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TAXONOMY ON THE PRODUCTION PROCESSES AND CHARACTERIZATION OF POWDER METALLURGY USED IN ADDITIVE MANUFACTURING PROCESS

Purpose. This article presents a concise and comprehensive review of the technologies that are typically used for manufacturing metal powders as well as the implications that particle features have on the properties of additive manufacturing (AM) techniques.

Methodology. We surveyed various experiments that have taken place on the effects of the qualities of the powder and how to guarantee the dependability and reproducibility of the parts that are manufactured as well as ways of optimizing a powder's performance. We classified the methods for producing metallic powders and highlighted the benefits, limitations, and image analysis of major production techniques.

Findings. The usage of different approaches to metallic powder characterization for the analysis of the physical, mechanical, and chemical processes has contributed to major steps in powder optimization. The characterization of these powders is critical for ensuring adequate additive material dimensions and specifications and recording the properties of powders used in an AM and bridging the gap of comprehension concerning the end output in AM.

Originality. This paper provides a thorough analysis of the efforts made in the powder characterization of AM components for the interpretation of the impact on the part materials' qualities and characteristics. Metallic powder characterization has contributed to substantial progress toward powder optimization in the analysis of particle structures.

Practical value. As the application of AM technology is moving away from the creation of prototypes and toward the production of finished products, it becomes important to understand the powder properties necessary to manufacture high-quality elements consistently.

Keywords: *metallurgy, additive manufacturing, metal powder production, powder properties, processes, method*

Introduction. Layer-by-layer construction method known as additive manufacturing (AM) uses a computer-aided design file for the generation of components. Installing the pieces instead of utilizing substratum methods to separate matter from a wider object, usually by heat input, binder, or chemical means connects successive layers of material [1–3]. This modern method promotes the manufacture through traditional processes of components with a large geometrical complexity. Within the domain of research on additive manufacturing, a considerable amount of emphasis has been placed, in recent years, on the exploitation of metallic powders as a result of the overwhelming demand to produce parts that can be put to practical use. Among others, Ti-6Al-4V [4, 5], 316L stainless steel [6, 7], 17-4 PH stainless steel [8], IN625 [9], and IN718 [5, 10] are among the materials that are researched in the most frequently.

While powder usage in AM is popular, it has presented a serious challenge for researchers to optimize powder properties to achieve desired performance characteristics. The fact that a powder's performance can be optimized in a variety of ways, each of which can affect a different set of particle attributes, is one explanation for this (Fig. 1). Each characteristic, such as packaging density, optical layer thickness, as well as thermal conductivity, contributes to the mass features that determine the characteristics of the manufactured pieces. Additional factors of powder properties could trigger problems with underlying particle physics causing the notorious phenomenon of balling and deteriorating properties of pieces. Several studies have observed the impact that particle size, shape, as well as surface roughness have on AM processes [11–14]. As a result, the qualities of the powder need to be investigated and managed to guarantee the dependability and reproducibility of the parts that are manufactured. While various experiments have taken place, the effects of the initial particle features on the properties of the components are still not well known. The need to close this information gap is becoming evident with the maturation of the AM industry and the desire for the development of usable AM components growing [15, 16]. The usage of powder characterization methods warrants the challenge of recognizing the impact of particle characteristics. This paper provides a thorough analysis of the efforts made in the powder characterization of AM components for the interpretation of the impact on the part materials' qualities and characteristics. After that, we discuss the findings of structural analyses of AM powder content characterization. The characterization of these powders is critical for ensuring adequate additive material dimensions and specifications and recording the properties of powders used in an AM material.

The following is a list of the notable contributions that this article review has made:

- presenting the review of a recent trend for AM process;
- providing other aspects of assessment as the taxonomy and classification of methods for producing metal powders used for additive manufacturing.

The remaining sections of this theme are organized as follows:

1. *Section 2* provides a brief description and classification of AM technology.
2. *Section 3* provides a discussion on the most common methods for metal powder production.
3. *Section 4* presents several examples of how the shape, and size of typical metal powders, and their alloys can be characterized.
4. *Section 5* contains the conclusions of this study.

