Chu F, Zhang K, Shen H, *et al.* Influence of satellite and agglomeration of powder on the processability of AlSi10Mg powder in laser powder bed fusion. *J Mater Res Technol.* 2021;11:2059-2073. doi: 10.1016/j.jmrt.2021.02.015
82. Ali U, Esmaeilizadeh R, Ahmed F, *et al.* Identification and characterization of spatter particles and their effect on surface roughness, density and mechanical response of 17-4 PH stainless steel laser powder-bed fusion parts. *Mater Sci Eng A.* 2019;756:98-107. doi: 10.1016/j.msea.2019.04.026
83. Elambasseril J, Song T, Mendis S. Effect of powder characteristics on layer density, defects, and tensile properties of Ti-6Al-4V via laser powder bed fusion: establishing benchmark parameters for quality. *Prog Addit Manuf.* 2025;10(10):7449-7470. doi: 10.1007/s40964-025-01046-z
84. Cheng C, Dou Z, Zhang T, *et al.* Oxygen content of high ferrotitanium prepared by thermite method with different melt separation temperatures. *Rare Met.* 2019;38(9):892-898. doi: 10.1007/s12598-019-01218-1
85. Muminovic A, Pervan N, Delic M, Muratovic E, Mesic E, Braut S. Failure analysis of nylon gears made by additive manufacturing. *Eng Fail Anal.* 2022;137:106272. doi: 10.1016/j.engfailanal.2022.106272
86. Qu M, Guo Q, Escano LI, *et al.* Controlling process instability for defect lean metal additive manufacturing. *Nat Commun.* 2022;13(1):1079. doi: 10.1038/s41467-022-28649-2
87. Liebgott N, Qaddah B, Zaied M, Durand R, Luiset B, Cribier V. Comparative Analysis of EIGA and VIGA Processes for Precious Metal Powders in Electrical Connector Applications. *Euro Powder Metallurgy 2025 Congress & Exhibition.* 2025. doi: 10.59499/EP256766697
88. Ren X, Wang Y, Wang Z, *et al.* Properties of Electrode Induction Melting Gas Atomization- and Vacuum Induction Melting Atomization-Produced Powders and Their As-HIPed Blanks. *Materials.* 2025;18(3):710. doi: 10.3390/ma18030710
89. Hou W, Meng J, Liang J, *et al.* Zeng cai zhi zao yong gao wen he jin fen mo zhi bei ji shu ji yan jiu jin zhan [Preparation technology and research progress of superalloy powders used for additive manufacturing]. *Powder Metall Technol.* 2022;40(2):131-138. [In Chinese] doi: 10.19591/j.cnki.cn11-1974/tf.2021030038
90. Wu J, Xia M, S Guo, Wang J, Ge C. Effect of Electrode Induction Melting Gas Atomization Process on Fine Powder Yields: Diameter of Free-Fall Gas Atomizer. *J Therm Spray Technol.* 2023;32(8):3390-3400. doi: 10.1007/s11665-022-07366-3
91. Belle M, Sherstneva A, Hauser M, Wendler M, Volkova O. Correlation between particle size, secondary dendrite arm spacing, and local cooling rate in gas-atomized stainless steel powders. *Powder Technol.* 2025;461:121096. doi: 10.1016/j.powtec.2025.121096
92. Du Y, Liu X, Xu S, *et al.* Numerical simulation of gas atomization and powder flowability for metallic additive manufacturing. *Metals.* 2024;14(10):1124. doi: 10.3390/met14101124
93. Liu J, Wang P, Dong Y, Zhao H, Pang J, Zhang J. Investigation on close-coupled gas atomization for Fe-based amorphous powder production via simulation and industrial trials: Part I. Melt breakup behaviors during primary atomization. *J Mater Res Technol.* 2023;27:6568-6580. doi: 10.1016/j.jmrt.2023.11.124
94. Ballesteros Martínez M, Becerra D, Gaukel V. Modelling the flow conditions and primary atomization of an air-core-liquid-ring (ACLR) atomizer using a coupled Eulerian-Lagrangian approach. *Flow Turbul Combust.* 2024;113(2):437-458. doi: 10.1007/s10494-024-00555-1
95. Guo K, Liu C, Chen W, Luo C, Li J. CFD modeling of primary breakup in an EIGA atomizer for titanium alloy powder production. *Materials.* 2023;16(17):5900. doi: 10.3390/ma16175900
96. Trautner E, Hasslberger J, Klein M. Towards LES of liquid jet atomization using an Eulerian-Lagrangian multiscale approach. *Flow Turbul Combust.* 2025;115(1):243-273. doi: 10.1007/s10494-024-00620-9
97. Wang J, Xia M, Wu J, Ge C. Nozzle clogging in vacuum

- p>induction melting gas atomization: influence of the delivery-tube and nozzle coupling.
