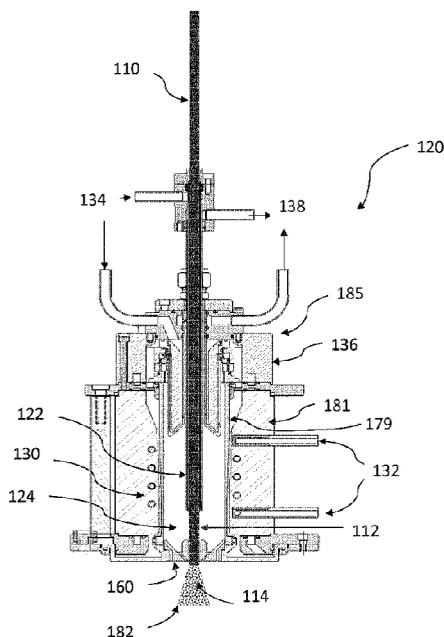




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(54) Title: PROCESS AND APPARATUS FOR PRODUCING POWDER PARTICLES BY ATOMIZATION OF A FEED MATERIAL IN THE FORM OF AN ELONGATED MEMBER



(57) **Abrégé/Abstract:**

The present disclosure relates to a process and an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member such as a wire, a rod or a filled tube. The feed material is introduced in a plasma torch. A forward portion of the feed material is moved from the plasma torch into an atomization nozzle of the plasma torch. A forward end of the feed material is surface melted by exposure to one or more plasma jets formed in the atomization nozzle. The one or more plasma jets being includes an annular plasma jet, a plurality of converging plasma jets, or a combination of an annular plasma jet with a plurality of converging plasma jets. Powder particles obtained using the process and apparatus are also described.

## **ABSTRACT**

The present disclosure relates to a process and an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member such as a wire, a rod or a filled tube. The feed material is introduced in a plasma torch. A forward portion of the feed material is moved from the plasma torch into an atomization nozzle of the plasma torch. A forward end of the feed material is surface melted by exposure to one or more plasma jets formed in the atomization nozzle. The one or more plasma jets being includes an annular plasma jet, a plurality of converging plasma jets, or a combination of an annular plasma jet with a plurality of converging plasma jets. Powder particles obtained using the process and apparatus are also described.

**PROCESS AND APPARATUS FOR PRODUCING POWDER  
PARTICLES BY ATOMIZATION OF A FEED MATERIAL IN THE  
FORM OF AN ELONGATED MEMBER**

TECHNICAL FIELD

**[0001]** The present disclosure relates to the field of materials processing. More specifically, the present disclosure relates to a process and to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member. Powder particles produced using the disclosed process and apparatus are also disclosed.

BACKGROUND

**[0002]** With the growing interest in rapid prototyping and manufacturing, commonly known as additive manufacturing or 3-D printing, a number of techniques have been developed for the production of dense spherical powders, which are useful for such technologies. The success of additive manufacturing and 3-D printing depends in a large extent on the availability of materials usable for parts manufacturing. Such materials need to be provided in the form of highly pure, fine (e.g. diameter less than 150  $\mu\text{m}$ ), dense, spherical, and free-flowing powders that have well-defined particle size distributions. Conventional melt atomization techniques such as gas, liquid and rotating disc atomization are unable to produce such high quality powders.

**[0003]** More recent techniques avoid the use of crucible melting, which is often responsible for material contamination. These recent techniques provide spherical, free-flowing powders.

**[0004]** For example, some plasma atomization processes are based on the use of a plurality of plasma torches producing plasma jets that converge toward an apex. By feeding a material to be atomized in the form of a wire or rod into the apex, the material is melted and atomized by thermal and kinetic

energy provided by the plasma jets. It has also been proposed to feed a material to be atomized in the form of a continuous molten stream directed towards an apex where several plasma jets converge. These types of plasma atomization processes are rather delicate and require laborious alignment of at least three plasma torches in order to have at least three plasma jets converging toward the apex. Due to the physical size of such plasma torches, the apex location is bound to be a few centimeters away from an exit point of the plasma jets. This causes a loss of valuable thermal and kinetic energy of the plasma jets before they reach the apex position and impinge on the material. Overall, these processes involve several difficulties in terms of requirements for precise alignment and power adjustment of the torches and for precise setting of the material feed rate.

**[0005]** Other technologies are based on the use of direct induction heating and melting of a wire or rod of a material to be atomized while avoiding contact between the melted material and a crucible. Melt droplets from the rod fall into a gas atomization nozzle system and are atomized using a high flow rate of an appropriate inert gas. A main advantage of these technologies lies in avoiding possible contamination of the material to be atomized by eliminating any possible contact thereof with a ceramic crucible. These technologies are however limited to the atomization of pure metals or alloys. Also, these technologies are complex and require fine adjustment of operating conditions for optimal performance. Furthermore, large amounts of inert atomizing gases are consumed.

**[0006]** Therefore, there is a need for techniques for efficient and economical production of powder particles from a broad range of feed materials.

## SUMMARY

**[0007]** According to a first aspect, the present disclosure relates to a process for producing powder particles by atomization of a feed material in the

form of an elongated member that includes introducing the feed material in a plasma torch, moving a forward portion of the feed material from the plasma torch into an atomization nozzle of the plasma torch; and surface melting a forward end of the feed material by exposure to one or more plasma jets formed in the atomization nozzle, the one or more plasma jets being selected from an annular plasma jet, a plurality of converging plasma jets, and a combination thereof.

[0008] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising a plasma torch including: an injection probe for receiving the feed material; and an atomization nozzle configured to receive a forward portion of the feed material from the injection probe, be supplied with plasma, produce one or more plasma jets, and melt a surface of a forward end of the feed material by exposure to the one or more plasma jets. The one or more plasma jets are selected from an annular plasma jet, a plurality of converging plasma jets, and a combination thereof.

[0008a] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising an inductively coupled plasma torch with a longitudinal axis and including: a coaxial injection probe at a first end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of a coaxial plasma confinement tube of the plasma torch for introducing the elongated member of the feed material axially into the plasma torch; and an atomization nozzle at a second end of the plasma torch opposite the first end, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the coaxial injection probe, and wherein the atomization nozzle is configured for producing, using plasma from the inductively coupled plasma torch, at least one atomizing plasma jet for surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet.

[0008b] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: an inductively coupled plasma torch defining a longitudinal axis, having

an upstream end and including an inner plasma confinement tube coaxial with the longitudinal axis, having a downstream end, and in which the inductively coupled plasma torch produces plasma; an injection probe coaxial with the longitudinal axis at the upstream end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of the plasma confinement tube for introducing the elongated member of the feed material axially into the plasma confinement tube; and an atomization nozzle at the downstream end of the plasma confinement tube, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the injection probe through the plasma confinement tube, and wherein the atomization nozzle is configured for producing, using plasma from the plasma confinement tube, at least one atomizing plasma jet for surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet.

[0008c] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: an inductively coupled plasma torch defining a longitudinal axis, having an upstream end and including an inner plasma confinement tube with a downstream end and coaxial with the longitudinal axis; an injection probe coaxial with the longitudinal axis at the upstream end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of the plasma confinement tube for introducing the elongated member of the feed material axially into the plasma confinement tube; and an atomization nozzle at the downstream end of the plasma confinement tube, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the coaxial injection probe through the plasma confinement tube.

[0008d] According to another aspect, the present disclosure relates to a process for producing powder particles by atomization of a feed material in the form of an elongated member, using an inductively coupled plasma torch including a longitudinal axis, a coaxial injection probe at a first end of the plasma torch and comprising an elongated conduit which extends through at least an upper portion of a coaxial plasma confinement tube, and an atomization nozzle comprising a coaxial aperture for the elongated member at a second end of the plasma torch

opposite the first end, said process comprising: introducing the elongated member into the plasma torch through the coaxial injection probe; moving the elongated member axially in the plasma torch through the coaxial injection probe and from the coaxial injection probe to the coaxial aperture of the atomization nozzle; producing at least one atomizing plasma jet by supplying plasma from the plasma torch to the atomization nozzle; and surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet produced by the atomization nozzle.

[0008e] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: a feeding mechanism configured to feed the feed material toward an atomization zone, along a feed path; and an atomization device in the atomization zone configured to perform atomization of the feed material, the atomization device comprising: a plasma containment chamber in which a body of plasma is generated; a nozzle allowing the plasma to egress the containment chamber, wherein the atomization device is configured for receiving the feed material directed toward the nozzle to define an annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets; and an elongated conduit for feeding the elongated member into the atomization zone toward the nozzle, the elongated conduit being configured for receiving the elongated member and extending along the feed path, the elongated conduit having an inlet end for receiving the elongated member and an outlet to release the forward end of the elongated member upstream of the nozzle in a direction of travel of the elongated member along the feed path.

[0008f] According to another aspect, the present disclosure relates to a method for producing powder particles by atomization of a feed material in the form of an elongated member, the method comprising: feeding the elongated member toward an atomization zone, the elongated member being dispensed through a elongated conduit along a feed path, the elongated conduit extending along the feed path; and generating an annular plasma jet in the atomization zone by: generating a body of plasma within a plasma containment chamber, allowing the plasma to egress the containment chamber via a nozzle, and receiving the feed material directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the

forward end of the elongated member and breakdown into molten droplets, the nozzle residing on the feed path downstream of the elongated conduit in a direction of travel of the elongated member along the feed path, the elongated conduit being configured for feeding the elongated member into the atomization zone, the elongated conduit having an inlet end for receiving the elongated member and an outlet end to release the forward end of the elongated member upstream of the nozzle in a direction of travel of the elongated member along the feed path.

[0008g] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: a feeding mechanism configured to feed the elongated member toward an atomization zone, along a feed path, an atomization nozzle, the apparatus being configured for generating an annular plasma jet into the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets, the nozzle residing on the feed path of the elongated member; and a pre-heating device located upstream of the nozzle in a direction of travel of the elongated member along the feed path, the pre-heating device configured to bring the forward end of the elongated member directed at the nozzle to a selected temperature which is below the melting point of the elongated member, the pre-heating of the elongated member at the selected temperature operating to increase a rate at which the feed material of the forward end of the elongated member is melted into the droplets by the annular plasma jet, the pre-heating device comprising an elongated conduit extending along the feed path for receiving the elongated member therein.

[0008h] According to another aspect, the present disclosure relates to a method for producing powder particles by atomization of a feed material in the form of an elongated member, the method comprising: progressively feeding the elongated member toward an atomization zone along a feed path; pre-heating a forward end of the elongated member upstream an atomization nozzle in a direction of travel of the elongated member along the feed path in a pre-heating zone to bring the forward end of the elongated member at a selected temperature which is below the melting point of the elongated member, the pre-heating zone comprising

an elongated conduit extending along the feed path for receiving the elongated member therein; and generating an annular plasma jet in the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets, the pre-heating of the forward end of the elongated member at the selected temperature increasing a rate at which the feed material of the forward end of the elongated member is melted into the droplets by the annular plasma jet.

[0008j] According to another aspect, the present disclosure relates to an apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: a feeding mechanism configured to feed the elongated member toward an atomization zone along a feed path; means to produce an annular plasma jet into the atomization zone, comprising a plasma containment chamber in which a body of plasma is generated and an atomization nozzle allowing the plasma to egress the containment chamber, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets; and an injection probe for feeding the elongated member toward the nozzle, the injection probe defining an elongated conduit for receiving the elongated member, the elongated conduit extending along the feed path, the injection probe including cooling means, the cooling means including a passageway for a cooling fluid.

