

Review on Plasma Atomizer Technology for Metal Powder

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Abstract. The application of plasma process is growing field covering a wide range of activities, from welding technology, coating technology, deposition technology, manufacturing technology of metal powder, and other important engineering technology. The manufacture of metal powders can be generated from the process of gas atomization, water atomization, plasma atomization, and plasma rotating electrodes process atomization. In the process of plasma atomization provides advantages in addition to producing round powder, it is also very potential for efficient processing and recycling of used and alloy materials, thus saving fuel and essential materials. These operations will have a continuing impact on our industrial society as a whole. The industry of future metal powder manufacturers that utilize plasma atomization technology is an investment strategy that has a great opportunity to grow rapidly. A variety of plasma processes for the manufacture of metal powders will be reviewed in this paper, among others, are plasma atomization and plasma rotating electrodes process atomization. They are all potentially able to control and to produce of metal powders of spherical particles, making it very profitable on powder technology applications. The purpose of this review is to summarize and provide future research for activities in the field of metal powders by plasma atomization processes. The emphasis on plasma engineering technology future research in powder making available for exploration and research needs to be met so that these future research can be realized. Finally, the future challenges of automation from the use of plasma atomization technology for additives manufacturing, powder welding and medical manufacturing.

1 Introduction

Currently, metal powder technology is in high demand of the world's engineering industry because there is almost no waste of material production in the manufacturing process. The manufacture of metal powders can be generated from the process of gas atomization, water atomization, plasma atomization, and plasma rotating electrodes process atomization. Each atomization process has advantages and disadvantages, both in terms of form, shape, and complexity of the process. In the powder metallurgy applications are generally required spherical particles, because they have better properties in flowability, and density. It can be obtained from the gas atomization, plasma atomization and plasma rotating electrodes process atomization [1] are shown in Table 1.

On the other hand, the plasma arc welding has long been known as one of the technologies in the welding field [2-4]. The plasma arc has a high-density of high heat source capable of melting various metals [3].

However, the application of the plasma arc covers a wide range of activities, from welding technology, coating technology, deposition technology, metal powder making technology, and other important engineering technologies. Recently, thermal plasmas produced by DC (Direct Current) [5, 6], inductively

coupled RF (Radio Frequency) [7-13] or microwave disposal [14], has been used extensively for nanopowder synthesis [15-17].

The plasma arc technology that has been developed at this time includes the use of magnetic field effects directed at arc shapes to improve the focus of plasma arc configurations, thereby reducing power consumption and increasing efficiency[18]. In addition, plasma arc was also developed in the vacuum arc melting process [19] to produce a purer metal [20]. Currently, metal powder technology is in high demand by the world's engineering industry because there is virtually no waste of material production in the manufacturing process. The method of manufacturing metal powders using the atomization process is the best choice of various ways of making metal powders, due to the consideration of the quality of powder purity and has the potential to be mass produced [21]. Looking at the observation of powder characteristics of various manufacturing processes, it can be seen that the round powder can be produced from the process of Gas Atomization, Plasma Atomization and plasma rotating electrodes process atomization [1].

Currently, the development of research on plasma atomization improvements has been used to produce round titanium powder of various sizes [22]. In addition, plasma can also be used to process irregularly shaped metal particles into spherical metal powders. The

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principle works by means of metal powder particles is injected into a plasma arc to form round droplets with rapid cooling [23]. The well-rounded powder is ideal for injection molding jobs. Application of Metal Injection Molding (MIM) because it can increase the flowability of materials [24]. In addition, the surface roughness of the MIM results can also be improved by the addition of nanopowder measuring approximately 280 nm [25].

A variety of plasma processes for the manufacture of metal powders will be reviewed in this paper, among others, are plasma atomization and plasma rotating electrodes process atomization. The purpose of this review is to summarize and provide opportunities for activities in the field of metal powders by plasma atomization processes. The emphasis on plasma engineering technology opportunities in powder making available for exploration and research needs to be met so that these opportunities can be realized.

2 Plasma Technology

2.1 Introduction to Plasma

Plasma contains a mixture of ions, electrons, and neutral particles. A high-pressure gas passes through an electrostatic field which has a sufficient amount of electron charge and will produce a plasma arc. The resulting electrons and gas molecules collide with each other so that it can lead to the formation of ion, atoms, and excited photons. The use of plasma arcs is mostly used for plasma spraying using different physical principles [26].