Additive manufacturing. The manufacturing process begins with the design strategy and definition of the content from which the products are made. New ways to generate three-dimensional (3D) metal components directly from Computed Design (CAD)

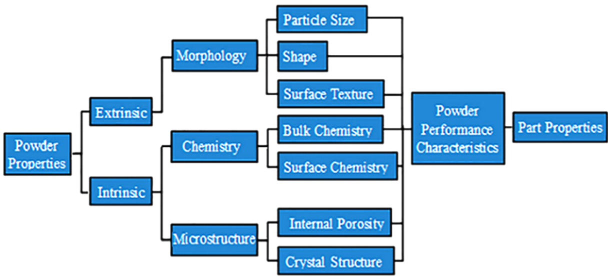

Fig. 1. Classification of powder properties into two main categories

model are recognized by AM technologies. AM was initially only treated as a creative prototype of resource and recognized as quick prototyping or strong development of free form. It has now become a universal need in the process of development and is predicted to quickly achieve a tipping point. The combined force of technical sophistication enables the manufacture of special and complicated individual components that cannot be managed by most manufacturing methods. Another benefit of AM includes manufacturing faster and cheaper goods, minimizing the environmental effects, reducing resource intensity, and reducing lead times. AM has an added advantage.

AM was then adopted in 2011 as a rising manufacturing process in many sectors such as healthcare and medicinal industries [17]. The technology involves customized tissue scaffolding products, vessel stents, dental functions, and biomedical instruments. The AM classification is grouped into powder, liquid, or solid-based processes (Fig. 2), integrating a vast variety of manufacturing technology that has established a wider scope of potentially industry-individual technologies. It encompasses a vast range of technologies recently listed under the American Society of Testing Materials (ASTM) Standard F2792 [18]. A detailed description of their applications and their distinct technological aspects have been contributed for example by Ian Gibson and David W. Rosen [19].

The two technologies most widely used for AM metallic components are Powder based fusion (PBF) and Directed Energy Deposition (DED) technologies. The two technologies use metal alloy powders but vary in the powder feeding process. Inside the frame of AM technologies in Fig. 2, different processes can be identified, where a mixture of materials (including plastics, metals, ceramics, or composites), different deposition techniques, and different ways of fusing/solidifying the materials are used.

Methods for producing metal powders used for additive manufacturing. This section provides a discussion on the most common methods for metal powder production. Metal powders must have clear powder characteristics to ensure that metal parts are produced repeatably [20]. For example, in the production of additives, the metal powder used is considered to be spherical and has a particulate-size distribution intended to facilitate making the finished product with excellent mechanical qualities, including shape, density, chemical properties, flowability, compressibility, green polish surface, and sintering and heat power. Particle scale (also known as granulometry), as well as particle structure, are the most important characteristics of powders (morphology). For the powder to have a proper clarification of these characteristics, based on certain features, it is vital to ensure both the prospective areas of application and the technical qualities of powders (relative density, flowability, regions, deformability, greenish strength, as well as thermal).

The increasing use of packaging technologies creates demand for specialized and efficiently controlled powders of various properties in terms of production, chemical composition, and morphology (part form), as this then has an impact on processing. The characteristics of the finished product are described by the particular powder character, which also depends on the base powder's manufacturing process. Different methods are often used to manufacture metal powders with different morphology and characteristics for each device. These methods include human, mechanical, and chemical processes as described in Fig. 3.

Physical Method. The Physical method of metal powder production is broken into two types, the atomization process, and the rotating electrode process.

Atomization Process. The methods of water atomization, gas atomization, centrifuge atomization, as well as plasma atomization can be used to produce metallic powders. Every atomization method has both shape, form, and complexity advantages and disadvantages. Applications to powder metallurgy typically allowed spherical particles as they had stronger flowability and density properties. This can be accomplished by the atomization of gas and plasma.