[0008k] According to another aspect, the present disclosure relates to a method for producing powder particles by atomization of a feed material in the form of an elongated member, comprising: feeding the elongated member toward an atomization zone along a feed path; receiving the elongated member in an injection probe for feeding the elongated member toward an atomization nozzle, the injection probe defining an elongated conduit for receiving the elongated member, the elongated conduit extending along the feed path, the injection probe including cooling means, the cooling means including a passageway for a cooling fluid; and producing an annular plasma jet in the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber

via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets.

[0009] The foregoing and other features will become more apparent upon reading of the following non-restrictive description of illustrative embodiments thereof, given by way of example only with reference to the accompanying drawings. Like numerals represent like features on the various figures of drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Embodiments of the disclosure will be described by way of example only with reference to the accompanying drawings, in which:

[0011] Figure 1 is a front elevation view of a plasma torch usable for atomization of feed material in the form of an elongated member such as, as non-limitative examples, a wire, rod or filled tube;

[0012] Figure 2a is a detailed, front elevation view of the plasma torch

of Figure 1, having an atomization nozzle according to an embodiment and a configuration for direct preheating of the elongated member by the plasma;

- [0013]** Figure 2b is a detailed, front elevation view of the plasma torch of Figure 1, having the atomization nozzle of Figure 2a and a configuration in which the elongated member is indirectly heated by the plasma through a radiation tube;
- [0014]** Figure 3 is a front elevation view of an apparatus for atomization of feed material in the form of an elongated member, the apparatus including the plasma torch of Figure 1;
- [0015]** Figure 4a is a perspective view of an atomization nozzle with a support flange according to an embodiment;
- [0016]** Figure 4b is a cross-sectional view of the atomization nozzle and support flange of Figure 4a;
- [0017]** Figures 4c, 4d and 4e are additional top, bottom and perspective views showing details of the atomization nozzle of Figure 4a, including a central aperture surrounded by radial apertures for producing plasma jets;
- [0018]** Figure 5 is a detailed, front elevation view of the plasma torch of Figure 1, showing an atomization nozzle according to another embodiment;
- [0019]** Figure 6 is a detailed, front elevation view of a variant of the plasma torch of Figure 1, showing the atomization nozzle of Figure 5 and further including a sheath gas port surrounding the exit end of the atomization nozzle;
- [0020]** Figure 7 is a flow chart showing operations of a process of producing powder particles by atomization of a feed material in the form of an elongated member such as, as non-limitative examples, a wire, rod or filled tube;

- [0021]** Figure 8 is a schematic view, including a graph showing modelling results for heating a 3.2 mm stainless steel wire introduced in an argon/hydrogen induction plasma at 60 kW;
- [0022]** Figure 9 is an electron micrograph of powder particles obtained by atomization of a 3.2 mm diameter stainless steel wire and a graph of corresponding particle size distribution; and
- [0023]** Figure 10 illustrates electron micrographs of different stainless steel spherical powder fractions produced using the process and apparatus for producing powder particles by atomization of a feed material in the form of an elongated member.

#### DETAILED DESCRIPTION

**[0024]** Generally speaking, the present disclosure addresses one or more of the problems of efficiently and economically producing powder particles from a broad range of feed materials.

**[0025]** More particularly, the present disclosure describes a plasma atomization process and an apparatus therefor, usable to produce powder particles from a broad range of feed materials, including for example pure metals, alloys, ceramics and composites. The disclosed technology may be used in the manufacture of a wide range of dense spherical metal, ceramic or composite powders from a feed material of the same nature in the form of an elongated member such as, as non-limitative examples, a rod, a wire or a filled tube. A powder may be defined as comprising particles with a diameter of less than one (1) millimeter, a fine powder may be defined as comprising of particles of diameter less than 10 micrometers, while an ultrafine powder may be defined as comprising particles of less than one (1) micrometer in diameter.

**[0026]** In a non-limitative embodiment, the plasma torch, which may optionally be an inductively coupled plasma torch, is supplied with the feed material along a central, longitudinal axis thereof. A speed of movement and/or

a distance of travel of the feed material in an optional preheating zone of the plasma torch may be controlled to allow the material to heat to a temperature as close as possible to its melting point while avoiding premature melting thereof within the plasma torch. In one embodiment, a forward end of the optionally preheated feed material enters the atomization nozzle to emerge from its downstream side and enter a cooling chamber. Due to its passage in the atomization nozzle, the forward end or tip of the feed material is exposed to a plurality of plasma jets, for example high velocity plasma jets, including, though not limited to, supersonic fine plasma jets. Upon impinging on the feed material, the plasma jets melt its surface and strip out molten material resulting in finely divided, spherical molten droplets of the material entrained with the plasma gas from the atomization nozzle. In another embodiment, the forward end of the optionally preheated feed material is exposed to an annular plasma jet within the atomization nozzle, the annular plasma jet also causing surface melting of the feed material. Resulting droplets are entrained by the plasma gas into the cooling chamber. In both embodiments, the droplets cool down and freeze in-flight within the cooling chamber, forming for example small, solid and dense spherical powder particles. The powder particles can be recovered at the bottom of the cooling chamber, for example in a downstream cyclone or in a filter, depending on their particle size distribution.

**[0027]** In the context of the present disclosure, powder particles obtained using the disclosed process and apparatus may include, without limitation, micron sized particles that may be defined as particles in a range from 1 to 1000 micrometer in diameter.

**[0028]** The following terminology is used throughout the present disclosure:

**[0029]** Powder particle: a grain of particulate matter, including but not limited to micron sized and nanoparticles.

**[0030]** Atomization: reduction of a material into particles.

- [0031]** Feed material: a material to be transformed by a process.
- [0032]** Filled tube: feed material provided in the form of a tube, made as non-limitative examples of metal, plastic or any other suitable material, filled with a powder composed of a pure metal, alloys, ceramic material, any other suitable material, or composed of a mixture of materials, so that melting the powder can give rise to the formation of an alloy or composite.
- [0033]** Plasma: a gas in a hot, partially ionized state.
- [0034]** Plasma torch: a device capable of turning a gas into plasma.
- [0035]** Inductively coupled plasma torch: a type of plasma torch using electric current as an energy source to produce electromagnetic induction of the energy into the plasma.
- [0036]** Injection probe: an elongated conduit that may be cooled using a cooling fluid, for insertion or supply of a feed material.
- [0037]** Preheating zone: area in a plasma torch in which feed material is elevated to a temperature below its melting point.
- [0038]** Atomization nozzle: element to produce plasma jets and to allow feed material to transfer from a plasma torch to a cooling chamber.
- [0039]** In-flight freezing: cooling of liquid droplets becoming solid particles while suspended within a gas.
- [0040]** Cooling chamber: a container in which in-flight freezing takes place.
- [0041]** Referring now to the drawings, Figure 1 is a front elevation view of a plasma torch usable for atomization of feed material in the form of an elongated member such as, as non-limitative examples, a wire, rod or filled tube. Obviously, other types of elongated member could potentially be used in the disclosed process and apparatus for atomization of feed material.

**[0042]** Figure 2a is a detailed, front elevation view of the plasma torch of Figure 1, having an atomization nozzle according to an embodiment and a configuration for direct preheating of the elongated member by the plasma, while Figure 2b is a detailed, front elevation view of the plasma torch of Figure 1, having the atomization nozzle of Figure 2a and a configuration in which the elongated member is indirectly heated by the plasma through a radiation tube. Figure 3 is a front elevation view of an apparatus for atomization of feed material in the form of an elongated member, the apparatus including the plasma torch of Figure 1.

**[0043]** Referring at once to Figures 1, 2 and 3, an apparatus 100 for producing powder particles by atomization of a feed material 110 in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube, comprises a plasma torch 120 producing plasma 126, and a cooling chamber 170. Without limiting the present disclosure, the plasma torch 120 as shown is an inductively coupled plasma torch. Use of other types of plasma torches is also contemplated. The apparatus 100 may further comprise a powder collector 190.

**[0044]** The plasma torch 120 comprises an injection probe 122 in the form of an elongated conduit mounted onto the head 185 coaxial with the inductively coupled plasma torch 120. As illustrated in Figure 1, the injection probe 122 extends through the head 185 and through the plasma confinement tube 179. The feed material 110 can be inserted in the plasma torch 120 via the injection probe 122 so that it is coaxial with the torch body 181. The feed material 110 may be supplied to the injection probe 122, in continuous manner, by a typical wire, rod or tube feeding mechanism (not shown) for example similar to commercially available units currently used in wire arc welding such as the units commercialized by Miller for MIG/Wire welding, and comprising a first set of wheels operated to control the feed rate of the elongated member to the injection probe 122. The feeding mechanism may be either preceded or followed by two successive sets of straightening wheels to straighten the

elongated member within two perpendicular planes. Of course, in some situations, only one set or more of straightening wheels may be required to straighten the elongated member within one plane only or multiple planes. The set(s) of straightening wheels are useful when the feed material is supplied under the form of rolls. In a variant, the feeding mechanism may be adapted to rotate the feed material 110 about a longitudinal axis thereof, specifically about a longitudinal axis of the plasma torch 120.

**[0045]** A preheating zone 124 for preheating a forward portion 112 of the feed material 110, either by direct contact with the plasma 126 as illustrated in Figure 2a or by radiation heating from a radiation tube 125 surrounding the feed material 110, the radiation tube 125 itself being heated by direct contact with the plasma 126, as illustrated in Figure 2b. The radiation tube 125 may be made, for example, of refractory material such as graphite, tungsten or hafnium carbide. The plasma torch 120 also comprises an atomization nozzle 160 with a channel through which the forward portion 112 of the feed material 110 from the preheating zone 124 travels to expose a forward end 114 of the feed material 110 to a plurality of plasma jets 180 and atomize the feed material. The channel may comprise a central aperture 162 allowing the forward portion 112 of the feed material 110 to exit the plasma torch 120 and enter the cooling chamber 170, and with radial apertures 166 for producing the plurality of plasma jets 180. The cooling chamber 170 is mounted to the lower end of the plasma torch 120, downstream of the nozzle 160. In the cooling chamber 170, the forward end 114 of the feed material 110 is exposed to the plurality of plasma jets 180.

**[0046]** Still referring to Figures 1, 2 and 3 and although other types of plasma torches could eventually be used, the plasma torch 120 is an inductively coupled plasma torch and comprises an outer cylindrical torch body 181, an inner cylindrical plasma confinement tube 179, and at least one induction coil 130 in a coaxial arrangement. The outer cylindrical torch body 181 may be made of moldable composite material, for example a moldable

composite ceramic material. The inner cylindrical plasma confinement tube 179 may be made of ceramic material and, as indicated hereinabove, is coaxial with the torch body 181. The at least one induction coil 130 is coaxial with and embedded in the torch body 181 to produce a RF (radio frequency) electromagnetic field whose energy ignites and sustains the plasma 126 confined in the plasma confinement tube 179 including preheating zone 124. The plasma is produced from at least one gas such as argon, helium, hydrogen, oxygen, nitrogen or a combination thereof, supplied within the plasma confinement tube 179 through a head 185 of the inductively coupled plasma torch 120 at the upper end of the torch body 181. RF current is supplied to the induction coil(s) 130 via power leads 132. Water or another cooling fluid is fed via inlets such as 134, flows in cooling channels such as 136, in particular through an annular spacing between the torch body 181 and the plasma confinement tube 179, for cooling the inductively coupled plasma torch. The water or other cooling fluid exits the apparatus 100 via outlets such as 138. Water or other cooling fluid may also flow (a) within a shield 140 of the injection probe 122 and into the induction coil(s) 130 which is (are) then tubular.