The advantages of the plasma arc technology compared to traditional technology with the principle of partial oxidation, among others are the desired temperature can be adjusted by rapid response through voltage and current parameters of the plasma source. Plasma arcs can operate under atmospheric temperatures or under vacuum, and there is no direct emission of CO₂ and because of the extremely high volumetric energy density that opens the way for processing the intensification [27], lower capital costs, portability, startup and fast shutdown [28].

The plasma arc is divided into two operation modes as shown in Figure 1. Thus plasma gas passes through the cavity to the end of the anode, part of the ionized plasma gas, and then plasma jet gas develops and begins to form a plasma arc column. Heat is generated by the impact of ions from the electrical power supply, thereby emitting electrons with thermo-ionic effects, and then transferred to the mainstream by diffusion, convection, and radiation.

The plasma arc column spreading throughout the entire anode cavity, the energy affecting the thermal gas-forming gas heat thermally to produce a high-speed jet [29]. The plasma arcs have very high speeds up to several hundred m. s⁻¹, which are affected by the effects of narrow nozzle diameters and gas heating resulting in thermal expansion of plasma gas [28].

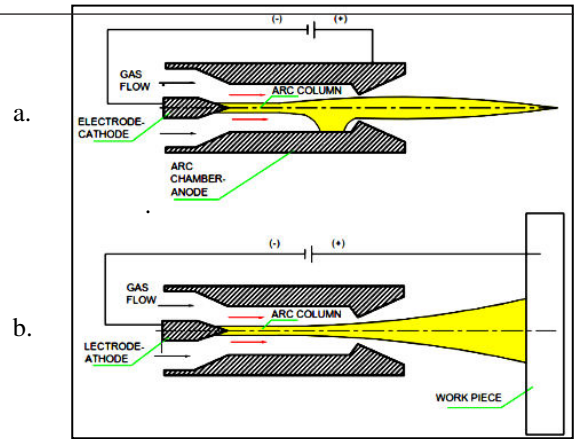


Fig. 1. Basic modes of plasma arc operation: (a). Non-transferred arc; (b). Transferred arc [30]

Plasma technology has been utilized in the steel processing industry because it has a high energy density or high specific heat. In principle, electrical energy is transformed into plasma energy which has a high temperature above 3000K [31].

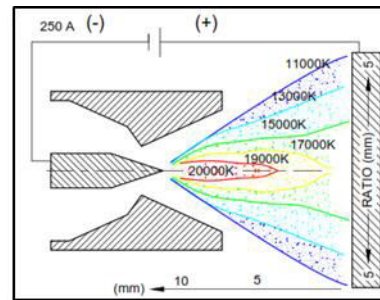


Fig.2. Distribution of temperature in the arc plasma [32]

Figure 2 shows the distribution of temperature in the arc plasma with a current of 250 Amperes. In the case of energy, this transfer is closely related to a gradient in the values of temperature, density, and composition [33].

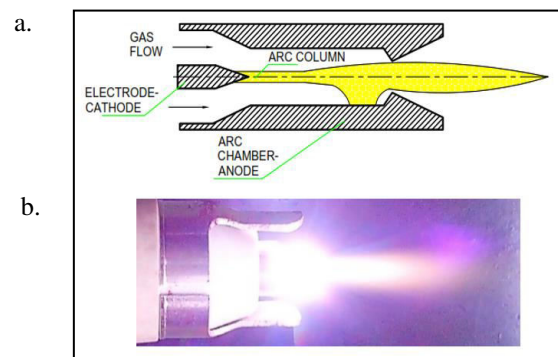


Fig. 3. (a). A simplified representation of the parallel flow arc ; (b). DC plasma arc

The plasma arcs generally have a geometry that is influenced by several parameters including the composition of the plasma gas mixture, the geometry of the electrode, the current, the voltage, the plasma nozzle design, and the flow rate of inert gas [28, 33]. The inert gas flow is also aimed at reducing the oxidation of environmental air [34].

The ion concentration in plasma arcs can be increased by several methods, including by the application of magnetic fields leading to arc cathodes, application of high-power microwave pulses, the application of additional currents to arc gaps and vacuum applications. A spot cathode vacuum arc is a modern concept based on the phenomenon of explosive electron emission [35, 36].

The emission occurs because of the high concentration of energy inside resulting in sudden warming and then the micro-explosion of the cathode surface area [37]. In addition, the result of a microburst forms a vacuum plasma arc extending into the interelectrode gap [38].

