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Powder Manufacturing Techniques: A Review

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ABSTRACT

The growing need for advanced materials has placed a significant emphasis on the production of top-tier metal powders. To fulfill this demand, several established powder production methods have emerged, aimed at delivering high-purity metal powders. This review paper explores the various techniques used in the production of metal powders, addressing their importance in meeting the evolving requirements of modern manufacturing.

Keywords: Atomization, Ball Milling, Melt Spinning, Electro-decomposition.

INTRODUCTION

The powder metallurgical process stands as a versatile method for crafting a wide array of materials tailored for both developmental and industrial applications. It encompasses a spectrum of techniques including gas atomization, water atomization, centrifugal atomization, plasma atomization, mechanical attrition, alloying, melt spinning, rotating electrode processing (REP), and various chemical processes, all contributing to the production of metal powders.

These metal powders are characterized by their morphology, which may take the form of irregular, blocky, or spherical particles, and their size. They exhibit diverse properties encompassing physical aspects like hardness and ductility, chemical traits including reactivity and impurity levels, and bulk properties such as flow behavior, apparent density, tap the paramount importance of high-quality, fine metal powders, devoid of refractory and oxide contaminants and possessing a narrow particle size distribution, cannot be overstated. Such powders find applications in crafting plasma spray coating targets, as well as in the production of structural and functional materials. The powder metallurgical approach frequently outpaces other manufacturing processes like casting and forging in terms of cost-efficiency, precision, and productivity. (1,2)

LITERATURE REVIEW

Currently, there is a notable trend in research focused on advancing powder production technologies and methods. Numerous endeavors are underway to enhance established commercial processes like atomization and reduction methods. Over the past two decades, significant strides have been made in this field, resulting in the production of exceptionally high-quality powders through the adoption of cutting-edge techniques. Notably, some of the prominent advancements include:

1. Atomizing process:

Atomization stands as the predominant method in powder production, involving the transformation of a liquid into a fine spray. This process harnesses high-pressure fluid jets to mechanically disintegrate molten metal, resulting in the formation of exceedingly fine droplets that subsequently solidify into fine powder particles. Atomization encompasses various subtypes, including water atomization, gas atomization, vacuum atomization, centrifugal atomization, plasma atomization, ultrasonic atomization, and more. Initially, this technique was employed to manufacture high-quality powders of materials like aluminum, iron, stainless steel, and tool steel. However, contemporary applications predominantly center around materials such as aluminum, zinc, lead, pure iron, noble metals, low alloy steel powders, high-temperature alloys, and special alloy powders. (3) The wide adoption of the atomization method can be attributed to several key factors:

i. Virtually all metals that are meltable can undergo atomization.
ii. It facilitates the direct preparation of higher purity and pre-alloyed powders from the melt.
iii. Precise control over particle size and shape is attainable by adjusting parameters like metal temperature and the pressure of the atomizing medium.
iv. Atomization offers the potential for enhanced productivity at a lower equipment cost compared to conventional methods.
v. It enables the production of powders with minimal or no non-metallic inclusions. Numerous sub-categorical atomization techniques have emerged, which we will delve into in the following sections.

Atomization is a dual-phase procedure, characterized by a two-step sequence. Initially, it involves the fragmentation of liquid metal, and subsequently, the solidification of liquid droplets. During the first step, a sizable quantity of liquid undergoes fragmentation, resulting in smaller liquid particles. The necessary energy for this fragmentation process is derived from various sources, including high-velocity gas jets, water jets, centrifugal forces, and plasma jets. Consequently, atomization processes are categorized into distinct types, such as gas atomization, water atomization, centrifugal atomization, and plasma atomization. In the second phase, the molten droplets generated during fragmentation endeavor to minimize their surface energy by adopting spherical shapes, ultimately solidifying. The efficiency and speed of this entire process are contingent upon factors like the surface tension of the molten metal and the temperature of the super-heated molten droplets. (4)

1.1 Thermal spray gas atomization

Additive manufacturing (AM) places stringent demands on the properties of the powders employed, prompting the exploration of novel techniques to produce more adaptable powders. Among these methods, gas atomization in an inert atmosphere has emerged as the most promising. In 2016, a groundbreaking thermal spray atomization process was introduced.