**[0047]** Exposure of the forward end 114 of the feed material 110 to the plurality of plasma jets 180 causes local melting of the feed material followed by instantaneous stripping and breakdown of the formed molten layer of feed material into small droplets 182. The droplets 182 fall into the cooling chamber 170, which is sized and configured to allow in-flight freezing of the droplets 182. The droplets 182, when freezing, turn into powder particles 184 collected in the collector 190.

**[0048]** The apparatus 100 of Figure 3 is configured to let the droplets 182 fall towards the collector 190 by gravity. However, other configurations in which the droplets 182 do not fall vertically, being propelled by a gas or by a vacuum, are also contemplated. In the embodiment of Figure 3 and in such other configurations, an exit pipe 192 may connect a lower part of the cooling

chamber 170 toward a vacuum pumping system (not shown) to withdraw gas from the cooling chamber 170.

**[0049]** The apparatus 100 includes other components such as casings, flanges, bolts, and the like, which are illustrated on Figures 1, 2a, 2b, 3, 4, 5 and 6. These elements are believed to be self-explanatory and are not described further herein. The precise configuration of the various components illustrated on these and other Figures do not limit the present disclosure.

**[0050]** Figure 4a is a perspective view of the atomization nozzle 160 with a support flange 171 according to an embodiment. Figure 4b is a cross-sectional view of the atomization nozzle 160 and support flange 171 of Figure 4a. Figures 4c, 4d and 4e are top, bottom and perspective views showing details of the atomization nozzle 160 of Figure 4a, including the central aperture 162 surrounded by radial apertures 166 for forming plasma jet channels, for example micro-plasma jet channels. Without limitation, the atomization nozzle 160 may be formed of a water-cooled metal or of a radiation cooled refractory material or a combination of both.

**[0051]** The nozzle 160 is supported by the flange 171. As shown in Figures 2a and 2b, the flange 171 can be secured between the lower end of the plasma torch 120 and a mounting annular member 173 in a sealing arrangement between the plasma torch 120 and the cooling chamber 170. Still referring to Figures 2a and 2b, the nozzle 160 comprises an annular, inner surface 177 which may define a portion of the cooling channels 136 to provide at the same time for cooling of the nozzle 160. The nozzle 160 also defines an annular groove 175 to receive the lower end 211 of the plasma confinement tube 179 in a proper sealing arrangement.

**[0052]** The nozzle 160 of Figures 4a-4e comprises, on the inner side, a central tower 168 defining the central aperture 162, which is co-axial with the injection probe 122. The central aperture 162 has an input funnel-shaped enlargement 169. This configuration of the tower 168 facilitates alignment and insertion of the forward portion 112 of the feed material 110. The central

aperture 162 of the nozzle 160 allows the forward portion 112 of the feed material 110 to exit the plasma torch 120 toward the inside of the cooling chamber 170.

**[0053]** The atomization nozzle 160 also comprises, around the central tower 168, a bottom wall formed with the plurality of radial apertures 166 equally, angularly spaced apart from each other. The radial apertures 166 are designed for allowing respective fractions of the plasma 126 to flow toward the cooling chamber 170 and generate the plasma jets 180. The number of radial apertures 166 and their angle of attack with respect to the central, geometrical longitudinal axis of the plasma torch 120 may be selected as a function of a desired distribution of the plasma jets 180 around the longitudinal axis of the plasma torch 120.

**[0054]** The central aperture 162 may be sized and configured to closely match a cross-section of the feed material 110 so that the central aperture 162 becomes substantially closed by insertion of the forward portion 112 of the feed material 110 therein. By closing the central aperture 162, a pressure of the plasma 126 in the plasma torch 120 builds up. This in turn causes respective fractions of the plasma 126 to be expelled from the zone 124 in the plasma confinement tube 179 via the radial apertures 166. These expelled fractions of the plasma 126 form the plasma jets 180. The radial apertures 166 are sized and configured to expel the plasma jets 180 at high velocity, which could possibly attain sonic or supersonic velocities.

**[0055]** In cases where the cross-section of the feed material 110 is smaller than the opening of the central aperture 162, the aperture 162 is not entirely blocked and pressure build-up within the plasma torch 120 may be of a lesser magnitude. Regardless, the sheer action of the plasma torch 120 and the partial blockage of the central aperture 162 by the feed material 110 still cause the plasma 126 to be at a significant pressure level. The plasma jets 180 may still be present, though potentially reduced in terms of flow and pressure. A portion of the plasma 126 is expelled through the central aperture

162, in a gap left between the feed material 110 and the opening of the central aperture 162. This portion of the plasma 126 forms an annular plasma jet, or flow, that surrounds the forward end 114 of the feed material 110. As it passes through the central aperture 162, the forward end 114 can be, in such cases, atomized in part by the annular plasma jet. The forward end 114 may further be atomized in a further part by plasma jets 180 that, though weaker, may still be expelled from the radial apertures 166 of the atomization nozzle 160 at a significant speed.

**[0056]** The radial apertures 166 may each be oriented so that the plasma jets 180 converge toward the forward end 114 of the feed material 110 in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube, within the cooling chamber 170 to enhance the atomization process. More particularly, Figures 4c and 4d show, respectively, top and bottom views of the atomization nozzle 160. It may be observed that the radial apertures 166 are angled inwardly about the central, geometrical longitudinal axis of the plasma torch 120 from top to bottom of the atomization nozzle 162. In this manner, the plasma jets 180 formed therein will converge within the cooling chamber 170 toward a convergence point in axial alignment with the central aperture 162. Without limitation, the radial apertures 166 may be cylindrical and have a diameter in the range of 0.5 mm up to 3 mm to produce sonic or supersonic plasma micro-jets and may be oriented at 20° to 70° angles with respect to the central, geometrical longitudinal axis of the plasma torch 120. Other shapes and diameters of the radial apertures 166 may of course be contemplated.

**[0057]** As expressed hereinabove, the atomization nozzle 160 generates a plurality of converging plasma jets and may further generate an annular plasma jet. Another embodiment of the atomization nozzle that only generates an annular plasma jet will now be described.

**[0058]** Figure 5 is a detailed, front elevation view of the plasma torch of Figure 1, showing an atomization nozzle according to another embodiment.

In this embodiment, the plasma torch 120 is modified to comprise an atomization nozzle 660 arranged centrally on a bottom closure piece of the torch 120 secured to the lower end of the torch body 181. The atomization nozzle 660 has a central aperture 662 at its exit end and an internal face 664 that tapers off toward the central aperture 662. In a non-limitative embodiment, the central aperture 662 of the atomization nozzle 660 is sized and configured to substantially match a cross-section of the elongated member forming the feed material 110 so moving the forward end 114 of the feed material 110 into the atomization nozzle 660 causes building up of a pressure of the plasma 126 in the plasma torch 120. The pressure of the plasma 126 in the plasma torch 120 causes some of the plasma to be expelled through the atomization nozzle 660, forming an annular plasma jet 665 between the forward end 114 of the feed material 110 and the internal face 664 of the atomization nozzle 660. Exposure of the forward end 114 of the feed material 110 to the annular plasma jet 665 causes surface melting and atomization of the feed material 110. The atomized feed material exits the plasma torch 120 through the central aperture 662 and enters the cooling chamber 170 in the form of fine or ultrafine droplets 182. The droplets 182 fall into the cooling chamber 170, which is sized and configured to allow in-flight freezing of the droplets 182. The droplets 182, when freezing, turn into powder particles 184 collected in the collector 190. Some of the plasma, forming the annular plasma jet 665, also enters the cooling chamber 170.

**[0059]** Figure 6 is a detailed, front elevation view of a variant of the plasma torch of Figure 1, showing the atomization nozzle of Figure 5 and further including a sheath gas port surrounding the exit end of the atomization nozzle. In this variant, the plasma torch 120 of earlier Figures is supplemented by the addition of an input port 410 for receiving a sheath gas 412. The sheath gas 412 is constrained underneath the plasma torch 120 by a cover 414 that forms with the bottom closure piece of the torch an annular cavity surrounding the central aperture 662 of the atomization nozzle 660. The sheath gas 412 is expelled from the annular sheath gas output port 416 to form a sheath gas

curtain 418 surrounding the plasma and the droplets 182 expelled from the atomization nozzle 660. Presence of the axial sheath gas curtain 418 prevents the droplets 182 from reaching and depositing on any downstream surface of the plasma torch 120, including the atomization nozzle 660. Specifically, the sheath gas curtain 418 prevents rapid expansion of the plasma flow emerging from the atomization nozzle 660 and, therefore, the droplets 182 from impinging on any downstream surfaces of the cooling chamber. As shown on Figure 6, the central aperture 662 of the atomization nozzle 660 may be extended slightly in a short annular flange 667 to better deflect the sheath gas 412 around the flow formed by the plasma gas and the droplets 182. The sheath gas may be of a same nature as the source of the plasma gas, including for example inert gases such as argon and helium to their mixtures with hydrogen, oxygen and/or nitrogen. The sheath gas may alternatively consist of a different gas.

**[0060]** The apparatus 100 may integrate either of the atomization nozzles 160 and 660. Though not illustrated, a further variant of the apparatus 100 including a combination of the atomization nozzle 160 with components providing the sheath gas 412 via the sheath gas port 416 is also contemplated.

**[0061]** Figure 7 is a flow chart showing operations of a process of producing powder particles by atomization of a feed material in the form of an elongated member such as, as non-limitative examples, a wire, rod or filled tube. On Figure 7, a sequence 500 comprises a plurality of operations that may be executed in variable order, some of the operations possibly being executed concurrently, some of the operations being optional.

**[0062]** The sequence 500 for producing powder particles by atomization of a feed material in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube is initiated at operation 510 by introducing the feed material in a plasma torch, for example in an inductively coupled plasma torch. Introduction of the feed material in the plasma torch may be made via an injection probe in continuous manner, using

a typical wire, rod or tube feeding mechanism to control the feed rate of the elongated member and, if required, to straighten the elongated member sometimes provided in the form of rolls.

**[0063]** Within the plasma torch, a forward portion of the feed material may be preheated by either direct or indirect contact with plasma at operation 520. When an injection probe is used, a section of the plasma torch beyond an end of the injection probe, specifically between the end of the injection probe and may form a preheating zone for preheating the forward portion of the feed material. Operation 530 comprises moving a forward portion of the feed material from into an atomization nozzle of the plasma torch, a forward end of the feed material reaching a central aperture of the atomization nozzle.

**[0064]** One or more plasma jets are produced by the atomization nozzle. The one or more plasma jets may include an annular plasma jet surrounding the forward end of the feed material, a plurality of converging plasma jets expelled by the atomization nozzle, or a combination of the annular and converging plasma jets. Generating additional plasma jets using a secondary plasma torch operably connected to the cooling chamber is also contemplated. Operation 540 comprises surface melting the forward end of the feed material by exposure to the one or more plasma jets formed in the atomization nozzle.

**[0065]** Droplets formed by atomization of the feed material are frozen in-flight within the cooling chamber, at operation 550. Then operation 560 comprises collecting powder particles resulting from in-flight freezing of the droplets.