Currently, a new design of plasma cathode-ray electron sources from the principle of vacuum arc discharges under magnetic fields are designed to regulate the current electron-beam to improve the efficiency of electron beam discharges by regulating currents to control the density of plasma electron beam sources [38, 39].

The current in plasma when raised from 15 A to 45 A can cause the intensity of the emission line to increase, the current density and the flow of electrons become larger, so the temperature in the plasma arc also will be higher [40].

The plasma arc is related to it is electrical conductivity and thermal. The electrical conductivity of argon gas, hydrogen gas, and nitrogen gas did not experience a significant difference in all temperatures. However, hydrogen gas and nitrogen gas have a much higher thermal conductivity compared to the thermal conductivity of argon gas, is due to the hydrogen gas and nitrogen gas including the diatom molecule so that the molecular separation into the diatoms can significantly improve the reactive thermal conductivity of the plasma gas [41] [42].

Highly high-speed plasma streams of plasma arc are generated from the dissociation process and the process of recombining the plasma gas molecules [43, 44]. Generally, argon gas is preferred because it has low ionization energy, a more stable arc pressure and a low erosion characteristic at the electrode [45].

The unavoidable weakness of DC plasma (Figure 3) is that electrode erosion that results in the electrodes in the plasma have a limited lifespan caused by very high thermal effects. (in the plasma arc nucleus can reach above 10,000-20,000 K)[27].

The plasma arc is the best choice because it has high enthalpy to increase reaction kinetics, Oxidation, high chemical reactivity, low exhaust gas, fast start-up, and small reactors. Besides, it can also be combined with a rapid cooling process that causes a relatively high volume reduction [46, 47].

The plasma arc in a plasma gas jet flow form that has high enthalpy. The thermal efficiency of the plasma arcs is [48]:

$$\eta = \frac{UI - (G_{H_2O} C_{pH_2O} \Delta T)}{UI} \quad (1)$$

Where, U is the source voltage, and I is the source current, P_{total} is the total power of a simple plasma arc, G_{H_2O} is the flow rate of cooling water mass, T is the gradient of the temperature of the cooling water, C_{pH_2O} is the specific heat of cooling water

The enthalpy from plasma jet, h (kJ / kg), calculated from the ratio between the total inert mass flow rate and the net power used in the plasma arcs is [48]:

$$\Delta h = \frac{\eta P_{total}}{G_{ar} + G_{powder}} \quad (2)$$

Here, G_{ar} is the mass flow of gas, G_{powder} is the mass flow of powder (kg / s). The influence of powder on h has been ignored [48].

Several experiments have been conducted by previous researchers, including experiments with varying pressure, atomization gas flow rate, feed flow rate, atomization probe gap size, and droplet product size distribution. The powder product results illustrate that the size of the powder distribution increases with the decrease in plasma flows [49].

Currently, the world largest industry of spherical metal alloy powder producer for additive manufacturing (AM) at the end of 2017, has created a new plasma atomization plant. This is a profitable investment and has many benefits of plasma atomizer technology for future metal powder [50].

2.2 Application of Plasma for Powder Technology

2.2.1 Plasma atomization

Plasma technology is partially applied to the process of making metal powders. Making metal powders with plasma technology is best known as plasma atomization. Plasma atomization has been widely developed, resulting in a high purity titanium powder in various sizes of powder grains. Atomization of plasma capable of producing various sizes of titanium powder from very fine (-25 μ m) to rough (+125 μ m) [22].

Round-shaped metal powders have the benefit of having the properties of good flowability and capable of producing high density. In powder manufacturing processes, in the case of good flowability powders means requiring fewer additives than low flow powders. Whereas in case of high density means that the powder, if used in the sintering process such as hot isostatic pressure (HIPing) at the densification stage, will occur minimally [22].

Figure 4 shows a plasma atomization process scheme using a three plasma arc, with titanium wire as a material feed. The plasma arc is utilized as a high-enthalpy heat source which will melt and spray molten titanium wire, resulting in a titanium powder that has a very high purity round shape [22].