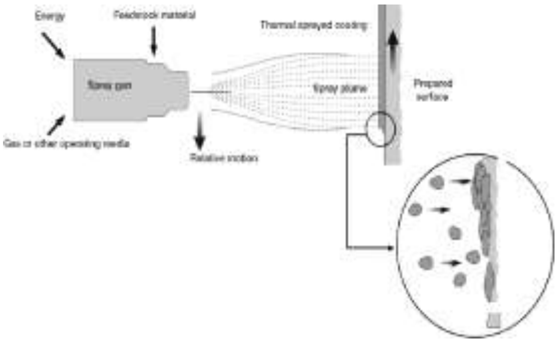

Figure 1: Schematic representation of thermal spray gas atomization model

In this process, spraying took place within a thermal spray cabin, and the powder was collected directly from the spray cone. Notably, two atomization media, air, and argon, were employed in the powder production, with the left side of the image illustrating the results. To optimize the design of the arc spray atomization chamber for experiments, a key consideration was minimizing its space requirements. Consequently, a counter gas flow was incorporated into the chamber from the right side, effectively reducing particle velocity and enhancing the cooling rate. The argon-sprayed powder particles thus generated exhibited a predominantly spherical shape, with some rounded, nodular particles discernible under scanning electron microscopy (SEM).

One of the primary benefits of using such powders in AM applications is weight reduction. It is conceivable that the utilization of AM-optimized lightweight components in lieu of conventional parts could lead to a substantial reduction in aircraft weight, potentially in the range of 4-7%. (5)

1.2 Free-Fall Atomization

In this method, a graphite crucible contains molten metal, and this molten metal is allowed to descend due to the force of gravity over a specific distance. During this descent, it encounters a gas field created by the collision of gas jets at the apex of the atomizer (as depicted in Figure 2). At the point of impact, the continuous stream of molten metal undergoes disruption, transforming into a cascading shower of droplets that swiftly solidify into spherical particles of varying sizes. It's worth noting that the size distribution of all the resulting powders follows a log-normal pattern. The mass median size of these powders exhibits a decrease when factors like gas velocity, higher gas-to-metal flow ratios, and sharper angles of interaction between the gas and metal streams are increased. (5)

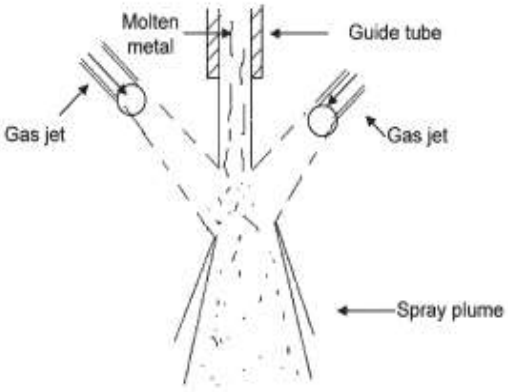

Figure 2: An illustrative representation of the free-fall atomization process.

To produce metal powder, a specialized free-fall gas atomizing unit was meticulously designed and constructed. The investigation delved into the impact of several parameters, including the focal length, number, and diameter of nozzles, as well as the apex angle of atomizers, on powder size, size distribution, atomization efficiency, and particle morphology. This disintegration of the molten stream was explored under varying plenum pressures, superheat levels, and free fall distances. It was observed that droplets tended to solidify and accumulate around the nozzles and the liquid delivery tube when the atomizer was operated beyond a specific plenum pressure threshold, which is referred to as the limiting plenum pressure.

Regardless of the wide array of conditions tested, all the resulting powder collectives adhered to a log-normal distribution function. The geometric standard deviation was found to maintain a consistent value. Additionally, a correlation was established between the mass median size of the powders and the dynamic parameters characterizing the atomization process, presenting a useful predictive tool. Furthermore, the atomization efficiency was correlated with the mass flow rate and gas velocity, shedding light on the efficiency of the atomization process in relation to these operational variables. (6,7)

1.3 Gas Atomization

The gas atomization process for powder production has garnered significant attention and widespread industrial application owing to its numerous advantages. These advantages encompass a high production capacity, exceptional flexibility for producing both elemental and pre-alloyed powders, and the capability to rapidly solidify metal powders. Notably, rapidly solidified metal powders often exhibit superior properties, stemming from their fine microstructure, chemical uniformity, extended solid solution, and the formation of metastable phases. Consequently, metal components crafted from such rapidly solidified metal powders tend to demonstrate superior mechanical characteristics.