- Arch Metall Mater.*
- 2022;67(4):1359-1370.
-
- doi: 10.24425/amm.2022.141063
98. Wang P, Li J, Liu HS, *et al.* Process modeling gas atomization of close-coupled ring-hole nozzle for 316L stainless steel powder production. *Chin Phys B.* 2021;30(5):057502.
doi: 10.1088/1674-1056/abd771
99. Wang Y, Dang Y, Chen X, *et al.* Numerical simulation of effect of various parameters on atomization in an annular slit atomizer. *J Iron Steel Res Int.* 2023;30(6):1128-1141.
doi: 10.1007/s42243-023-00943-3
100. Zhang C, Chu F, Zhong J, *et al.* Numerical analysis of gas-liquid flow dynamics in metal powder production by gas atomization. *Powder Technol.* 2026;478:122504.
doi: 10.1016/j.powtec.2026.122504
101. Xu L, Zhou X, Li J, *et al.* Numerical simulations of molten breakup behaviors of a de Laval-type nozzle, and the effects of atomization parameters on particle size distribution. *Processes.* 2020;8(9):1027.
doi: 10.3390/pr8091027
102. Hua J, Gobber FS, Grande MA, Mortensen D, Odden JO. A numerical modeling framework for predicting the effects of operational parameters on particle size distribution in the gas atomization process for Nickel-Silicon alloys. *Powder Technol.* 2024;435:119408.
doi: 10.1016/j.powtec.2024.119408
103. Qaddah B, Chapelle P, Bellot JP, *et al.* Swirling supersonic gas flow in an EIGA atomizer for metal powder production: numerical investigation and experimental validation. *J Mater Process Technol.* 2023;311:117814.
doi: 10.1016/j.jmatprotec.2022.117814
104. Thompson J, Hassan O, Rolland S, Sienn J. The identification of an accurate simulation approach to predict the effect of operational parameters on the particle size distribution (PSD) of powders produced by an industrial close-coupled gas atomiser. *Powder Technol.* 2016;291:75-85.
doi: 10.1016/j.powtec.2015.12.001
105. Zeoli N, Tabbara H, Gu S. CFD modeling of primary breakup during metal powder atomization. *Chem Eng Sci.* 2011;66(24):6498-6504.
doi: 10.1016/j.ces.2011.09.014
106. Hirt C, Nichols B. Volume of fluid (VOF) method for the dynamics of free boundaries. *J Comput Phys.* 1981;39(1):201-225.
doi: 10.1016/0021-9991(81)90145-5
107. Maxey M, Riley J. Equation of motion for a small rigid sphere in a nonuniform flow. *Phys Fluids.* 1983;26(4):883-889.
doi: 10.1063/1.864230
108. Liu A, Mather D, Reitz R. Modeling the effects of drop drag and breakup on fuel sprays. In: *International Congress & Exposition.* SAE International; 1993:83-95.
doi: 10.4271/930072
109. Luo S, Ouyang Y, Yang H, *et al.* Predicting the element loss in aluminum (AA2195) powder produced by gas atomization with a numerical model. *Powder Technol.* 2023;430:119013.
doi: 10.1016/j.powtec.2023.119013
110. O'Rourke PJ, Amsden AA. The TAB method for numerical calculation of spray droplet breakup. In: *SAE Technical Paper Series.* Vol 1. SAE International; 1987.
doi: 10.4271/872089
111. Vedovato G, Zambon A, Ramous E. A simplified model for gas atomization. *Mater Sci Eng A.* 2001;304-306:235-239.
doi: 10.1016/S0921-5093(00)01475-1
112. Antipas G. Gas atomization of aluminium melts: comparison of analytical models. *Metals.* 2012;2(2):202-210.
doi: 10.3390/met2020202
113. Aydin O, Unal R. Experimental and numerical modeling of the gas atomization nozzle for gas flow behavior. *Comput Fluids.* 2011;42(1):37-43.