1. *Water Atomization Process.* In the process of water atomization, the metal is melted inside an induction furnace and down to the tundish (Fig. 4) [21].

Water atomized powders usually consist of irregular shapes which permit the interlocking among particles during powder compacting, and these powders' compacts are easily dealt with. The more the irregularity of powders is, in general, the more the apparent density decreases.

2. *Gas Atomization Process.* It is similar to the water atomization process in that the molten alloy comes out of the induction furnace and falls through the tundish nozzle (Fig. 5) [22].

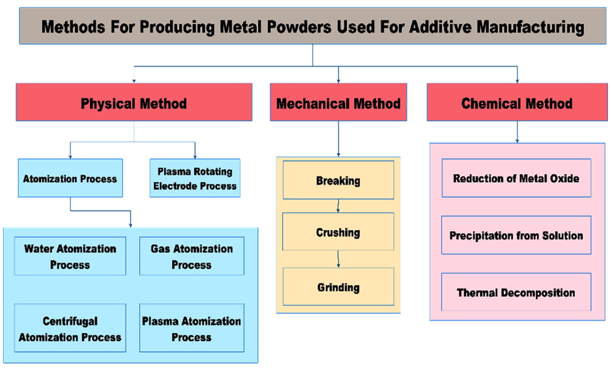

Fig. 3. Classification of methods for producing metal powders

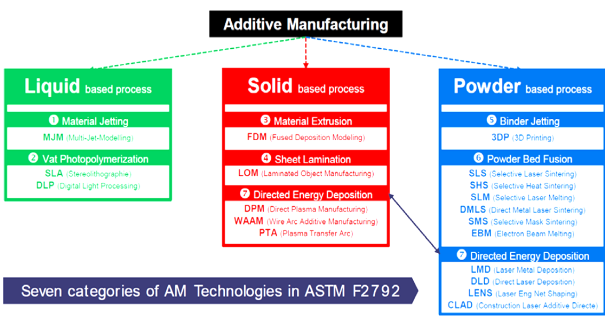

Fig. 2. Classification of additive manufacturing technologies

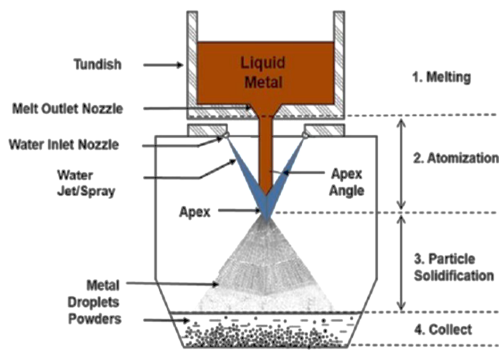

Fig. 4. Water atomization process [21]

The inert gas with a few MPa of pressure is sprayed producing the alloy powder. The gas jet nozzle and other conditions delicately influence the powder characteristics as they do in the water atomization process. Therefore, careful control is important in powder production.

3. *Centrifugal Atomization Process.* The alloy melted by an induction furnace falls into a disc revolving at a high speed. After that, the powder is created through the use of centrifugal force, which at the stage of crystallization, produces a more spherical powder (Fig. 6). The circumferential speed of the disc is usually limited to about 100 m/s. This process is advantageous in that the atomizing conditions and cooling speed of droplets may be controlled independently.

4. *Plasma Atomization Process.* The process of producing metal powders incorporates plasma technology in several stages of the process which can produce different sizes of metal powder from very fine 25 to rough 125 μm (Fig. 7) [23]. With the advantages of having strong flowability properties and being capable of producing high densities. When it comes to the manufacturing of powders, having a powder with good flowability means having fewer additives than flow powders.