In essence, the fundamental principle behind gas atomization lies in the destabilization of the molten metal by external forces, resulting in its fragmentation into smaller fragments or droplets. This melt disintegration process in gas atomization unfolds through five distinct stages:

i. The impingement of atomizing gas onto the molten metal induces an unstable, undulating melt stream.
ii. At the extremity of the melt stream wave, ligaments begin to form.
iii. These ligaments further disintegrate into individual droplets, marking the primary atomization phase.
iv. Subsequently, the melt droplets undergo further fragmentation in the secondary atomization stage.
v. Occasionally, satellite particles form as a result of collisions between melt droplets.

Within the gas atomization process, several crucial factors exert control over the size and size distribution of the resulting powder particles. These factors encompass the design of the atomization nozzle, the rate of atomizing gas flow, the flow rate of the molten metal, the specific type of metal melt utilized, and the degree of melt superheat. Thorough investigations into the influence of these processing parameters on powder particle size are invaluable. This research not only provides valuable insights but also facilitates the development of information, correlations, and predictive models essential for the powder production industry. (8,9)

1.4 Centrifugal Atomization

Centrifugal atomization is a method employed in the production of fine metal powder, involving the shearing of molten metal using a high-speed rotary disc in a tangential direction, as illustrated in Figure 3. The resulting powders typically have an average diameter exceeding 100 µm. The control over the average particle size hinges on the rotational speed of the rotor, which is somewhat constrained by mechanical friction. Essentially, the higher the rotor speed, the finer the particle size of the resulting powder. To achieve even finer powders using this technique, specialized self-lubricating centrifugal atomization equipment has been developed, enabling rotor speeds up to 5-6 times higher than those attainable with conventional .mechanical driving equipment . (11)

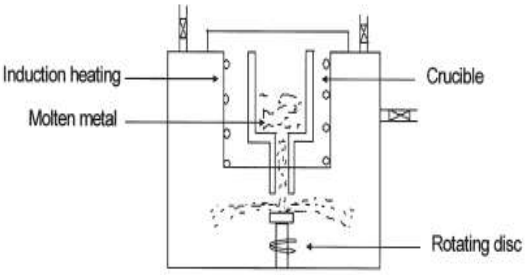

Figure 3: A schematic sketch of a rotating-disc process

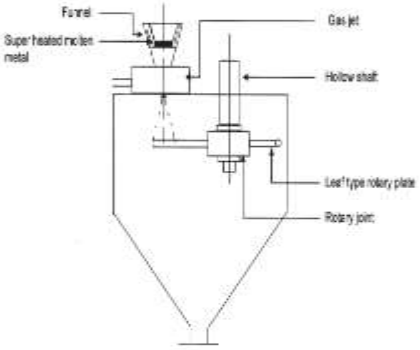

Figure 4: A schematic sketch of equipment combining gas with centrifugal atomization of spray rotation.

A synergistic approach combines the centrifugal technique of spray rotation with the spray powder method of gas atomization, yielding the production of finer powders, such as Al-20Si alloy particles in the 7-8 µm range. (13) In this process, superheated molten metal is introduced into a funnel, from which it cascades down to a jet and subsequently encounters a leaf-type rotary plate. Consequently, the molten metal undergoes atomization twice in this innovative technique. It stands out for its remarkable working efficiency, convenient speed regulation, and the exceptional speed achievable by the rotary plate, as depicted in Figure 8. (11)

1.5 Plasma Atomization

Plasma atomization stands out as a patented technology jointly developed by Pyro-Genesis and Hydro-Quebec (LTEE), (12,13) designed for the production of high-purity spherical titanium powders spanning a wide range of size options. Additionally, this innovative method has been successfully applied to the production of other metallic powders such as molybdenum, copper, and IN 718, a nickel-based super alloy. (15) The fundamental process involves the conversion of electrical energy into high thermal energy within a plasma torch. This transformation generates a jet of intensely hot ionized inert gas, characterized by its high velocity (as depicted in Figure 5).

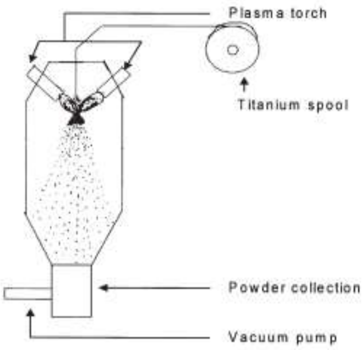

Figure 5: A schematic sketch of a plasma atomization process

The remarkable velocity of this gas plays a crucial role in ensuring effective atomization, while the extended high-temperature zone facilitates the completion of the spheroidization process. (13) In practice, a titanium wire is introduced at the apex of three converging plasma torches, each inclined vertically at angles ranging from 20 to 40 degrees. This precise design maximizes thermal and kinetic energy output, resulting in the wire's melting and atomization occurring in a single, seamless operation. A notable advantage of this process is its avoidance of molten baths. Moreover, since the entire operation unfolds in an inert atmosphere, the molten droplets generated remain free from moisture, yielding spherical powders with minimal impurities. The applications of plasma atomized powders are diverse, spanning from sporting goods to biomedical uses.