**[0066]** Production of the powder particles using the sequence 500 of Figure 7 may be made continuous by continuously advancing the feed material into the plasma torch while maintaining the plasma and plasma jets at proper temperature levels. Generally, a duration of the travel of the forward portion of the feed material in the preheating zone, whether by direct contact between the feed material and the plasma or indirect radiation heating by the plasma

through a radiation tube is controlled so that the forward portion of the feed material reaches a predetermined temperature before moving into the atomization nozzle. The predetermined temperature obtained in the preheating operation 520 is below a melting point of the feed material. Control of the duration of the preheating time of the feed material may be made by controlling a rate of feeding of the feed material and/or a length of the preheating zone in the plasma torch.

**[0067]** Through temperature control of the plasma and of the plasma jets, production of the powder particles using the sequence 500 may apply to a broad range of materials such as pure metals, for example titanium, aluminum, vanadium, molybdenum, copper, alloys of those or other metals including for example titanium alloys, steel and stainless steel, any other metallic materials having a liquid phase, ceramics including for example those of oxide, nitride, or carbide families, or any combination thereof, or any other ceramic material that has a liquid phase, composites or compounds thereof. The foregoing list of materials is not intended to limit the application of the process and apparatus for producing powder particles by atomization of a feed material in the form of an elongated member.

*First Example*

**[0068]** According to a first example, the process for producing powder particles by atomization of a feed material in the form of an elongated member may comprise the following operations. This first example may make use of the apparatus 100 illustrated in whole or in parts in Figure 1-6 that includes the plasma torch 120 for heating, melting and atomizing the feed material 110. The process involves an axial introduction of the feed material 110 in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube, through the injection probe 122, into the center of a discharge cavity where the plasma 126 is generated. The feed material 110 may be supplied to the injection probe 122 in continuous manner by a typical wire, rod or tube feeding mechanism (not shown) for example similar to commercially available

units currently used in wire arc welding such as the units commercialized by Miller for MIG/Wire welding, and comprising, as indicated in the foregoing description, wheels operated to control the feed rate of the elongated member and, if required, to straighten the elongated member sometimes provided in the form of rolls. As the feed material 110 emerges from the injection probe 122 and traverses the plasma 126, it is heated in the preheating zone 124 before entering into the downstream atomization nozzle 160 at the lower end of the plasma torch 120. A distance between the end of the injection probe 122 and the entrance point of the atomization nozzle 160 defines a length of the preheating zone 124. A time of heating of the feed material 110 by the plasma in the preheating zone 124 depends on the length of the preheating zone 124 and on a linear speed at which the elongated member travels in the plasma torch 120. An amount of energy received by the feed material 110 in the preheating zone 124 depends in turn not only on the time of preheating of the feed material 110 in the preheating zone 126 but also on thermo-physical properties of the plasma 126 as well as on a diameter of the elongated member forming the feed material 110. Through control of the length of the preheating zone 124, the linear speed of the elongated member forming the feed material 110, and the plasma temperature, it is possible to control the temperature of the forward end 114 of the feed material 110 as it enters into the atomization nozzle 160. For optimal results, the temperature of the feed material 110, as it penetrates into the atomization nozzle 160, may be as high as possible, though preferably not too close to the melting point of the feed material 110 in order to avoid premature melting of the feed material 110 in the discharge cavity of the plasma torch 120.

**[0069]** As the preheated forward end 114 of the feed material 110 emerges from the atomization nozzle 160 in the cooling chamber 170, it is exposed to a plurality of plasma jets, for example a high velocity, sonic or supersonic, micro-plasma jets 180 that impinge on the surface of the forward end 114 of the elongated member forming the feed material 110, melts the material and, *in statu nascendi*, strips out molten material in the form of finely

divided, spherical molten droplets 182 that are entrained by the plasma gas. As the atomized droplets 182 are transported further downstream into the cooling chamber 170, they cool down and freeze in-flight forming dense spherical powder particles 184 of the feed material. The powder particles 184 are recovered in the container 190 located at the bottom of the cooling chamber 170, or may be collected in a downstream cyclone (not shown) or collection filter (also not shown), depending on their particle size distribution.

*Second Example*

**[0070]** Again, this second example may make use of the apparatus 100 that includes the plasma torch 120 for heating, melting and atomizing the feed material 110. According to the second example usable to manufacture powders of dense spherical particles of metals, metal alloys and ceramics, the process for producing powder particles by atomization of a feed material in the form of an elongated member comprises the following operations:

**[0071]** a. An inductively coupled plasma source, for example an inductive plasma torch, comprising a fluid-cooled plasma confinement tube surrounded by a fluid-cooled induction coil is provided. The plasma is generated inside the plasma confinement tube through electromagnetic coupling of the energy from the induction coil into the discharge cavity in the plasma confinement tube. The inductively coupled plasma source operates typically, without limitation of generality, in a frequency range of 100 kHz to 10 MHz with a pressure ranging between soft vacuum of about 10 kPa up to 1.0 MPa. The plasma gases can range from inert gases such as argon and helium to their mixtures with hydrogen, oxygen and/or nitrogen. The inductively coupled plasma source comprises a head responsible for the distribution of a cooling fluid, such as water, that provides efficient cooling of all its components. The head may further provide a uniform distribution of a plasma sheath gas into the discharge cavity in order to stabilize the discharge at the center of the tube. The plasma sheath gas also protects the plasma confinement tube from high heat fluxes emanating from the plasma discharge.

On a downstream end of the inductively coupled plasma source, an exit flange-mounted nozzle allows the plasma to flow towards a cooling chamber. The inductively coupled plasma source may also be equipped with a centrally located, water-cooled, material injection probe that serves to introduce the material to be processed into the discharge cavity.

**[0072]** b. The feed material to be atomized is introduced through the injection probe in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube, in a well-controlled feed rate, using an appropriate feeding mechanism. The feed material may be supplied to the injection probe in continuous manner by a typical wire, rod or tube feeding mechanism (not shown) for example similar to commercially available units currently used in wire arc welding such as the units commercialized by Miller for MIG/Wire welding, and comprising wheels operated to control the feed rate of the elongated member and, if required to straighten the elongated member sometimes provided in the form of rolls.

**[0073]** c. As the feed material to be processed emerges from the injection probe, it is directed towards a central aperture in an atomization nozzle. The presence of the feed material closes at least in part this central aperture of the atomization nozzle.

**[0074]** d. Closing at least in part of the nozzle central aperture causes a pressure of the plasma in the discharge cavity to build-up. The pressure may be in a range of 50 kPa up to 500 kPa or more. This pressure causes a flow of plasma through a plurality of radial apertures in the atomization nozzle, the radial apertures being uniformly distributed over a circular perimeter surrounding the central aperture of the nozzle. This result in the creation of a plurality of focused plasma micro-jets having a very high speed, possibly reaching sonic or supersonic values, depending on the configuration and operational parameters.

**[0075]** e. Exposure of the forward end of the elongated member forming the feed material exits central aperture of the atomization nozzle to

penetrate a cooling chamber, it is subjected to intense heating by the plasma jets. This completes the melting of the feed material at its surface and atomizes it in the form of fine or ultrafine molten droplets. With this second example, droplets having diameters in the range of 5  $\mu\text{m}$  to few hundred micrometers may be obtained.

**[0076]** f. As the atomized material is entrained in the cooling chamber by the emerging plasma gas, the molten droplets cool down and solidify in-flight, forming dense spherical particles that are collected at the downstream part of the system.

*Third example*

**[0077]** According to a third example, which may make use of the apparatus 100, the process for producing powder particles by atomization of a feed material in the form of an elongated member comprises the following operations.

**[0078]** Feed material 110 in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube is introduced through the injection probe 122 axially oriented along a centerline of the plasma torch 120.

**[0079]** As the feed material 110 emerges from the injection probe 122, at a downstream end of the plasma torch 120, its forward portion 112 is heated either by direct contact with the plasma 126 or indirectly using the radiation tube 125 in the preheating zone 124. A distance of travel in the preheating zone 124 and a speed of movement of the feed material 110 may be adjusted to allow sufficient time for the forward portion 112 of the elongated member to heat to a temperature as close as possible to the melting point of the feed material, without actually reaching that melting point.

**[0080]** At this point, the forward end 114, or tip, of the feed material 110 reaches the atomization nozzle 160 and penetrates through its central aperture 162, which in this third example has substantially the same diameter

as that of the elongated member. As the forward end 114 of the feed material 110 emerges in the cooling chamber 170 from a downstream side of the atomization nozzle 160, it is exposed to the plurality of plasma jets 180, for example the high-velocity plasma micro-jets 180 impinging thereon. Since the forward end of the feed material 110, being already preheated in the preheating zone 124, i.e. in the discharge cavity, to near its melting point, it rapidly melts at its surface and is stripped away by the plasma jets 180, turning into fine or ultrafine droplets 182 that are entrained by a plasma flow resulting from the plasma jets 180. As the droplets 182 travel down the cooling chamber 170, they cool down and solidify in the form of dense spherical particles 184 that deposits by gravity in the container 190 at the bottom of the cooling chamber 170 or are transported by the plasma gas to a downstream powder collection cyclone or to a fine metallic filter.

*Fourth example*

**[0081]** According to a fourth example, which may make use of the apparatus 100, the process for producing powder particles by atomization of a feed material in the form of an elongated member comprises the following operations.

**[0082]** Feed material 110 in the form of an elongated member such as, as non-limitative examples, a wire, a rod or a filled tube has smaller diameter than that of the central aperture 162. The feed material 110 is introduced through the injection probe 122 axially oriented along a centerline of the plasma torch 120.

**[0083]** As in the third example, the feed material 110 emerges from the injection probe 122, at a downstream end of the plasma torch 120, its forward portion 112 is heated either by direct contact with the plasma 126 or indirectly using the radiation tube 125 in the preheating zone 124. A distance of travel in the preheating zone 124 and a speed of movement of the feed material 110 may be adjusted to allow sufficient time for the forward portion 112 of the elongated member to heat to a temperature as close as possible to

the melting point of the feed material, without actually reaching that melting point.

**[0084]** At this point, the forward end 114, or tip, of the feed material 110 reaches the atomization nozzle 160 and penetrates through its central aperture 162, which in this fourth example has a larger diameter than that of the elongated member. As the forward end 114 of the feed material 110 travels through the central aperture 162 of the atomization nozzle 160, it is exposed to an annular plasma jet present in a gap formed of a difference between the diameter of the central aperture 162 and the diameter of the elongated member. Since the forward end 114 of the feed material 110, is already preheated in the preheating zone 124, i.e. in the discharge cavity, to near its melting point, exposition of the forward end 114 of the feed material 110 to this annular plasma jet causes a rapid melting at its surface, being stripped away by the annular plasma jet, turning into fine or ultrafine droplets 182 that are entrained by a plasma flow resulting from the annular plasma jet. If the forward end 114 is not entirely atomized by the annular plasma jet, remaining feed material emerges in the cooling chamber 170 from a downstream side of the atomization nozzle 160. The remaining feed material is exposed to the plurality of plasma jets 180 impinging thereon. The remaining feed material continues melting at its surface and, being stripped away by the plasma jets 180, turning into more fine or ultrafine droplets 182 that are entrained by a plasma flow resulting from the annular plasma jet and from the plasma jets 180. As the droplets 182 travel down the cooling chamber 170, they cool down and solidify in the form of dense spherical particles 184 that deposits by gravity in the container 190 at the bottom of the cooling chamber 170 or are transported by the plasma gas to a downstream powder collection cyclone or to a fine metallic filter.