Plasma Rotating Electrode Process. Another type of powder production process, where the metal powder can be generated, is the Plasma Rotations Electrode Process (PREP). Here, the material that is fed into the machine is in the form of rods, and nitrogen or argon plasma arc melts the head of the rod, the

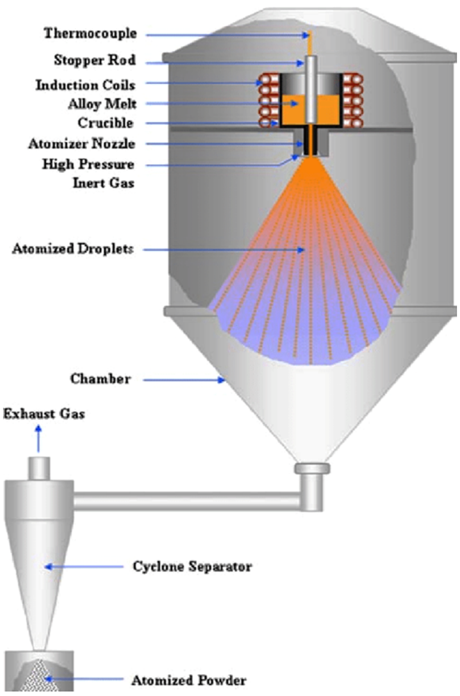

Fig. 5. Gas atomization process [22]

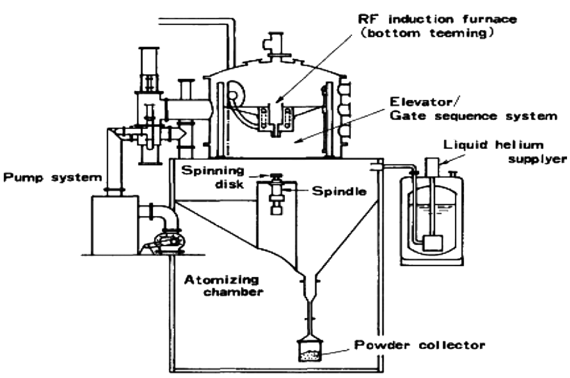

Fig. 6. Centrifugal atomization process

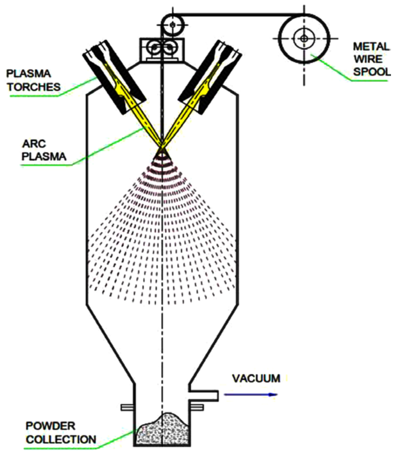

Fig. 7. Plasma atomization process [23]

rods are rotated very quickly and throw melt through the high centrifugal rotational forces in a metal grain (Fig. 8) [23].

The metal powder continues to be exposed to another sealing phase to manufacturing powders of standard grain size. Compared with conventional technology. One of the advantages offered by the plasma arc technique is the capability of rapidly adjusting the appropriate temperature by adjusting the parameters governing the plasma source voltage and current.

Mechanical Method. The mechanical method of powder production called the comminution of test specimens is among the most crucial processes, in all chemical laboratory analysis activities, but the most error-prone ones (Fig. 9). The comminution process normally depends on the following parameters:

- the total quantity and number of samples of the material to be homogenized;
- the initial particle size of the original sample;
- the ultimate fineness of the sample after comminution;
- chemical/physical properties of the original sample and the grinding elements (contamination/volatilization);
- the hardness of the material to be homogenized.

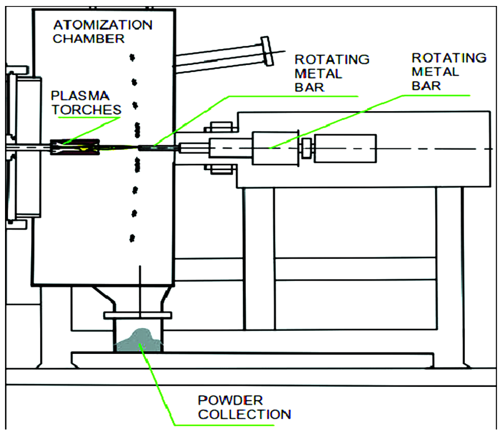

Fig. 8. Plasma rotating electrode process [23]

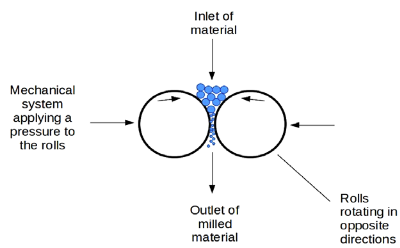

Fig. 9. Mechanical process

It is performed in the following three sequential steps: breaking, crushing, and grinding.