doi: 10.1016/j.compfluid.2010.10.013
114. Guo KK, Chen J, Shang S, Liu CS. Numerical simulation of atomization process of nickel-based alloy powders prepared by vacuum induction melting gas atomization. *Vibroengineering Procedia.* 2020;32:185-189.
doi: 10.21595/vp.2020.21386
115. Qaddah B, Chapelle P, Bellot JP, *et al.* Numerical modeling and experimental study of swirling supersonic gas flow in the EIGA atomizer for metal powder production. In: *World PM2022 Proceedings.* EPMA; 2022.
doi: 10.59499/wp225370728
116. Shi Y, Lu W, Sun W, Zhang S, Yang B, Wang J. Impact of gas pressure on particle feature in Fe-based amorphous alloy powders via gas atomization: simulation and experiment. *J Mater Sci Technol.* 2022;105:203-213.
doi: 10.1016/j.jmst.2021.06.075
117. Wang K, Zhou Z, Sun W, Zhang Y, Zhang S, Wang J. Impact of novel nozzles on atomization flow field and particle features: simulation and experimental validation. *Metals.* 2025;15(3):313.
doi: 10.3390/met15030313
118. Wu J, Xia M, Wang J, Zhao B, Ge C. Effect of electrode induction melting gas atomization on powder quality: satellite formation mechanism and pressure. *Materials.*

- 2023;16(6):2499.
doi: 10.3390/ma16062499
119. Zhao T, Chen C, Wu X, Zhang C, Volinsky A, Hao J. FeSiBCrC amorphous magnetic powder fabricated by gas-water combined atomization. *J Alloys Compd.* 2021;857:157991.
doi: 10.1016/j.jallcom.2020.157991
120. Du K, Gao X, Li Z, *et al.* Numerical analysis on secondary breakup process of metal droplet in gas atomization. *Atom Sprays.* 2019;29(5):455-476.
doi: 10.1615/AtomizSpr.2019030629
121. Schwenck D, Ellendt N, Fischer-Bühner J, Hofmann P, Uhlenwinkel V. A novel convergent-divergent annular nozzle design for close-coupled atomisation. *Powder Metall.* 2017;60(3):198-207.
doi: 10.1080/00325899.2017.1291098
122. Zhao X, Xu J, Zhu X, Zhang S. Effect of atomization gas pressure variation on gas flow field in supersonic gas atomization. *Sci China Ser E Technol Sci.* 2009;52(10):3046-3053.
doi: 10.1007/s11431-009-0158-5
123. Mates S, Settles G. A study of liquid metal atomization using close-coupled nozzles, part 2: atomization behavior. *Atom Sprays.* 2005;15(1):19-40.
doi: 10.1615/AtomizSpr.v15.i1.30
124. Wang P, Liu J, Dong Y, Zhao H, Pang J, Zhang J. Industrial-scale fabrication of amorphous magnetic powder cores with excellent high-frequency magnetic properties: optimization for kinds and content of insulating agents. *J Non Cryst Solids.* 2023;602:122082.
doi: 10.1016/j.jnoncrysol.2022.122082
125. Wang P, Liu J, Dong Y, Zhu Z, Pang J, Zhang J. Breakup process modeling and production of FeSiAl magnetic powders by close-coupled gas atomization. *J Mater Res Technol.* 2023;23:730-743.
doi: 10.1016/j.jmrt.2022.12.169
126. Slotwinski J, Garboczi E, Hebenstreit K. Porosity measurements and analysis for metal additive manufacturing process control. *J Res Natl Inst Stand Technol.* 2014;119:494-528.
doi: 10.6028/jres.119.019
127. Brika S, Letenneur M, Dion C, Brailovski V. Influence of particle morphology and size distribution on the powder flowability and laser powder bed fusion manufacturability of Ti-6Al-4V alloy. *Addit Manuf.* 2020;31:100929.
doi: 10.1016/j.addma.2019.100929
128. Apell N, Tropea C, Roisman IV, Hussong J. Experimental investigation of a supersonic close-coupled atomizer employing the phase Doppler measurement technique. *Int J Multiphase Flow.* 2023;167:104544.
doi: 10.1016/j.ijmultiphaseflow.2023.104544
129. García J, Santolaya J, Lozano A, Barreras F, Calvo E. Experimental characterization of the viscous liquid sprays generated by a Venturi-vortex atomizer. *Chem Eng Process Process Intensif.* 2016;105:117-124.