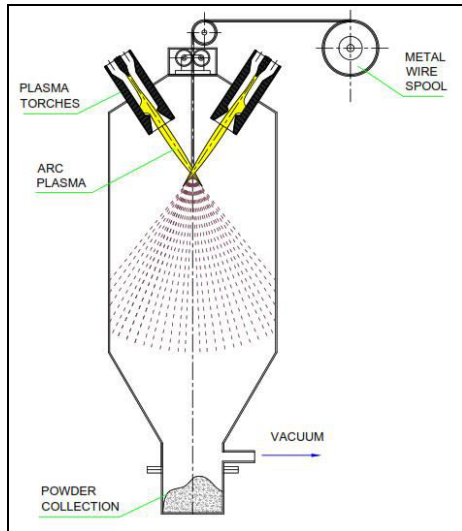


Fig. 4. Schematic representation of the plasma atomization process for the production of Ti powders [51]

2.2.2 Plasma Rotating Electrode Process Atomization

The plasma technology for other metal atomization applications is plasma rotating electrode process atomization. Where the rod-shaped feed material is rotated at a high rotation when the argon or nitrogen plasma arc melts the tip of the rod so that the molten metal is thrown into a grain of metal due to the high centrifugal force of the rotation of the rod. As shown in the schematic in Figure 5 [52].

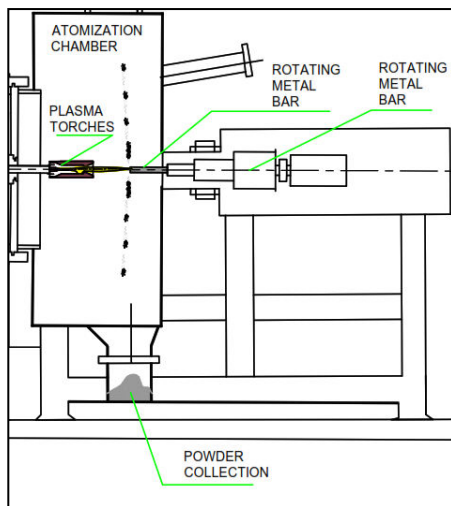


Fig. 5. Schematic set-up of the Plasma Rotating Electrode Process Atomization [52]

Various experimental conditions have been conducted to examine the droplets of metal powder thrown from the spinning metal rod as the centrifugal force has overcome the force of the melt surface stress of the metal rod. The surface tension of the metal surface of the experimental results is set as follows [45]:

$$d_p = \frac{\epsilon_0 \sqrt{3\sigma_s}}{\sqrt{D_a \cdot \rho_m}} \pi n \quad (3)$$

Where, d_p is diameter of particle (m); σ_s is molten metal surface tension (N/m); D_a is the metal electrode diameter (m); ρ_m is molten metal density (kg/m^3); n is metal electrode rotation (rpm)

In the experiment, the material used is austenitic steel with variations of 5000 RPM rotation up to 15000 RPM, the powder yield contains nitrogen mass from 0.48 % to 0.96%. The result of the metal powder is still to be processed again by the process of the sieve to the next gradation so that collected powder with a uniform grain size [52].

2.2.3 Plasma Centrifugal Atomization

Plasma technology for other metal powder applications is Plasma Centrifugal Atomization is shown in Figure 6. The Centrifugal Atomization plasma application is not only a melting process of the feed material but uses a rotating container to produce a centrifugal force which will improve the more rounded powder form in the crystallization stage

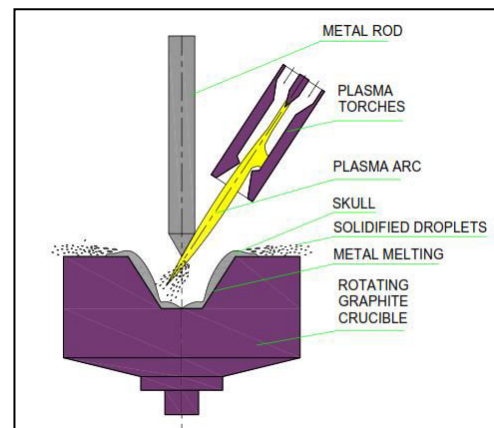


Fig.6. Schematic of the plasma centrifugal atomization design [53].