Typically, it refers to converting fragmenting solid samples primarily composed of big particles into powdered constituent substances that have smaller particle sizes. During these processes, there is no change in the aggregate condition of the substance that is to be homogenized, while the sample's physical and chemical characteristics can well change. The goal is to produce a uniformly powdered representative sample for additional chemical/physical processing. The vast parent mass, which can range anywhere from kilograms to tons and can be found in the form of mixed garbage dump pieces, rock strata debris, and so on, is one of the challenges that must be overcome when doing sampling, in particular when conducting the ecological study. Reducing particle size by grinding is also of limited use and is energy-consuming. The tendency of the small particle to stick together is against disintegration.

A 'grinding equilibrium' state is reached when aggregation equals the rate of surface formation to surface loss. Under these conditions, more friction does not increase the surface area. While the reduction in a particle size is of great importance in powder technology; this method is not a generally viable approach for industrial adsorption production. Another significant challenge that frequently arises is the potential for contamination and/or evaporation of individual components, which is especially problematic in the realms of trace and ultra-trace analysis in ecological research. The possibility of contamination is also found in the case of the high percentage of content (for instance, iron or chromium in stainless steel mills) in the grinding materials themselves, or if these volatilized combinations escape the sample due to over-heat.

Chemical Method. The Chemical process is one of the most popular metal powder processing methods. They involve metal oxide reduction, solution precipitation, and thermal decomposition. Nearly all metallic elements can be produced by appropriate chemical reactions or decomposition in powder form. For example, when heated to temperatures that are sufficiently high all chemical compounds can be decomposed into their elements. If the non-metallic radical can be eliminated, e.g., by continuous evacuation or by inert gas trapping, then practical methods for producing metal powders may be feasible. They are based on heating or with the aid of any catalyst, decomposing a compound into the elemental. In most situations, at least two reactants (a metal compound and a reducing agent) are involved in such processes.

1. Reduction of Metal Oxide. Most metal powers manufactured by reduction of oxides are produced using solid carbon or hydrogen, cracked ammonia, carbon monoxide, or a mixture of such gases. As a reducing agent for metal oxides, carbon holds an important and peculiar position – because of its general cheapness and availability. This reaction involves an increase in the number of gaseous molecules, a considerable increase in entropy, and a considerable free energy change. This implies that within temperature normally used metallurgically, carbon monoxide becomes increasingly stable the higher the temperature. In this condition, an uneven powder of a spongy consistency and a grain size of less than 100 mesh will be created. Precipitation from Solution

The processing of metals and certain metal compounds through reactions in water or organic solvents is dealt with in hydrometallurgy. The first is meant to manufacture metals in vast amounts, utilizing the feed matter of an oil, waste metal, or a residue from some other operation, while the second is to precipitate metals in special shapes, such as a covering of another substance. It may be a separate method of hydrometallurgical technique. The steps in a hydrometallurgical method for metal processing of an impure raw material are solution preparation by leaching, solution purification, and metal precipitation.

2. Thermal Decomposition. The production of powdered forms of nearly all metallic elements is possible through the application of appropriate chemical reactions or by decomposition. For example, all chemical compounds can be decomposed into their elements when heated to sufficiently high temperatures. If the non-metallic radical could be removed by continuous evacuation or by entrainment in an inert gas, the practical methods for making metal powders might be feasible.