1.6 Pressure-Gas Atomization

Conventional gas atomization methods have historically presented challenges in achieving a consistent powder size distribution and have been associated with high specific gas consumption. To address these issues, a novel process was introduced, leveraging the combined effects of pressure and gas atomization. The primary culprit behind the wide-ranging powder sizes was identified as the instability of the molten film at the nozzle tip. To counteract this instability, a slotted nozzle was introduced, with the slots playing a crucial role in stabilizing the thin melt film, thereby improving powder quality.

In this innovative process, molten metal is subjected to a pressure differential of up to 1.0 MPa. The molten metal is directed into a swirl chamber where it circulates until it reaches sufficient pressure to exit through a small cylindrical hole in the pressure nozzle. Within the chamber, the centrifugal swirling force imparts a conical shape to the thin melt film, as depicted in the figure. High-velocity gas jets then come into play, causing the thin film to disintegrate into small droplets, ultimately resulting in the formation of powder.

Among the various parameters that can

influence the process, including melt flow rate, gas flow rate, gas pressure within the nozzle, and gas nozzle design, the only parameter that underwent variation was the atomization gas supply pressure. This novel technique marked a significant breakthrough as it successfully atomized molten metals, including pure tin and certain alloys, using different gas flow rates. (14) This advancement opened up new possibilities for the atomization of molten metals, enhancing their utility in various applications.

1.7 Water atomization of molten metal:

In this method, the atomization of molten metal is achieved through the use of high-pressure water jets. The process commences with the material being melted within an induction furnace and subsequently poured into a tundish. From there, a fine jet of metal is propelled while high-pressure water, generated by a pump, is simultaneously directed towards it, resulting in the atomization of the metal. The ensuing powder is then subjected to drying and classification processes tailored to its intended particle size for specific applications.

This technique harnesses the exceptional atomization capability of the V-jet nozzle, a technological innovation developed by Kobe Steel. To prevent oxidation of the melt stream, the atomization process can be conducted in an inert atmosphere, or alternatively, the area surrounding the water jet nozzle can be sealed with a chamber filled with inert gas. (10,15)

It's noteworthy that at higher water jet pressures, the final product tends to exhibit more irregular characteristics. Conversely, when water jet pressure falls below a certain threshold, atomization becomes hindered. Thus, achieving an optimal level of pressure is crucial for the successful execution of the atomization process. (4,10)

2. Milling:

1.5 Dry ball milling:

The basic configuration of a ball mill comprises a grinding compartment with trunnions at both ends one serving as the inlet for feed material and the other for the discharge of the final product, complete with a protective screen to contain the media.

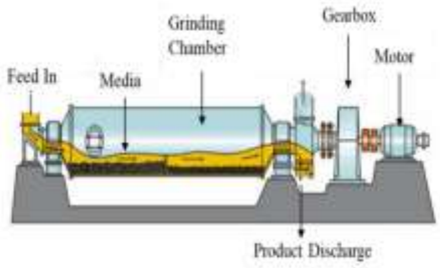

Figure 6: Schematic diagram of ball mill

The energy required for grinding is transmitted via a motor-gear assembly to the mill compartment, where it is imparted to the grinding media. Additionally, the interior surface of the grinding compartment is equipped with a liner to shield against abrasion. Several critical factors influence the final product size, including the size and weight of the media, the rotational speed of the mill, the rate at which feed material is introduced, its properties, the charge-to-feed ratio, and the inclination or slope of the mill. (16)

1.6 Jet milling process:

The jet mill has undergone significant development and has emerged as a primary production method for obtaining high-purity fine particles, including minerals, pigments, and metal oxides typically ranging from 1 to 10 µm in size. (17) Often referred to as fluid energy mills, jet mills operate without the use of any moving parts and achieve particle size reduction by employing high-velocity gases like nitrogen, air, and/or steam. While these mills are commonly employed in the pharmaceutical industry, their application in powder metallurgy is somewhat limited. (18)

The utilization of jet mills for fine particles offers several advantages, including enhanced particle fineness, a narrow size distribution, reduced product contamination, and lower grinding compartment temperatures. (18) Jet mills are particularly well-suited for producing ultra-high purity powders of abrasive materials, thanks to reduced wear. However, it's essential to note that the high-energy input demands of this method can be cost-prohibitive, often necessitating process optimization to manage operational costs effectively. (19,20)

In terms of construction, there are five distinct types of jet mills available

1. Fluid impact mill
2. opposed jet mill
3. Spiral jet mill
4. Oval chamber jet mill
5. Fluidized bed opposed jet mill. Figure 7 illustrates the schematics of a fluidized bed opposed jet mill.