**[0085]** An overall view of a typical plasma atomization apparatus 100 is shown in Figure 3. The basic dimensions and shapes of the shown components of the apparatus 100 may widely vary depending on the material

to be atomized and depending on desired production rates. A power level of the plasma torch 120 may, without loss of generality, vary between 10 or 20 kW up to hundreds of kW for a commercial production scale unit.

**[0086]** Referring again to Figures 4a-4e, an example of design of the atomization nozzle 160 is shown. The nozzle 160 comprises the flange 171. The atomization nozzle 160 may be made of fluid-cooled copper or stainless steel. Alternatively, the atomization nozzle 160 may be made of a refractory material such as graphite, in combination with a water-cooled flange 171.

**[0087]** The atomization nozzle 160 has a central aperture 162 optionally adapted to closely match a diameter of the elongated member forming the feed material 110. The atomization nozzle 160 has a plurality of radial apertures 166 equally distributed around the central aperture 162 and which, according to an embodiment, are directed at an angle of 45° about the central, geometrical longitudinal axis of the plasma torch 120. Successful operation was obtained using sixteen (16) radial apertures 166 having a diameter of 1.6 mm, the radial apertures 166 being equally distributed around the central aperture 162. The diameter, the number and the angle of the radial apertures 166 can be adjusted depending on thermo physical properties of the materials to be atomized and on a desired particle size distribution.

**[0088]** It should be pointed out that the atomized material may change its chemical composition during atomization through the reaction between different components premixed into the feed material. A non-limitative example is the production of an alloy by mixing different metals forming the particles filling a tube forming the feed material. Another non-limitative example is a chemical reaction between the chemical components forming the particles in the filled tube. It should also be pointed out that the atomized material may change its chemical composition during atomization as a result of a chemical reaction between the plasma gas(es) and/or sheath gas(es) and the atomized material, for example by oxidation, nitration, carburization, etc.

**[0089]** Based on fluid dynamic modeling of the flow and temperature

field in the discharge cavity of the plasma torch it is possible to calculate the temperature profile in the elongated member forming the feed material as it traverses the preheating zone in the torch. Figure 8 is a schematic view, including a graph showing modelling results for heating a 3.2 mm stainless steel wire introduced in an argon/hydrogen induction plasma at 60 kW. Figure 8 provides typical results that can be obtained using an inductively coupled plasma torch as shown on Figures 1-6. Figure 8 shows, on its left hand side a two-dimensional temperature field in the discharge cavity for the argon/hydrogen plasma operated with a radio frequency power supply with an oscillator frequency of 3 MHz, and a plate power of 60 kW. At the bottom of Figure 8, a corresponding temperature field in a 3.2 mm diameter stainless steel rod is given for rod translation velocities of 40 and 60 mm/s. As expected the overall temperature of the rod drops with the increase of its translation speed across the preheating zone in the discharge cavity of the plasma torch. The center of Figure 8 is a graph showing a variation of the maximum temperature achieved at the tip of the elongated member, for different speeds, and different length of the preheating zone 124, identified on the left hand side of Figure 8 as 'z'. It may be noted that depending on the length of the preheating zone 124, maintaining the rod translation velocity within a relatively narrow window allows to avoid the premature melting of the material in the discharge cavity or its arrival at the atomization nozzle at too low a temperature, which would have a negative impact on the quality of the atomized product.

**[0090]** Figure 9 is an electron micrograph of powder particles obtained by atomization of a 3.2 mm diameter stainless steel wire and a graph of corresponding particle size distribution. Such particles can be obtained using the plasma torch of Figures 1-6. Stainless steel powder particles were obtained using the induction plasma atomization process. The powder particles had a mean particle diameter,  $d_{50}$  of about 62  $\mu\text{m}$  and the powder production rate was about 1.7 kg/hour. The powder was mostly composed of dense spherical particles. A certain number of splats and satellites were observed

depending on the operating conditions and process optimization.

**[0091]** Figure 10 illustrates electron micrographs of different stainless steel spherical powder fractions produced using the process and apparatus for producing powder particles by atomization of a feed material in the form of an elongated member. Such particles can be obtained using the inductively coupled plasma torch of Figures 1, 2a and 2b. Again, the powder was mostly composed of dense spherical particles; only few splats and satellites were observed depending on the operating conditions and process optimization.

**[0092]** Those of ordinary skill in the art will realize that the description of the process and apparatus for producing powder particles and the description of powder particles so produced are illustrative only and are not intended to be in any way limiting. Other embodiments will readily suggest themselves to such persons with ordinary skill in the art having the benefit of the present disclosure. Furthermore, the disclosed process, apparatus and powder particles may be customized to offer valuable solutions to existing needs and problems related to efficiently and economically producing powder particles from a broad range of feed materials.

**[0093]** Various embodiments of the process for producing powder particles by atomization of a feed material in the form of an elongated member, of the apparatus therefor, and of the powder particles so produced, as disclosed herein, may be envisioned. Such embodiments may comprise a process for the production of a broad range of powders including, though not limited to, fine and ultrafine powders of high purity metals, alloys and ceramics in an efficient cost effective way that is scalable to an industrial production level. The process is applicable for the production of powders of pure metals, alloys and ceramics, causes minimal or no contamination of the atomized material, causes minimal or no oxygen pickup especially for reactive metals and alloys, produces fine or ultrafine particle size, for example with particle diameter less than 250  $\mu\text{m}$ , the particles being dense and spherical, with minimal or no contamination with satellites.

**[0094]** In the interest of clarity, not all of the routine features of the implementations of process, apparatus, and use thereof to produce powder particles are shown and described. It will, of course, be appreciated that in the development of any such actual implementation of the process, apparatus, and use thereof to produce powder particles, numerous implementation-specific decisions may need to be made in order to achieve the developer's specific goals, such as compliance with application-, system-, and business-related constraints, and that these specific goals will vary from one implementation to another and from one developer to another. Moreover, it will be appreciated that a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the field of materials processing having the benefit of the present disclosure.

**[0095]** Although the present disclosure has been described hereinabove by way of non-restrictive, illustrative embodiments thereof, these embodiments may be modified at will within the scope of the appended claims.

## Claims

1. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising an inductively coupled plasma torch with a longitudinal axis and including:
  - a coaxial injection probe at a first end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of a coaxial plasma confinement tube of the plasma torch for introducing the elongated member of the feed material axially into the plasma torch; and
  - an atomization nozzle at a second end of the plasma torch opposite the first end, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the coaxial injection probe, and wherein the atomization nozzle is configured for producing, using plasma from the inductively coupled plasma torch, at least one atomizing plasma jet for surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet.
2. The apparatus of claim 1, comprising a preheating zone for preheating a forward portion of the elongated member of the feed material, using the plasma produced in the inductively coupled plasma torch, the preheating zone being positioned within the plasma torch between the coaxial injection probe and the atomization nozzle.
3. The apparatus of claim 2, wherein the forward portion of the elongated member of the feed material is preheated by direct contact with the plasma in the preheating zone.
4. The apparatus of claim 2, comprising a radiation tube in the preheating zone, wherein the forward portion of the elongated member of the feed material is preheated through the radiation tube heated by direct contact with the plasma in the preheating zone.
5. The apparatus of any of claims 1 to 4, comprising a cooling chamber downstream of the atomization nozzle and on which the inductively coupled plasma torch is mounted coaxially with an axis of the cooling chamber.

6. The apparatus of claim 5, wherein the at least one atomizing plasma jet comprises a plurality of plasma jets, the forward end of the elongated member of the feed material exits the plasma torch through the coaxial aperture into the cooling chamber in which the forward end of the elongated member of the feed material is exposed to the plurality of plasma jets spaced apart around the longitudinal axis and converging toward the longitudinal axis.
7. The apparatus of claim 5, wherein the cooling chamber is sized and configured to allow in-flight freezing of droplets formed by the atomization of the feed material using the atomization nozzle.
8. The apparatus of any one of claims 1 to 5, wherein the at least one atomizing plasma jet comprises a plurality of plasma jets and the atomization nozzle comprises a plurality of radial apertures spaced apart around the longitudinal axis and in which the plasma from the inductively coupled plasma torch flows to produce the plurality of plasma jets converging toward the longitudinal axis.
9. The apparatus of claim 8, wherein the coaxial aperture of the atomization nozzle is sized and configured to closely match a cross-section of the elongated member of the feed material so that the coaxial aperture is substantially closed by insertion of a forward portion of the elongated member of the feed material, building up a pressure of the plasma in the plasma torch and causing the production of the plurality of converging plasma jets.
10. The apparatus of any of one claims 1 to 9, comprising a mechanism for supplying the elongated member of the feed material to the injection probe, the mechanism being adapted to control a feed rate of the elongated member.
11. The apparatus of claim 10, wherein the mechanism is also adapted to straighten the elongated member within at least one plane.
12. The apparatus of any one of claims 1 to 11, wherein the inductively coupled plasma torch generates the plasma from a gas selected from argon, helium and a combination thereof.
13. The apparatus of claim 12, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
14. The apparatus of any one of claims 1 to 13, wherein the coaxial aperture of the atomization nozzle is sized and configured to leave a gap between the coaxial aperture and the

elongated member of the feed material so that the at least one atomizing plasma jet is formed as an annular plasma jet within the coaxial aperture and around the forward end of the elongated member of the feed material.

15. The apparatus of any one of claims 1 to 13, wherein:

the atomization nozzle comprises an internal face tapering off toward the coaxial aperture; and

the coaxial aperture of the atomization nozzle is sized and configured to closely match a cross-section of the elongated member of the feed material so that moving the elongated member of the feed material toward the coaxial aperture builds up a pressure of the plasma in the inductively coupled plasma torch and causes the production of an annular plasma jet.

16. The apparatus of any one of claims 1 to 15, comprising:

an input port for receiving a sheath gas; and

an annular output port positioned downstream of the atomization nozzle for injecting the sheath gas surrounding the atomized feed material from the inductively coupled plasma torch.

17. The apparatus of claim 16, wherein the inductively coupled plasma torch generates plasma from a plasma gas, and wherein the sheath gas and the plasma gas are a same gas.

18. The apparatus of claim 16, wherein the inductively coupled plasma torch generates plasma from a plasma gas, and wherein the sheath gas and the plasma gas are different gases.

19. The apparatus of claim 16, wherein the apparatus is configured to change a chemical composition of the atomized feed material obtained by surface melting and atomizing of the feed material through a reaction between different components premixed into the feed material, or as a result of a chemical reaction between a plasma gas or the sheath gas and the atomized feed material.

20. The apparatus of any one of claims 1 to 19, wherein the at least one atomizing plasma jet is a high velocity plasma jet, and wherein the high velocity is selected from the group consisting of sonic and supersonic velocities.

21. The apparatus of any one of claims 1 to 20, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
22. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:
  - an inductively coupled plasma torch defining a longitudinal axis, having an upstream end and including an inner plasma confinement tube coaxial with the longitudinal axis, having a downstream end, and in which the inductively coupled plasma torch produces plasma;
  - an injection probe coaxial with the longitudinal axis at the upstream end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of the plasma confinement tube for introducing the elongated member of the feed material axially into the plasma confinement tube; and
  - an atomization nozzle at the downstream end of the plasma confinement tube, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the injection probe through the plasma confinement tube, and wherein the atomization nozzle is configured for producing, using plasma from the plasma confinement tube, at least one atomizing plasma jet for surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet.
23. The apparatus of claim 22, comprising a mechanism provided with wheels for feeding the elongated member to the elongated conduit of the injection probe in continuous manner and adapted to rotate the elongated member about a longitudinal axis thereof.
24. The apparatus of claim 22 or 23, comprising, in the plasma confinement tube between the injection probe and the atomization nozzle, a preheating zone in which the elongated member of the feed material is preheated by direct contact with the plasma in the plasma confinement tube.
25. The apparatus of claim 22 or 23, comprising, in the plasma confinement tube between the injection probe and the atomization nozzle, a preheating zone in which the elongated

member of the feed material is preheated, wherein the preheating zone comprise a radiation tube surrounding the elongated member in the plasma confinement tube between the injection probe and the atomization nozzle, and wherein the elongated member of the feed material is preheated by radiation from the radiation tube itself heated by direct contact with the plasma in the plasma confinement tube.