doi: 10.1016/j.cep.2016.01.004
130. Korobeinikov I, Perminov A, Dubberstein T, Volkova O. Modification of liquid steel viscosity and surface tension for inert gas atomization of metal powder. *Metals.* 2021;11(3):521.
doi: 10.3390/met11030521
131. Li M, Yang H, Wang J, Li G, Tang J. An experimental investigation of the impact of surface tension and viscosity on the atomization effect of a solid cone nozzle. *Appl Sci.* 2023;13(7):4522.
doi: 10.3390/app13074522
132. Ouyang H, Xin C, Huang B. Influence of melt superheat on breakup process of close-coupled gas atomization. *Trans Nonferrous Met Soc China.* 2007;17(5):967-973.
doi: 10.1016/S1003-6326(07)60209-X
133. Snyder H, Senser D, Lefebvre A. Mean drop sizes from fan spray atomizers. *J Fluids Eng.* 1989;111(3):342-347.
doi: 10.1115/1.3243650
134. Bartzsch G, Scherbring S, Richter J, *et al.* Gas atomization of Al-steels. *Mater Today Commun.* 2023;34:105388.
doi: 10.1016/j.mtcomm.2023.105388
135. Dubberstein T, Heller HP. Effect of surface tension on gas atomization of a CrMnNi steel alloy. *Steel Res Int.* 2013;84(9):845-851.
doi: 10.1002/srin.201200321
136. Wang J, Xia M, Wu J, Ge C. Ladle nozzle clogging in vacuum induction melting gas atomization: influence of the melt viscosity. *Metall Mater Trans B.* 2022;53(4):2386-2397.
doi: 10.1007/s11663-022-02537-y
137. Ünal A. Effect of processing variables on particle size in gas atomization of rapidly solidified aluminium powders. *Mater Sci Technol.* 1987;3(12):1029-1039.
doi: 10.1179/mst.1987.3.12.1029
138. Basyir A, Kurnia R, Firdharini C, *et al.* Investigation of effect of various hot gas atomisation and melting pot temperatures on tin alloy powder product. *Sains Malays.* 2022;51(9):3027-3041.
doi: 10.17576/jsm-2022-5109-23
139. Yodoshi N, Endo T, Masahashi N. Evaluation of porosity in gas-atomized powder by synchrotron X-ray CT and investigation of the effect of gas species. *Mater Trans.*

- 2021;62(10):1549-1555.
doi: 10.2320/matertrans.MT-Y2021001
140. Yodoshi N, Sakurai I, Kudo K, Shinagawa K. Evaluation and suppression of porosity in gas-atomized powders. *J Jpn Soc Powder Powder Metall.* 2025;72(suppl):S99-S104.
doi: 10.2497/jjspm.14C-SIS1-02
141. Kim D, Kim Y, Lee H, *et al.* Gas atomization parametric study on the Viga-CC based synthesis of titanium powder. *Arch Metall Mater.* 2020;65(3):997-1000.
doi: 10.24425/amm.2020.133205
142. Cui C, Stern F, Ellendt N, *et al.* Gas atomization of duplex stainless steel powder for laser powder bed fusion. *Materials.* 2023;16(1):435.
doi: 10.3390/ma16010435
143. Zhang S, Alavi S, Kashani A, *et al.* Simulation of supersonic high-pressure gas atomizer for metal powder production. *J Therm Spray Technol.* 2021;30(7):1968-1994.
doi: 10.1007/s11666-021-01256-1
144. Frolov S, Ivanov V, Aksenov V, *et al.* Metal powder production by atomization of free-falling melt streams using pulsed gaseous shock and detonation waves. *J Manuf Mater Process.* 2025;9(1):20.
doi: 10.3390/jmmp9010020
145. Beckers D, Ellendt N, Fritsching U, Uhlenwinkel V. Impact of process flow conditions on particle morphology in metal powder production via gas atomization. *Adv Powder Technol.* 2020;31(1):300-311.
doi: 10.1016/j.apt.2019.10.022
146. Ciftci N, Ellendt N, Coulthard G, Barreto E, Mädler L, Uhlenwinkel V. Novel cooling rate correlations in molten metal gas atomization. *Metall Mater Trans B.* 2019;50(2):666-677.
doi: 10.1007/s11663-019-01508-0
147. Morks M, Zahiri S, Chen X, Gulizia S, Vargas-Uscategui A, Cole I. Influence of gas temperature and heat treatment on microstructure and properties of cold sprayed commercially pure titanium. *J Mater Eng Perform.* 2022;31(7):5549-5558.
doi: 10.1007/s11665-022-06621-x
148. Aksoy A, Ünal R. Effects of gas pressure and protrusion length of melt delivery tube on powder size and powder morphology of nitrogen gas atomised tin powders. *Powder Metall.* 2006;49(4):349-354.
doi: 10.1179/174329006X89425
149. Anderson I, Figliola R, Terpstra R, Rau S, Rauscher B. Progress in experimental analysis of gas atomization process physics. In: Proceedings of the 2002 World Congress on Powder Metallurgy & Particulate Materials. June 16-21, 2002; Orlando, FL. Metal Powder Industries Federation (MPIF); 2002:150-162.