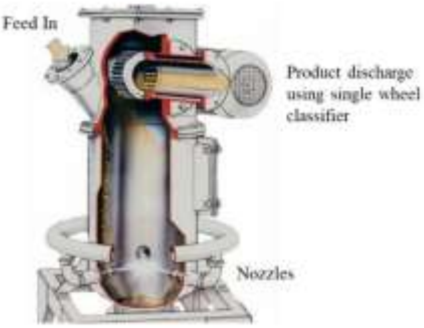

Figure 7: Schematics of a fluidized bed opposed jet mill.

3. Solid-state reduction:

Reduction of compounds (particularly oxides) by the use of reducing agents, in the form of either solid or gas is the most widely employed and probably the oldest method of producing metal powders. This is a convenient, economical and extremely flexible method for controlling the properties of product regarding size, shape & porosity. It is extensively used for manufacturing Fe, Cu, Ni, W, Mo, Co, Ta, Th, Zr, Ti, and even Al. In solid state reduction, selected ore is crushed, typically mixed with carbon (or any other reducing agent) and passed through a continuous furnace. A reaction takes place, reducing the carbon & oxygen from the powder that leaves a cake of sponge metal which is then crushed, separated from all nonmetallic material and sieved to produce powder. In recent years, metal powders particularly Ni, Co and Cu are precipitated on commercial scale by hydrometallurgical method, by the reduction of aqueous solutions or slurry of salts of metals. A distinct advantage of the process is that it can be operated on low grade ores. (21)

4. Electrodeposition:

Metal powders can also be produced by Electrodeposition from aqueous solutions and fused salts. Electrodeposition is a well-known method to produce in situ metallic coatings by the action of an electric current on a conductive material immersed in a solution containing a salt of metal to be deposited. As a result, powder formation occurs on the cathode. As many as 30 metals have been prepared as powder by electrolysis but this technique is mainly employed for making metal powders such as Cu, Be, Fe, Zn, Sn, Ni, Cd, Sb, Ag and Pb. High current density, low metal- ion concentration, high acidity, low temperature, etc. yields in good quality powder production and easy removal of powder from cathode. The process has a number of advantages such as – obtaining powders of high purity with excellent sinter ability & wide range of powder quality can be produced by altering bath composition.

5. Chemical processes:

The most common chemical powder treatments involve oxide reduction, precipitation from solutions and thermal decomposition (TD). TD involves devolatilization or decomposition of vapor which produces metal powders particularly Fe, Ni and even Zn, Mg, Co, W, Mo, Cr. TD is most often used to process carbonyls.

Metal powder is also obtained by milling process. The material to be disintegrated is tumbled in a rotating, cylindrical container with a large number of hard, wear resistant solid balls which by hitting the material, causes them to break down. During milling impact, shear and compression forces are acted upon particles. The main disadvantages of this process are work hardening and excessive oxidation as both are harmful. The former reduces compressibility while latter causes chemical reaction on sintering.

SUMMARY

The powder metallurgy process stands as a valuable method for manufacturing a diverse array of materials, serving both developmental and industrial applications. It revolves around the utilization of metal powders, each characterized by its distinct morphology, which can range from irregular and blocky to spherical, alongside variations in particle size. These powders possess a spectrum of properties that encompass physical attributes like hardness and ductility, chemical qualities including reactivity and impurity content, and bulk characteristics such as flow properties, apparent density, tap density, compressibility, and green strength.

The production of high-quality, fine metal powder is particularly crucial, as these powders need to be free from refractory and oxide contaminants while maintaining a narrow particle size distribution. They find utility in various applications, including the fabrication of plasma spray coating targets and the production of both structural and functional materials. Compared to alternative processes like casting and forging, the powder metallurgical route often proves more economically advantageous in terms of cost, precision, and productivity. It offers a versatile and cost-effective means of creating a wide range of materials tailored to specific industrial needs.

Declaration by Authors

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