26. The apparatus of any one of claims 22 to 25, wherein the atomization nozzle defines an annular groove to receive the downstream end of the plasma confinement tube in a sealing arrangement.
27. The apparatus of any one of claims 22 to 26, wherein the coaxial aperture of the atomization nozzle has an input funnel-shaped enlargement to facilitate alignment and insertion of a forward portion of the elongated member of the feed material into the coaxial aperture of the atomization nozzle.
28. The apparatus of any one of claims 22 to 26, wherein the atomization nozzle comprises a plurality of radial apertures spaced apart around the longitudinal axis, and supplied with the plasma from the plasma confinement tube and angled inwardly about the longitudinal axis to produce a plurality of plasma jets converging toward a point in axial alignment with the coaxial aperture of the atomization nozzle.
29. The apparatus of any one of claims 22 to 26, wherein the atomization nozzle comprises an internal face that tapers off toward the coaxial aperture thereof, wherein the coaxial aperture of the atomization nozzle is sized and configured to substantially match a cross-section of the elongated member of the feed material, whereby moving the forward end of the elongated member of the feed material into the coaxial aperture of the atomization nozzle causes building up of pressure of the plasma in the plasma confinement tube to produce an annular plasma jet between the forward end of the elongated member of the feed material and the internal face of the atomization nozzle.
30. The apparatus of claim 29, wherein the atomization nozzle comprises an input port for receiving a sheath gas and an annular output port to form a sheath gas curtain surrounding the annular plasma jet and droplets of the atomized feed material expelled from the atomization nozzle to prevent the droplets from contacting a downstream surface of the plasma torch including the atomization nozzle.

31. The apparatus of any one of claims 22 to 26, wherein the at least one atomizing plasma jet comprises a combination of an annular plasma jet and a set of converging plasma jets.
32. The apparatus of any one of claims 22 to 31, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
33. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:
  - an inductively coupled plasma torch defining a longitudinal axis, having an upstream end and including an inner plasma confinement tube with a downstream end and coaxial with the longitudinal axis;
  - an injection probe coaxial with the longitudinal axis at the upstream end of the inductively coupled plasma torch and comprising an elongated conduit which extends through at least an upstream portion of the plasma confinement tube for introducing the elongated member of the feed material axially into the plasma confinement tube; and
  - an atomization nozzle at the downstream end of the plasma confinement tube, wherein the atomization nozzle comprises an aperture coaxial with the longitudinal axis for receiving the elongated member of the feed material from the coaxial injection probe through the plasma confinement tube.
34. A process for producing powder particles by atomization of a feed material in the form of an elongated member, using an inductively coupled plasma torch including a longitudinal axis, a coaxial injection probe at a first end of the plasma torch and comprising an elongated conduit which extends through at least an upper portion of a coaxial plasma confinement tube, and an atomization nozzle comprising a coaxial aperture for the elongated member at a second end of the plasma torch opposite the first end, said process comprising:
  - introducing the elongated member into the plasma torch through the coaxial injection probe;
  - moving the elongated member axially in the plasma torch through the coaxial injection probe and from the coaxial injection probe to the coaxial aperture of the atomization nozzle;

- producing at least one atomizing plasma jet by supplying plasma from the plasma torch to the atomization nozzle; and
- surface melting and atomizing the feed material of a forward end of the elongated member by exposure to the at least one atomizing plasma jet produced by the atomization nozzle.
35. The process of claim 34, comprising:
- preheating a forward portion of the elongated member in a preheating zone of the plasma torch between the injection probe and the atomization nozzle, using a coaxial annular plasma discharge produced in a central cavity of the plasma torch; and
- controlling a duration of the preheating of the forward portion of the elongated member by the plasma discharge so that the forward portion of the elongated member reaches a predetermined temperature before moving into the atomization nozzle.
36. The process of claim 35, wherein the forward portion of the elongated member is preheated by direct contact with the plasma.
37. The process of claim 35, wherein the forward portion of the elongated member is preheated indirectly using a coaxial radiation tube surrounding the elongated member and heated by direct contact with the plasma discharge in the central cavity.
38. The process of any one of claims 35 to 37, comprising selecting a length of the preheating zone to adjust a time of preheating of the forward portion of the elongated member.
39. The process of any one of claims 35 to 38, comprising controlling a feed rate of the elongated member introduced in the plasma torch to control the duration of the preheating of the forward portion of the elongated member by the plasma discharge.
40. The process of any one of claims 35 to 39, wherein a temperature of the plasma and a temperature of the at least one atomizing plasma jet are controlled to respectively preheat and atomize the feed material selected from the group consisting of a pure metal, an alloy, a ceramic, a composite and a compound thereof.

41. The process of any one of claims 34 to 40, comprising axially moving the forward end of the elongated member via the coaxial aperture of the atomization nozzle, wherein producing at least one atomizing plasma jet comprises expelling a plurality of plasma jets from the plasma torch via radial apertures of the atomization nozzle, and wherein the plasma jets are equally spaced apart around the longitudinal axis and converge toward the longitudinal axis.
42. The process of any one of claims 34 to 40, wherein producing at least one atomizing plasma jet comprises forming an annular plasma jet for surface melting and atomizing the forward end of the elongated member.
43. The process of any one of claims 34 to 42, comprising expelling the at least one atomizing plasma jet into a cooling chamber at high velocities selected from the group consisting of sonic and supersonic velocities.
44. The process of any one of claims 34 to 43, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
45. The process of any one of claims 34 to 44, comprising changing a chemical composition of the atomized feed material obtained by the surface melting and the atomizing of the feed material of the elongated member through a reaction between different components premixed into the feed material, or as a result of a chemical reaction between a plasma gas or a sheath gas and the atomized feed material.
46. The process of claim 45, comprising injecting the sheath gas downstream of the atomization nozzle, the sheath gas surrounding the atomized feed material expelled from the plasma torch.
47. The process of claim 46, wherein the sheath gas and the plasma are generated from a same gas.
48. The process of claim 46, wherein the sheath gas and the plasma are generated from different gases.
49. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:

- a) a feeding mechanism configured to feed the feed material toward an atomization zone, along a feed path; and
  - b) an atomization device in the atomization zone configured to perform atomization of the feed material, the atomization device comprising:
    - i) a plasma containment chamber in which a body of plasma is generated;
    - ii) a nozzle allowing the plasma to egress the containment chamber,
 

wherein the atomization device is configured for receiving the feed material directed toward the nozzle to define an annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets; and
    - iii) an elongated conduit for feeding the elongated member into the atomization zone toward the nozzle, the elongated conduit being configured for receiving the elongated member and extending along the feed path, the elongated conduit having an inlet end for receiving the elongated member and an outlet to release the forward end of the elongated member upstream of the nozzle in a direction of travel of the elongated member along the feed path.
50. The apparatus of claim 49, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
51. The apparatus of claim 50, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
52. The apparatus of any one of claim 49 to 51, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
53. The apparatus of any one of claims 49 to 52, wherein the elongated conduit has a cross-sectional shape that is circular.
54. The apparatus of any one of claims 49 to 53, wherein the powder particles have a mean diameter d50 of less than 65  $\mu\text{m}$ .

55. The apparatus of any one of claims 49 to 54, wherein the feeding mechanism is configured to feed the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
56. The apparatus of any one of claims 49 to 55, wherein the apparatus is configured for producing the powder particles at a rate of at least 1.7 kg/hour.
57. The apparatus of any one of claims 49 to 56, wherein the feeding mechanism is configured to feed the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
58. The apparatus of any one of claims 49 to 57, wherein the powder particles are spherical.
59. The apparatus of claim 57, wherein the powder particles are free of satellites.
60. The apparatus of claim 57, wherein the powder particles are free from splats and satellites.
61. The apparatus of any one of claims 49 to 60, wherein the apparatus is configured to generate the plasma with a power level of between 10 kW and 60 kW.
62. The apparatus of claim 61, wherein the plasma is generated from a gas comprising argon, helium, or a combination thereof.
63. The apparatus of claim 62, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
64. The apparatus of any one of claims 49 to 63, further comprising a cooling zone for receiving the molten droplets to solidify the molten droplets into the powder particles.
65. The apparatus of claim 64, wherein the atomization and cooling zones are contained in a chamber.
66. The apparatus of claim 64 or 65, wherein the cooling zone is configured to produce in-flight freezing of the molten droplets.
67. The apparatus of any one of claims 64 to 66, further comprising a powder collector configured to collect the powder particles from the cooling zone.
68. The apparatus of claim 67, wherein the powder collector resides below the cooling zone.

69. The apparatus of any one of claims 64 to 66, further comprising a powder collector configured to collect the powder particles from the cooling zone, wherein the powder particles travel from the cooling zone toward the powder collector along a direction other than a vertical direction.
70. The apparatus of claim 69, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
71. The apparatus of claim 70, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
72. The apparatus of any one of claims 64 to 66, further comprising a powder collector configured to collect the powder particles from the cooling zone, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
73. The apparatus of claim 72, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
74. The apparatus of claim 73, wherein the conduit is configured to transport the powder particles along a direction other than a vertical direction.
75. The apparatus of any one of claims 67 to 74, wherein the powder collector includes a cyclone.
76. The apparatus of claim 75, wherein the cyclone is configured to separate the powder particles into two or more fractions according to size.
77. The apparatus of any one of claims 49 to 76, wherein the feed material comprises a pure metal, an alloy, a ceramic, or a composite.
78. The apparatus of any one of claims 49 to 77, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
79. The apparatus of any one of claims 49 to 77, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .

80. The apparatus of any one of claims 49 to 77, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
81. The apparatus of any one of claims 49 to 77, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .
82. The apparatus of any one of claims 49 to 81, wherein the feeding mechanism includes wheels for linearly feeding the elongated member toward the atomization zone.
83. The apparatus of any one of claims 49 to 82, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube
84. A method for producing powder particles by atomization of a feed material in the form of an elongated member, the method comprising:
  - a) feeding the elongated member toward an atomization zone, the elongated member being dispensed through an elongated conduit along a feed path, the elongated conduit extending along the feed path; and
  - b) generating an annular plasma jet in the atomization zone by:
    - i) generating a body of plasma within a plasma containment chamber,
    - ii) allowing the plasma to egress the containment chamber via a nozzle, and
    - iii) receiving the feed material directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets, the nozzle residing on the feed path downstream of the elongated conduit in a direction of travel of the elongated member along the feed path, the elongated conduit being configured for feeding the elongated member into the atomization zone, the elongated conduit having an inlet end for receiving the elongated member and an outlet end to release the forward end of the elongated member upstream of the nozzle in the direction of travel of the elongated member along the feed path.