Benefits and Limitations of Powder Production Processes. When choosing and/or optimizing a particle for a specific procedure, the benefits and limitations must be considered. The benefits and limitations of metal powder production for image analysis are summarized in Table 1, which can be found here.

Powder Parameters and Characterisation Methods. In this part, several examples as to how the form and size of typical powder metallurgy as well as related alloys can be defined are presented. These examples focus on the shape of the powders. The great majority of researchers have made scaffolds for tissue applications using AM as a technique. Moreover, there is a general lack of comprehension regarding the connection that exists between the characteristics of the metal powders used in AM and the final output. As such for better understanding, there are a variety of principles of measurement for measuring particle size distribution. Among these are Dynamic Image Analysis (DIA), Laser Diffraction (LD), and Mechanical Sieve Analysis (MSA), by Dynamic Image (DI).

Dynamic Image Analysis (DIA) offers a direct approach to particle size analysis. The fundamental idea is simple: "What you see is what you get". Automatic algorithms in software describe morphology and dimension dependent on photographs of single particles. The knowledge is given explicitly on the width and duration of the particle. The data of the DIA on particle size and form are all relevant. The calculation results are based on a significant volume of the analyzed particles and thus are statistically more precise and give greater reproducibility in contrast to the laser diffraction or mechanical sieve experiments. Laser diffraction (LD) can be applied on scales ranging from the nanoscale to the millimeter unit, in increments of tens of nanometers at a time. However, it is important to keep in mind that the actual numerical values produced by the laser diffraction particle size analyzer are dependent not only on the optical system of the analyzer but also on the method that was used to sample the measurement target (sample). Table 2 provides a list of some of the powder characterization methods that are frequently utilized in AM. The comparison of powder characterization methods in AM.

Table 2 provides techniques for powder characterization that has been used in AM. The techniques are categorized into three particle parameters: Morphology, Chemistry, and Microstructure. There are quite a several methods used to determine particle morphology of which the most common includes: sieve analysis, microscopy, and laser diffraction. When analyzing the same material, the results of different approaches frequently do not correspond well with one another. Likewise, if measured against the parameters of other samples, sieve analysis is applied to a large variety of samples and has a longer period of calculation and vulnerability to binding which makes the technique less used. While microscopy allows qualitative as well as quantitative analysis of particle structure, it is highly costly with decreasing particle size. Laser diffraction, on the other hand, can be applied to both a small and large variety of samples, it is cost-effective, requires short analytical time, and repeated findings are needed. Although, errors caused by irregular particles (by either water atomization or centrifugal atomization) can be corrected by using spherical particles produced by gas atomization. In terms of general usage, the advantages of laser diffraction are well-known and this has contributed to its dominance in the instrumental particle sizing arena.

However, Particle chemistry is categorized into two: destructive and non-destructive techniques. The techniques within the destructive category are AES (Auger electron spectroscopy), Spectroscopy of atomic emission performed using inductively coupled plasma, and Inert gas fusion. This sole disadvantage has made it less practicable. Considering the non-destructive techniques which are XPS (X-ray photoelectron spectroscopy), EDS (Energy dispersive spectroscopy), and Fourier transform infrared spectroscopy (FTIR).

X-ray photoelectron spectroscopy (also known as electron spectroscopy) is a method for analyzing particle chemistry that makes use of emitted electrons. This method could indeed measure elementary composition in addition to the electronic and chemical state of the atoms within a material. In comparison to FITR and EDS, XPS is significantly faster and more accurate. The FTIR spectra are dominated by info originating from the structures of particulates and capable of rapidly and easily identifying functional groups in the content but are limited to relatively small sizes. Most materials completely absorb infrared radiation, which makes this technique impossible to get a dependable result. On the other hand, EDS uses a signal from emitted X-rays, which is quite a fast and dependable technique but not as accurate as XPS.