150. Arachchilage K, Haghshenas M, Park S, *et al.* Numerical simulation of high-pressure gas atomization of two-phase flow: effect of gas pressure on droplet size distribution. *Adv Powder Technol.* 2019;30(11):2726-2732.
doi: 10.1016/j.apt.2019.08.019
151. Ayers J, Anderson I. Very fine metal powders. *JOM.* 1985;37(8):16-21.
doi: 10.1007/BF03257673
152. Bigg T, Mullis A. Spatially resolved velocity mapping of the melt plume during high-pressure gas atomization of liquid metals. *Metall Mater Trans B.* 2020;51(5):1973-1988.
doi: 10.1007/s11663-020-01899-5
153. Ibrahim M, Gobber FS, Hulme C, Grasmø G, Aune R. Influence of atomizing gas pressure on microstructure and properties of nickel silicide intended for additive manufacturing. *Metals.* 2024;14(8):930.
doi: 10.3390/met14080930
154. Lee S, Park S. Experimental study on spray break-up and atomization processes from GDI injector using high injection pressure up to 30 MPa. *Int J Heat Fluid Flow.* 2014;45:14-22.
doi: 10.1016/j.ijheatfluidflow.2013.11.005
155. Leon G, Lamberti V, Seals R, Abu-Lebdeh T, Hamoush S. Gas atomization of molten metal: Part I. Numerical modeling conception. *Am J Eng Appl Sci.* 2016;9(2):303-322.
doi: 10.3844/ajeassp.2016.303.322
156. Liu J, Dong Y, Wang P, *et al.* Simulation and experiment investigations on fabrication of Fe-based amorphous powders by a novel atomization process equipped with assisted gas nozzles. *J Iron Steel Res Int.* 2023;30(6):1142-1155.
doi: 10.1007/s42243-022-00855-8
157. Mandal S, Sadeghianjahromi A, Wang C. Experimental and numerical investigations on molten metal atomization techniques—a critical review. *Adv Powder Technol.* 2022;33(11):103809.
doi: 10.1016/j.apt.2022.103809
158. Miller R, Miller SA, Savkar S, Mourer D. Two phase flow model for the close-coupled atomization of metals. *Metal Powder Report.* 1997;52(5):50.
doi: 10.1016/s0026-0657(97)86668-4
159. Motaman S, Mullis A, Cochrane R. Use of computational modelling for investigation the effect of melt delivery nozzle tip length on gas flow separation in supersonic gas atomization. In: Proceedings of the 12th Triennial International Conference on Liquid Atomization and Spray Systems. September 2-6, 2012; Heidelberg, Germany.

160. Planche M, Khatim O, Dembinski L, Bailly Y, Coddet C. Evaluation of the splats properties and relation with droplets diameters in atomization process using a De Laval nozzle. *Mater Chem Phys*. 2013;137(3):681-688.
doi: 10.1016/j.matchemphys.2012.09.040
161. Saleh M, Ismail F, Muhamad N. Gas atomization of fine aluminum alloy powder for metal injection molding. In: Proceedings of the 3rd International Powder Metallurgy Conference. May 26-30, 2002; Eindhoven, The Netherlands. Turkish Powder Metallurgy Association (TTMD).