85. The method of claim 84, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
86. The method of claim 85, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
87. The method of any one of claim 84 to 86, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
88. The method of any one of claims 84 to 87, wherein the elongated conduit has a cross-sectional shape that is circular.
89. The method of any one of claims 84 to 88, wherein the powder particles have a mean diameter d50 of less than 65  $\mu\text{m}$ .
90. The method of any one of claims 84 to 89, wherein a feeding mechanism feeds the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
91. The method of any one of claims 84 to 90, comprising producing the powder particles at a rate of at least 1.7 kg/hour.
92. The method of any one of claims 84 to 91, wherein the feeding mechanism feeds the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
93. The method of any one of claims 84 to 92, wherein the powder particles are spherical.
94. The method of claim 92, wherein the powder particles are free of satellites.
95. The method of claim 92, wherein the powder particles are free from splats and satellites.
96. The method of any one of claims 84 to 95, comprising generating the plasma with a power level of between 10 kW and 60 kW.
97. The method of claim 96, comprising generating the plasma from a gas comprising argon, helium, or a combination thereof.
98. The method of claim 97, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.

99. The method of any one of claims 84 to 98, comprising receiving the molten droplets in a cooling zone to solidify the molten droplets into the powder particles.
100. The method of claim 99, wherein the cooling zone produces in-flight freezing of the molten droplets.
101. The method of claim 99 or 100, wherein the atomization and cooling zones are contained in a chamber.
102. The method of any one of claims 99 to 101, further comprising collecting the powder particles from the cooling zone into a powder collector.
103. The method of claim 102, wherein the powder collector resides below the cooling zone.
104. The method of any one of claims 99 to 103, further comprising collecting the powder particles from the cooling zone into the powder collector by causing the powder particles to travel from the cooling zone toward the powder collector along a direction other than a vertical direction.
105. The method of claim 104, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
106. The method of claim 105, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
107. The method of any one of claims 99 to 103, further comprising collecting the powder particles from the cooling zone into the powder collector, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
108. The method of claim 107, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
109. The method of claim 108, comprising transporting the powder particles in the conduit along a direction other than a vertical direction.

110. The method of any one of claims to 102 to 109, wherein the powder collector includes a cyclone.
111. The method of claim 110, wherein the cyclone separates the powder particles into two or more fractions according to size.
112. The method of any one of claims 84 to 111, wherein the feed material comprises a pure metal, an alloy, a ceramic, or a composite.
113. The method of any one of claims 84 to 112, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
114. The method of any one of claims 84 to 112, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .
115. The method of any one of claims 84 to 112, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
116. The method of any one of claims 84 to 112, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .
117. The method of any one of claims 84 to 116, wherein the feeding mechanism linearly feeds the elongated member toward the atomization zone with wheels.
118. The method of any one of claims 84 to 117, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
119. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:
  - a) a feeding mechanism configured to feed the elongated member toward an atomization zone, along a feed path,
  - b) an atomization nozzle, the apparatus being configured for generating an annular plasma jet into the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the

nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets, the nozzle residing on the feed path of the elongated member; and

- c) a pre-heating device located upstream of the nozzle in a direction of travel of the elongated member along the feed path, the pre-heating device configured to bring the forward end of the elongated member directed at the nozzle to a selected temperature which is below the melting point of the elongated member, the pre-heating of the elongated member at the selected temperature operating to increase a rate at which the feed material of the forward end of the elongated member is melted into the droplets by the annular plasma jet, the pre-heating device comprising an elongated conduit extending along the feed path for receiving the elongated member therein.

- 120. The apparatus of claim 119, wherein the pre-heating device comprises a radiation structure extending along the feed path, and a heat source to heat the radiation structure which is configured in turn to heat the forward end of the elongated member through radiation while the elongated member is travelling along the radiation structure.
- 121. The apparatus of claim 119, wherein the pre-heating device comprises an induction coil, wherein the induction coil is configured to pre-heat the elongated member as the elongated member is fed through the elongated conduit and passes through the induction coil.
- 122. The apparatus of claim 120 or 121, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
- 123. The apparatus of claim 122, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
- 124. The apparatus of any one of claim 119 to 123, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
- 125. The apparatus of any one of claims 119 to 124, wherein the elongated conduit has a cross-sectional shape that is circular.
- 126. The apparatus of any one of claims 119 to 125, wherein the powder particles have a mean diameter d50 of less than 65  $\mu\text{m}$ .

127. The apparatus of any one of claims 119 to 126, wherein the feeding mechanism is configured to feed the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
128. The apparatus of any one of claims 119 to 127, wherein the apparatus is configured for producing the powder particles at a rate of at least 1.7 kg/hour.
129. The apparatus of any one of claims 119 to 128, wherein the feeding mechanism is configured to feed the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
130. The apparatus of any one of claims 119 to 129, wherein the powder particles are spherical.
131. The apparatus of claim 129, wherein the powder particles are free of satellites.
132. The apparatus of claim 129, wherein the powder particles are free from splats and satellites.
133. The apparatus of any one of claims 119 to 132, wherein the apparatus is configured to generate the plasma with a power level of between 10 kW and 60 kW.
134. The apparatus of claim 133, wherein the plasma is generated from a gas comprising argon, helium, or a combination thereof.
135. The apparatus of claim 134, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
136. The apparatus of any one of claims 119 to 135, further comprising a cooling zone for receiving the molten droplets to solidify the molten droplets into the powder particles.
137. The apparatus of claim 136, wherein the atomization and cooling zones are contained in a chamber.
138. The apparatus of claim 136 or 137, wherein the cooling zone is configured to produce in-flight freezing of the molten droplets.
139. The apparatus of any one of claims 136 to 138, further comprising a powder collector configured to collect the powder particles from the cooling zone.
140. The apparatus of claim 139, wherein the powder collector resides below the cooling zone.

141. The apparatus of any one of claims 136 to 138, further comprising a powder collector configured to collect the powder particles from the cooling zone, wherein the powder particles travel from the cooling zone toward the powder collector along a direction other than a vertical direction.
142. The apparatus of claim 141, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
143. The apparatus of claim 142, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
144. The apparatus of any one of claims 136 to 138, comprising a powder collector to collect the powder particles from the cooling zone, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
145. The apparatus of claim 144, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
146. The apparatus of claim 145, wherein the conduit is configured to transport the powder particles along a direction other than a vertical direction.
147. The apparatus of any one of claims 139 to 146, wherein the powder collector includes a cyclone.
148. The apparatus of claim 147, wherein the cyclone is configured to separate the powder particles into two or more fractions according to size.
149. The apparatus of any one of claims 119 to 148, wherein the feed material comprises a pure metal, an alloy, a ceramic, or a composite.
150. The apparatus of any one of claims 119 to 149, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
151. The apparatus of any one of claims 119 to 149, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .

152. The apparatus of any one of claims 119 to 149, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
153. The apparatus of any one of claims 119 to 149, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .
154. The apparatus of any one of claims 119 to 153, wherein the feeding mechanism includes wheels for linearly feeding the elongated member toward the atomization zone.
155. The apparatus of any one of claims 119 to 154, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
156. A method for producing powder particles by atomization of a feed material in the form of an elongated member, the method comprising:
- a) progressively feeding the elongated member toward an atomization zone along a feed path;
  - b) pre-heating a forward end of the elongated member upstream an atomization nozzle in a direction of travel of the elongated member along the feed path in a pre-heating zone to bring the forward end of the elongated member at a selected temperature which is below the melting point of the elongated member, the pre-heating zone comprising an elongated conduit extending along the feed path for receiving the elongated member therein; and
  - c) generating an annular plasma jet in the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets, the pre-heating of the forward end of the elongated member at the selected temperature increasing a rate at which the feed material of the forward end of the elongated member is melted into the droplets by the annular plasma jet.
157. The method of claim 156, the pre-heating zone comprising a radiation structure extending along the feed path, and a heat source to heat the radiation structure which is configured in

turn to heat the forward end of the elongated member through radiation while the elongated member is travelling along the radiation structure.

158. The method of claim 156, the pre-heating zone comprising an induction coil, wherein the induction coil is configured for pre-heating the forward end of the elongated member as the elongated member is fed through the elongated conduit and passes through the induction coil.
159. The method of claim 157 or 158, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
160. The method of claim 159, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
161. The method of any one of claims 156 to 160, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
162. The method of any one of claims 156 to 161, wherein the elongated conduit has a cross-sectional shape that is circular.
163. The method of any one of claims 156 to 162, wherein the powder particles have a mean diameter  $d_{50}$  of less than 65  $\mu\text{m}$ .
164. The method of any one of claims 156 to 163, wherein the feeding mechanism feeds the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
165. The method of any one of claims 156 to 164, comprising producing the powder particles at a rate of at least 1.7 kg/hour.
166. The method of any one of claims 156 to 165, wherein the feeding mechanism feeds the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
167. The method of any one of claims 156 to 166, wherein the powder particles are spherical.
168. The method of claim 166, wherein the powder particles are free of satellites.
169. The method of claim 166, wherein the powder particles are free of splats and satellites.

170. The method of any one of claims 156 to 169, comprising generating the plasma with a powder level of between 10 kW and 60 kW.
171. The method of claim 170, comprising generating the plasma from a gas comprising argon, helium, or a combination thereof.
172. The method of claim 171, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
173. The method of any one of claims 156 to 172, comprising receiving the molten droplets in a cooling zone to solidify the molten droplets into the powder particles.
174. The method of claim 173, wherein the atomization and cooling zones are contained in a chamber.
175. The method of claim 173 or 174, wherein the cooling zone produces in-flight freezing of the molten droplets.
176. The method of any one of claims 173 to 175, comprising collecting the powder particles from the cooling zone into a powder collector.
177. The method of claim 176, wherein the powder collector resides below the cooling zone.
178. The method of any one of claims 173 to 177, comprising collecting the powder particles from the cooling zone into a powder collector by causing the powder particles to travel from the cooling zone toward the powder collector along a direction other than a vertical direction.
179. The method of claim 176, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
180. The method of claim 179, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
181. The method of any one of claims 173 to 177, comprising collecting the powder particles from the cooling zone into a powder collector, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.

182. The method of claim 181, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
183. The method of claim 182, comprising transporting the powder particles in the conduit along a direction other than a vertical direction.
184. The method of any one of claims 176 to 183, wherein the powder collector includes a cyclone.
185. The method of claim 184, wherein the cyclone separates the powder particles into two or more fractions according to size.
186. The method of any one of claims 156 to 185, wherein the feed material comprises a pure metal or an alloy.
187. The method of any one of claims 156 to 186, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
188. The method of any one of claims 156 to 186, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .
189. The method of any one of claims 156 to 186, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
190. The method of any one of claims 156 to 186, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .
191. The method of any one of claims 156 to 190, wherein the feeding mechanism feeds the elongated member toward the atomization zone with wheels.
192. The method of any one of claims 156 to 191, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
193. The method of any one of claims 156 to 192, wherein the elongated conduit comprises a cooling circuit to receive a coolant for cooling at least a portion of the elongated conduit.
194. An apparatus for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:

- a) a feeding mechanism configured to feed the elongated member toward an atomization zone along a feed path;
  - b) means to produce an annular plasma jet into the atomization zone, comprising a plasma containment chamber in which a body of plasma is generated and an atomization nozzle allowing the plasma to egress the containment chamber, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets; and
  - c) an injection probe for feeding the elongated member toward the nozzle, the injection probe defining an elongated conduit for receiving the elongated member, the elongated conduit extending along the feed path, the injection probe including cooling means, the cooling means including a passageway for a cooling fluid.
195. The apparatus of claim 194, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
196. The apparatus of claim 195, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
197. The apparatus of any one of claim 194 to 196, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
198. The apparatus of any one of claims 194 to 197, wherein the elongated conduit has a cross-sectional shape that is circular.
199. The apparatus of any one of claims 194 to 198, wherein the powder particles have a mean diameter  $d_{50}$  of less than 65  $\mu\text{m}$ .
200. The apparatus of any one of claims 194 to 199, wherein the feeding mechanism is configured to feed the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
201. The apparatus of any one of claims 194 to 200, wherein the apparatus is configured for producing the powder particles at a rate of at least 1.7 kg/hour.