Finally, XRD (x-ray diffraction), FTB (focused ion beam), Transmission electron microscopy, and Thermal analysis are some techniques of particle microstructure. The thermal analysis which was not considered, although it provides information regarding the endothermic and exothermic transitions that are linked with the sample, is destructive. While transmission electron microscopy, whose imaging and diffraction capabilities are provided as part of its service, needs a well-informed operator for the complex sample preparation. Though FIB is an extension of a scanning electron microscope (SEM) which can image and modify a specimen by site-specific material removal, deposition, and manipulation. It also helps in the fabrication of TEM samples and cross-sections but its redeposition of material that has been milled makes it less efficient. Nevertheless, XRD is a non-destructive test method that is capable of determining the crystalline structures of different

Table 1

Summary of the benefits, limitations, and image analysis of major metal powder production techniques

Processes	Material	Melting point, °C	Granulometry, μm	Powder	Advantages	Disadvantages
Water Atomization	AISI316L	463–671	44–06	Irregular	- rates of output are strong; - huge particle size range; - components in the form of ingots	- an additional water reduction method is underway; - wide distribution of particle size
Gas Atomization	Ti alloy	1670	0–250	Spherical	- can be used for different kinds of alloys with reactive characteristics in ingots; - huge particle size range	Wide particle size distribution
Centrifugal Atomization	Mg alloy	349–649	50–800	Irregular	i. huge particle size range ii. There is not much variation in particle size across the board	Hard to make decent quality powder
Plasma Atomization	Ti alloy	1670	25–125	Spherical		- the feedstock is required to be in the type of either wire or powder; - requires additional process; - costly
Plasma Rotating Electrode Process	Tungsten	3400	160–500	Spherical	High purity	- low productivity; - highly expensive; - requires additional process
Reduction of Metal Oxide	Iron	1127–1593				Requires additional process
Reduction of Metal Ore	Iron	1127–1593				Requires additional process

Table 2

Summary of powder characterization methods for AM

Particle parameters	Technique	Material	Resolution	Particle size range	Advantages	Disadvantages
Particle morphology	Sieve analysis	Solids	The size of the bin is determined by the size of the sieves used for separation	20 μm–125 nm	Applied to a large variety of samples, minimum processing, and low cost	There is little visibility into the part's form, a longer period of calculation, and vulnerability to blinding
	Microscopy	Dependent on microscope	$d = \frac{0.61\lambda}{NA}$ d – resolution distance λ – light source wavelength	Determined by system resolution	Allows for the qualitative as well as quantitative analysis of particle structure, the versatility of particle size, as well as form analysis	The work required to prepare samples for scanning electron microscopy and transmission electron microscopy is greater than that required for optical microscopy, resulting in a cost rise with decreasing particle size
	Laser diffraction	Solids	Depends on the design of the device and the algorithm used to analyze the data	0.04–8000 μm	Short analytical time, no qualified and highly repeated findings are needed	Errors can be caused by irregular particles, measurements might be affected by the architecture of the device, and agglomeration detection can be challenging

Particle parameters	Technique	Material	Resolution	Particle size range	Advantages	Disadvantages
Particle chemistry	XPS	Conductive solids	1 μm	Any conductive particles that are larger than the size of the X-ray spot	The overall structure and chemical bonding assessment, higher penetration, elemental study relative to XPS facilitate depth profiling	Sputtering via spherical particles is not able to detect H, can be difficult to utilize, and requires a trained operator
	AES	Conductive solids	0.5–2 μm	Any conducting particles that are larger than the size of the electron beam	When compared to XPS, elemental analysis was performed at a shallower penetration depth	Destructive
	EDS	Conductive solids	2 μm	Conducting particles that are more substantial than the width of the electron beam	Quite fast, it makes it possible to scan points, scan lines, and map elementary analyses	Semi-quantitative
	Fourier transform IR spectroscopy	Organic materials, some used with metals	> 15 μm	< 1 μm	Capable of rapidly and easily identifying functional groups in the content	In general, qualitative must pulverize particles to allow for the transmission of IR light
	Spectroscopy of atomic emission performed using inductively coupled plasma	Utilized primarily for metals	20–50 μm	A liquid must dissolve the particles	Quantification of certain components from a broad variety of concentrations	Destructive and expensive, unable to detect C, N, O, F, and H
	Inert gas fusion	Solids	Depending mostly on the resolution of the cells that were utilized to conduct the H, N, and O analyses	Any	Permits the detection of oxygen, nitrogen, and hydrogen	Destructive
Particle micro-structure	XRD	Solids	Phases are required to have concentrations of less than or equal to 5 percent	The ideal situation is when the powder particles are spherical	Capable of determin-ing the crystalline structures of different phases	Only capable of measuring phases that are presently greater than 5 percent of the time
	FIB	Conductive solids	1 μm	Any conductive particles with a size greater than the spot size of the ion beam	It also helps in the fabrication of TEM samples and cross-sections, and it enables direct visualization of powder microstructure	Redeposition of material that has been milled
	Transmission electron microscopy	Electron transparent conductive solids	Atoms	It is required that particles be diluted if their size is greater than 500 nanometers	Imaging and diffraction capabilities are provided as part of this service	A knowledgeable operator is required for the complicated sample preparation
	Thermal analysis	Solids and liquids	1–2 °C	Any	Provides information regarding the endothermic and exothermic transitions that are linked with the sample	Destructive