162. Si C, Zhang X, Wang J, Li Y. Design and evaluation of a Laval-type supersonic atomizer for low-pressure gas atomization of molten metals. *Int J Miner Metall Mater*. 2014;21(6):627-635.
doi: 10.1007/s12613-014-0951-4
163. Ting J, Peretti MW, Eisen WB. The effect of wake-closure phenomenon on gas atomization performance. *Mater Sci Eng A*. 2002;326(1):110-121.
doi: 10.1016/S0921-5093(01)01437-X
164. Ünal R. 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. *J Mater Process Technol*. 2006;180(1-3):291-295.
doi: 10.1016/j.jmatprotec.2006.06.018
165. Wei M, Chen S, Sun M, Liang J, Liu C, Wang M. Atomization simulation and preparation of 24CrNiMoY alloy steel powder using VIGA technology at high gas pressure. *Powder Technol*. 2020;367:724-739.
doi: 10.1016/j.powtec.2020.04.030
166. Khatim O, Planche M, Dembinski L, Bailly Y, Coddet C. Processing parameter effect on the splat diameters of the droplets produced by liquid metal atomization using De Laval nozzle. *Surf Coat Technol*. 2010;205(4):1171-1175.
doi: 10.1016/j.surfcoat.2010.08.032
167. Pinotti V, Andreoli A, Gargarella P. Gas atomization of AA2017 aluminum alloy: effect of process parameters in the physical properties of powders for additive manufacturing. *J Mater Res Technol*. 2024;30:3650-3662.
doi: 10.1016/j.jmrt.2024.04.104
168. Prashanth W, Thotarat SL, Sarkar S, Anand T, Bakshi S. Experimental investigation on the effect of melt delivery tube position on liquid metal atomization. *Adv Powder Technol*. 2021;32(3):693-701.
doi: 10.1016/j.appt.2021.01.017
169. Silva F, Lima M, Colombo G. Evaluation of a mathematical model based on Lubanska equation to predict particle size for close-coupled gas atomization of 316L stainless steel. *Mater Res*. 2022;25:e20210364.
doi: 10.1590/1980-5373-MR-2021-0364
170. Li X, Zeng K, He P, Luo H, Zhu J, Song X. Jin ou he qi wu hua can shu dui 3D da yin yong jin shu fen mo xing neng de ying xiang [Effect of tightly coupled gas atomization parameters on the properties of metal powders used for 3D printing]. *Powder Metall Technol*. 2021;39(2):172-176. [In Chinese]
doi: 10.19591/j.cnki.cn11-1974/tf.2019100003
171. Allimant A, Planche M, Bailly Y, Dembinski L, Coddet C. Progress in gas atomization of liquid metals by means of a De Laval nozzle. *Powder Technol*. 2009;190(1-2):79-83.
doi: 10.1016/j.powtec.2008.04.071
172. Chen X, Bai X, Fan C, Ge S, Deng C, Ma G. Experimental investigation of atomization characteristics of sonic blasting nozzle based on De-Laval dynamics. *Energy*. 2024;297:131188.
doi: 10.1016/j.energy.2024.131188
173. Guo K, Chen J, Liu C, Chen S. Shu zhi mo ni pen she jia jiao dui VIGA zhi fen wu hua guo cheng de ying xiang [Numerical simulation of the intersection angle influence on atomization process of powders produced by VIGA]. *J Northeastern Univ Nat Sci*. 2020;41(5):729-735. [In Chinese]
doi: 10.12068/j.issn.1005-3026.2020.05.020
174. Guo S, Yao J, Chen Z, Luo C, Wu H. Pen zui jie gou dui qi wu hua ji guang rong fu zhuan yong he jin fen mo de ying xiang [Effects of structure of nozzle on gas atomization for laser cladding alloy powders]. *J Mater Eng*. 2013;3(7):50-53. [In Chinese]
doi: 10.3969/j.issn.1001-4381.2013.06.001
175. Hamdi F, Agrebi S, Idrissi M S, et al. Impact of spray cone angle on the performances of methane/diesel RCCI engine combustion under low load operating conditions. *Entropy*. 2022;24(5):650.
doi: 10.3390/e24050650
176. Wang P, Zhou X, Li X, et al. Numerical and experimental investigation of close-coupled twin-nozzle gas atomization towards fine high-entropy alloy powder production. *J Mater Process Technol*. 2024;324:118238.
doi: 10.1016/j.jmatprotec.2023.118238
177. Zhang Z, Yi B, Tan Z. Numerical Simulation of Flow Field in the Laval Nozzle Based on Euler Equation. *J Phys Conf Ser*. 2021;2012(1):012089.
doi: 10.1088/1742-6596/2012/1/012089
178. Zhao W, Cao F, Ning Z, Zhang G, Li Z, Sun J. A computational fluid dynamics (CFD) investigation of the flow field and the primary atomization of the close coupled atomizer. *Comput Chem Eng*. 2012;40:58-66.
doi: 10.1016/j.compchemeng.2012.02.014