Experiments have been performed to calculate numerical results, and the initial analysis results of kinetic properties on the rotary container accommodates molten metal droplets. The calculation of the total kinetic energy approach of molten metal granules released from the rotary container surface is as follows [53]:

$$E = \frac{(4\pi r^3/3)w^2}{2} + \frac{j\omega^2}{2}, \quad (4)$$

Where, w is the speed of the container rotational (m/sec); J is the inertia moment of the molten metal drop ($\text{kg}\cdot\text{m}^2$); ω is the speed of angular rotation of the molten metal drop (rad); r is the radius of the molten metal drop (m), and ρ is the molten metal density (kg/m^3). The melt metal separation conditions from the melt surface of the feed material are primarily determined by its motion kinetic energy. The separation conditions of the grains of the radius r from the melting surface are as follows [53]:

$$2\pi r\sigma \leq \frac{(4\pi r^3/3)w^2}{2R}, \quad (5)$$

Where, R is the edge radius of the melt on the rotary container (m), and σ is the melt surface tension (N/m). When separating from the surface of molten metal, the granular radius can be estimated as follows [53]:

$$r_{cr} = \frac{16.55}{n} \sqrt{\frac{\sigma}{R\rho}} \cdot m, \quad (6)$$

Where n is the rotating frequency of the crucible with the melted metal (min^{-1}). The radius of crucible about $3 \cdot 10^{-2}$ m and frequency of rotating about 10^4 min^{-1} , The melt density about $7.8 \cdot 10^3 \text{ kg}/\text{m}^3$ and the surface tension approximately 1.85 N/m [53].

If the calculation is done with this formula on titanium metal alloy material with the same conditions of the actual experiment at surface tension 1.33 N / m and density $4.5 \cdot 10^3 \text{ kg} / \text{m}^3$, resulting in a granules radius formed approximately equal to 160 μm . From the results of these calculations when compared with the results of actual experiments that produce 150 μm granules in the same conditions more or less have a difference of 6% difference [53].

Table 1. Advantages and disadvantages on the process of powder manufacturing

Manufacturing Process	Material	Particle Size Range	Advantages	Disadvantages	References
Water Atomization	AISI316L	44-106 μm	High production rates, large particle size range, ingredients in ingot form	There is an additional process of removing water, irregular particle shape, wide particle size distribution	[54]
Gas Atomization	Ti Alloy	0 -250 μm	Can be used for various types of alloy metals that have reactive properties in ingots, large particle size range, spherical particles	Wide particle size distribution	[55]
Plasma Atomization	Ti Alloy	25-125 μm	The particles are more spherical	The feedstock must be in the form of wire or powder, costly	[22]
Plasma Rotating Electrode Process	Tungsten	160-500 μm	High purity, more spherical particles	Low productivity, expensive cost	[52, 56]
Plasma-Centrifugal Atomization	45 Steel, HSS, Ti Alloy	0-385 μm	Spherical particles, produced easily	The fractional composition on the distribution of particle size is quite wide	[53]
Centrifugal Atomization	Magnesium alloy	50-800 μm	Large particle size range, distribution of particle size is narrow	Difficulty in making the powder with good quality.	[57]

2.3 Powder Standart for Medical Manufacturing

Based on previous studies that powder manufacturing results have ease of fabrication, good mechanical properties, and economic advantages applied to very complex shapes. Therefore, it is indispensable in medical manufacturing. Although there are limits to lower corrosion resistance because high areas can affect corrosion reactions. Various studies have been conducted to optimize corrosion resistance, one of them by adding alloying elements of metal.[58]

The result of the addition of alloy elements using powder among them is found in AISI 316L, Ti-6Al-4V alloy, Co-Cr-Mo alloy, as a medical manufacturing material. Materials such medical manufacturing as an orthopedic metallic implant material [59]. Standard Characteristics of medical manufacturing are shown in Table 2.

Table 2. Characteristics of metallic powder standart for medical manufacturing [59]

Material	Designation	Elements (wt%)
Stainless steels	ASTM F-138 (AISI 316 L)	Cr(17.0–20.0), Ni(12.0–14.0), Mo(2.0–4.0), Fe(balance.),
Cobalt-alloys	ASTM F-1537 ASTM F-799	Cr(19.0–30.0) Mo(0–10.0), Ni(0–37.0, Co(balance),
Ti and Ti-alloys	ASTM F-1295 ASTM F-136	V(4), Al(6), Nb(7), Ti(balance),

3 Future Researches

Based on several atomization processes of plasma technology that have been studied and published in the description above, the next research is promising, among others, research to overcome the erosion that occurs in DC plasma arc electrode [60] to keep the gap distance between the cathode and anode is always stable in the condition the same so that the plasma arc temperature can always be kept stable. In the end, it can produce more uniform powder grains. The preliminary design of future research that we are working on has been shown in Figure 7.