phases. The crystalline phases that are present in a material can be identified by the examination of a crystal structure with the use of XRD analysis, which then reveals information about the substance's chemical makeup. It is utilized for the primary purpose of characterizing the qualities of a material such as its crystal structure, crystal size, as well as strain. Because of its many different uses, XRD is increasingly being put to use in scientific studies. This trend is expected to continue. It is most successful when applied to crystalline substances.

Conclusion. The market for metal powders with very specific features is growing with the increasingly dominating AM technology. Both chemical structure, particle size, and shape are very important for powder production. The study has centered on the production of process parameters for manufacturing components with a resistance comparable to wrought products, low surface resistance, and reduced porosity. While characterizing a powder, three key fields are importantly explored: morphology of particles, particle chemistry, and particle microstructure. In general, additional research is needed to comprehend the impact that powder has on the entire AM system.

Because of the imprecise understanding of morphological powder properties along with an insufficient understanding of particle chemistry as well as microstructure in these procedures, it is necessary to conduct a more in-depth assessment of powders that have been prepared for AM. Furthermore, the focus of research in the future should not only be to refine process parameters but also to integrate process variables with powder properties.

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Таксономія виробничих процесів і опис особливостей використання порошкової металургії у процесі адитивного виробництва

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Мета. У цій роботі наведено короткий і всебічний огляд технологій, що зазвичай використовуються для виробництва металевих порошків, а також вплив властивостей частинок на особливості адитивного виробництва (АВ).

Методика. Ми розглянули різні експерименти, які проводилися, щоб визначити вплив якості порошку та як гарантувати надійність і стабільність виробництва деталей, а також способи оптимізації характеристик порошку. Ми класифікували методи виробництва металевих порошків і відзначили переваги, обмеження та аналіз зображень основних методів виробництва.

Результати. Використання різних підходів до опису характеристики металевих порошків для аналізу фізичних, механічних і хімічних процесів сприяло розвитку основних етапів оптимізації порошків. Характеристика даних порошків має важливе значення для забезпечення належних розмірів і специфікацій додаткового матеріалу, а також для врахування властивостей порошків, що використовуються в АВ, і ліквідації прогалин у розумінні кінцевого результату АВ.

Наукова новизна. У даній роботі представлений докладний аналіз досліджень, зроблених для опису характеристики порошку компонентів АВ, для розуміння їх впливу на якість і характеристики матеріалів деталей. Визначення властивостей металевого порошку сприяло суттєвому прогресу в оптимізації його характеристик при аналізі структури частинок.

Практична значимість. У міру того як застосування технології АВ переходить від створення прототипів до виробництва готових виробів, стає важливим розуміння властивостей порошку, необхідних для стабільного виробництва високоякісних елементів.

Ключові слова: *металургія, адитивне виробництво, виробництво металевого порошку, властивості порошку, процеси, метод*

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