The working principle of gear 1 will continuously rotate the gear 2 with the screw so that the cathode electrode will decrease according to the amount of erosion occurring at the electrode based on previous experiments so that the gap between the cathode electrode and anode electrode can always be stable.

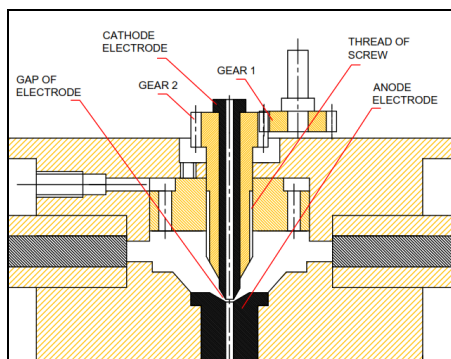


Fig. 7. Schematic of the initial design to overcome the erosion of the plasma electrode

Development of plasma atomization based on several atomization processes of plasma technology, which has been studied and published in the above description, subsequent research is quite promising, among others, research for the application of controls with machine vision [61] that is applied to the plasma atomization. The preliminary design of future research that we are working on has been shown in Figure 8. The atomization angle of the plasma arc is visualized by the camera to characterize the plasma arc, with card data acquisition (DAQ) [62] is used to control the atomization process of plasma.

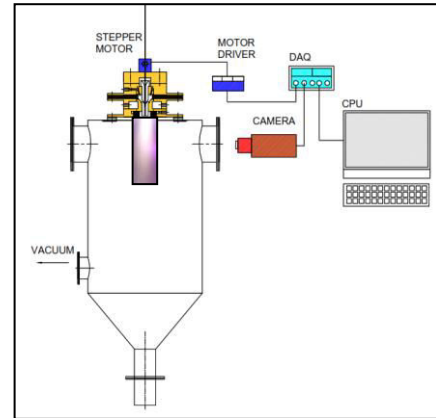


Fig. 8. Schematic diagrams of machine vision of plasma atomization

Machine vision on atomization by modifying, using a microcontroller to adjust the input speed of the material for the purpose of adjusting the results of the plasma arc in atomization. The size of the small particles is estimated based on the data the arc pattern obtained from the machine vision base on currents, metal feed rate, and gas flow rate. It used to get a series of data to be performed as a preliminary experiment to train and to build a system of neural networks [61,62].

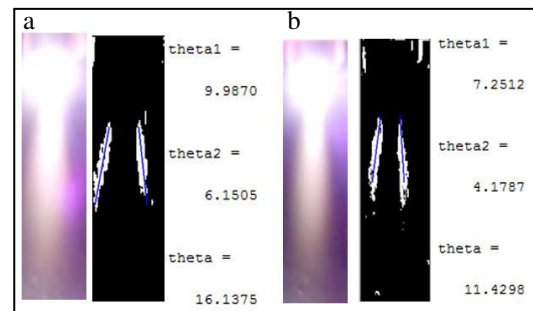


Fig. 9. Samples of Detection Edge Mask Sobel and BW Threshold 0,2 with Matlab; (a). The effect of the gas pressure of 80 psi; (b). The effect of the gas pressure of 70 psi

Figure 9 shows the plasma arc angle values of (a) 16.1375° and (b) 11.4298°, with the gas pressure of 80 psi and 70 psi respectively. Due to the rapid spread of the air jet is generated from the higher airflow resulting in a wider spray angle [63]. The phenomenon that occurs can be seen with the image processing using Detection Edge Mask Sobel Method with threshold 0,2 shows that function on plasma atomization to keep the atomization results have a specific particle size allows using machine vision. If the plasma arc atomic angle is wider, it is possible to produce a smaller powder size.

4 Conclusion

The process of plasma atomization for the manufacture of metal powders of spherical particles can be produced from plasma atomization, plasma centrifugal atomization, and Plasma Rotating Electrode Process.

The phenomenon of plasma arc angle values that occur can be identified by image processing using the Detection Edge Mask Sobel Method with threshold 0,2. It is possible to be used as a sensor input on the machine vision controller to keep the atomization results having a specific particle size.

They all potentially can be developed equipped with a machine vision system to control and to produce of metal powders of spherical particles, making it particularly advantageous in the application of powder technology for additive manufacturing, powder welding and medical manufacturing.

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