202. The apparatus of any one of claims 194 to 201, wherein the feeding mechanism is configured to feed the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
203. The apparatus of any one of claims 194 to 202, wherein the powder particles are spherical.
204. The apparatus of claim 202, wherein the powder particles are free of satellites.
205. The apparatus of claim 202, wherein the powder particles are free of splats and satellites.
206. The apparatus of any one of claims 194 to 205, wherein the apparatus is configured to generate the plasma with a power level of between 10 kW and 60 kW.
207. The apparatus of claim 206, wherein the plasma is generated from a gas comprising argon, helium, or a combination thereof.
208. The apparatus of claim 207, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
209. The apparatus of any one of claims 194 to 208, further comprising a cooling zone for receiving the molten droplets to solidify the molten droplets into the powder particles.
210. The apparatus of claim 209, wherein the atomization and cooling zones are contained in a chamber.
211. The apparatus of any one of claims 209 to 210, wherein the cooling zone is configured to produce in-flight freezing of the molten droplets.
212. The apparatus of any one of claims 209 to 211, further comprising a powder collector configured to collect the powder particles from the cooling zone.
213. The apparatus of claim 212, wherein the powder collector resides below the cooling zone.
214. The apparatus of any one of claims 209 to 211, further comprising a powder collector configured to collect the powder particles from the cooling zone, wherein the powder particles travel from the cooling zone toward the powder collector along a direction other than a vertical direction.

215. The apparatus of claim 214, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
216. The apparatus of claim 215, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
217. The apparatus of any one of claims 209 to 211, further comprising a powder collector configured to collect the powder particles from the cooling zone, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
218. The apparatus of claim 217, wherein the apparatus is configured to transport the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
219. The apparatus of claim 218, wherein the conduit is configured to transport the powder particles along a direction other than a vertical direction.
220. The apparatus of any one of claims 212 to 219, wherein the powder collector includes a cyclone.
221. The apparatus of claim 220, wherein the cyclone is configured to separate the powder particles into two or more fractions according to size.
222. The apparatus of any one of claims 194 to 221, wherein the feed material comprises a pure metal, an alloy, a ceramic, or a composite.
223. The apparatus of any one of claims 194 to 222, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
224. The apparatus of any one of claims 194 to 222, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .
225. The apparatus of any one of claims 194 to 222, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
226. The apparatus of any one of claims 194 to 222, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .

227. The apparatus of any one of claims 194 to 226, wherein the feeding mechanism includes wheels for linearly feeding the elongated member toward the atomization zone.
228. The apparatus of any one of claims 194 to 227, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.
229. A method for producing powder particles by atomization of a feed material in the form of an elongated member, comprising:
- a) feeding the elongated member toward an atomization zone along a feed path;
  - b) receiving the elongated member in an injection probe for feeding the elongated member toward an atomization nozzle, the injection probe defining an elongated conduit for receiving the elongated member, the elongated conduit extending along the feed path, the injection probe including cooling means, the cooling means including a passageway for a cooling fluid; and
  - c) producing an annular plasma jet in the atomization zone by generating a body of plasma within a containment chamber and allowing the plasma to egress the containment chamber via the nozzle, wherein the feed material is directed toward the nozzle to define the annular plasma jet between a forward end of the elongated member and the nozzle causing progressive melting of the feed material at the forward end of the elongated member and breakdown into molten droplets.
230. The method of claim 229, wherein the elongated conduit has a longitudinal axis coaxial with the feed path.
231. The method of claim 230, wherein the longitudinal axis of the elongated conduit is parallel with the annular plasma jet.
232. The method of any one of claim 229 to 231, wherein the elongated conduit has a cross-sectional shape that corresponds to a cross-sectional shape of the feed material.
233. The method of any one of claims 229 to 232, wherein the elongated conduit has a cross-sectional shape that is circular.
234. The method of any one of claims 229 to 233, wherein the powder particles have a mean diameter  $d_{50}$  of less than 65  $\mu\text{m}$ .

235. The method of any one of claims 229 to 234, wherein the feeding mechanism feeds the elongated member at a feed rate of between 2.3 kg/hour and 15.5 kg/hour in the atomization zone.
236. The method of any one of claims 229 to 235, comprising producing the powder particles at a rate of at least 1.7 kg/hour.
237. The method of any one of claims 229 to 236, wherein the feeding mechanism feeds the elongated member at a linear speed of between 40 mm/s and 60 mm/s.
238. The method of any one of claims 229 to 237, wherein the powder particles are spherical.
239. The method of claim 237, wherein the powder particles are free of satellites.
240. The method of claim 237, wherein the powder particles are free of splats and satellites.
241. The method of any one of claims 229 to 240, comprising generating the plasma with a power level of between 10 kW and 60 kW.
242. The method of claim 241, comprising generating the plasma from a gas comprising argon, helium, or a combination thereof.
243. The method of claim 242, wherein the gas further comprises hydrogen, oxygen, nitrogen or a combination thereof.
244. The method of any one of claims 229 to 243, comprising receiving the molten droplets in a cooling zone to solidify the molten droplets into the powder particles.
245. The method of claim 244, wherein the atomization and cooling zones are contained in a chamber.
246. The method of any one of claims 244 or 245, wherein the cooling zone produces in-flight freezing of the molten droplets.
247. The method of any one of claims 244 to 246, further comprising collecting the powder particles from the cooling zone into a powder collector.
248. The method of claim 247, wherein the powder collector resides below the cooling zone.

249. The method of any one of claims 244 to 246, further comprising collecting the powder particles from the cooling zone into a powder collector by causing the powder particles to travel from the cooling zone toward the powder collector along a direction other than a vertical direction.
250. The method of claim 249, wherein the powder collector is in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
251. The method of claim 250, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
252. The method of any one of claims 244 to 246, further comprising collecting the powder particles from the cooling zone into a powder collector, the powder collector being in fluid communication with the cooling zone by a conduit through which the powder particles travel from the cooling zone toward the powder collector.
253. The method of claim 252, comprising transporting the powder particles through the conduit by creating a flow of a gaseous medium through the conduit.
254. The method of claim 253, comprising transporting the powder particles in the conduit along a direction other than a vertical direction.
255. The method of any one of claims 247 to 254, wherein the powder collector includes a cyclone.
256. The method of claim 255, wherein the cyclone separates the powder particles into two or more fractions according to size.
257. The method of any one of claims 229 to 256, wherein the feed material comprises a pure metal, an alloy, a ceramic, or a composite.
258. The method of any one of claims 229 to 257, wherein the powder particles have a particle diameter less than 250  $\mu\text{m}$ .
259. The method of any one of claims 229 to 257, wherein the powder particles have particle size diameter of between 1 and 1000  $\mu\text{m}$ .

260. The method of any one of claims 229 to 257, wherein the powder particles have a particle diameter of less than 10  $\mu\text{m}$ .
261. The method of any one of claims 229 to 257, wherein the powder particles have a particle diameter of less than 1  $\mu\text{m}$ .
262. The method of any one of claims 229 to 261, wherein the feeding mechanism feeds the elongated member toward the atomization zone with wheels.
263. The method of any one of claims 229 to 262, wherein the elongated member is selected from the group consisting of a wire, a rod and a filled tube.

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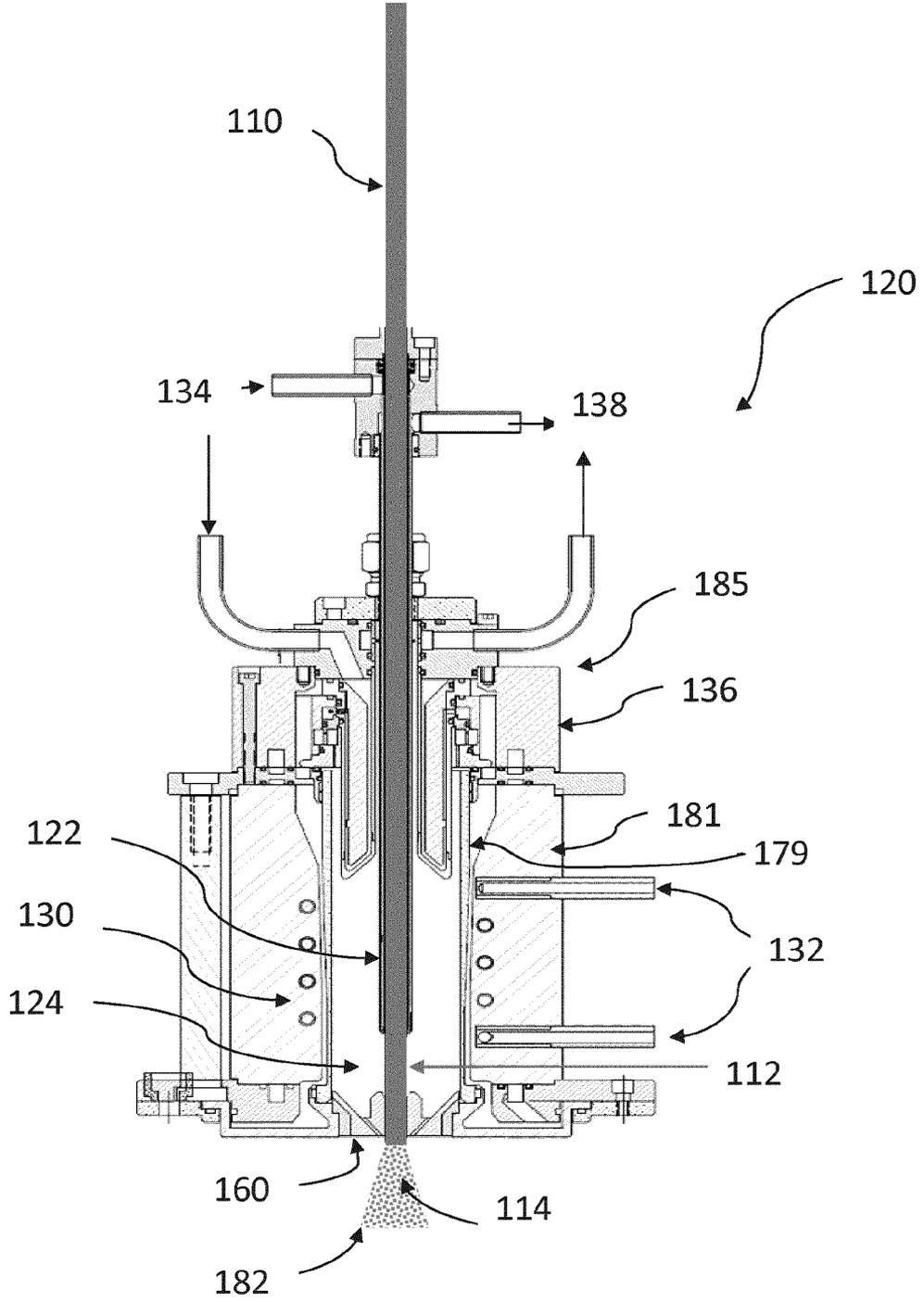


Figure 1

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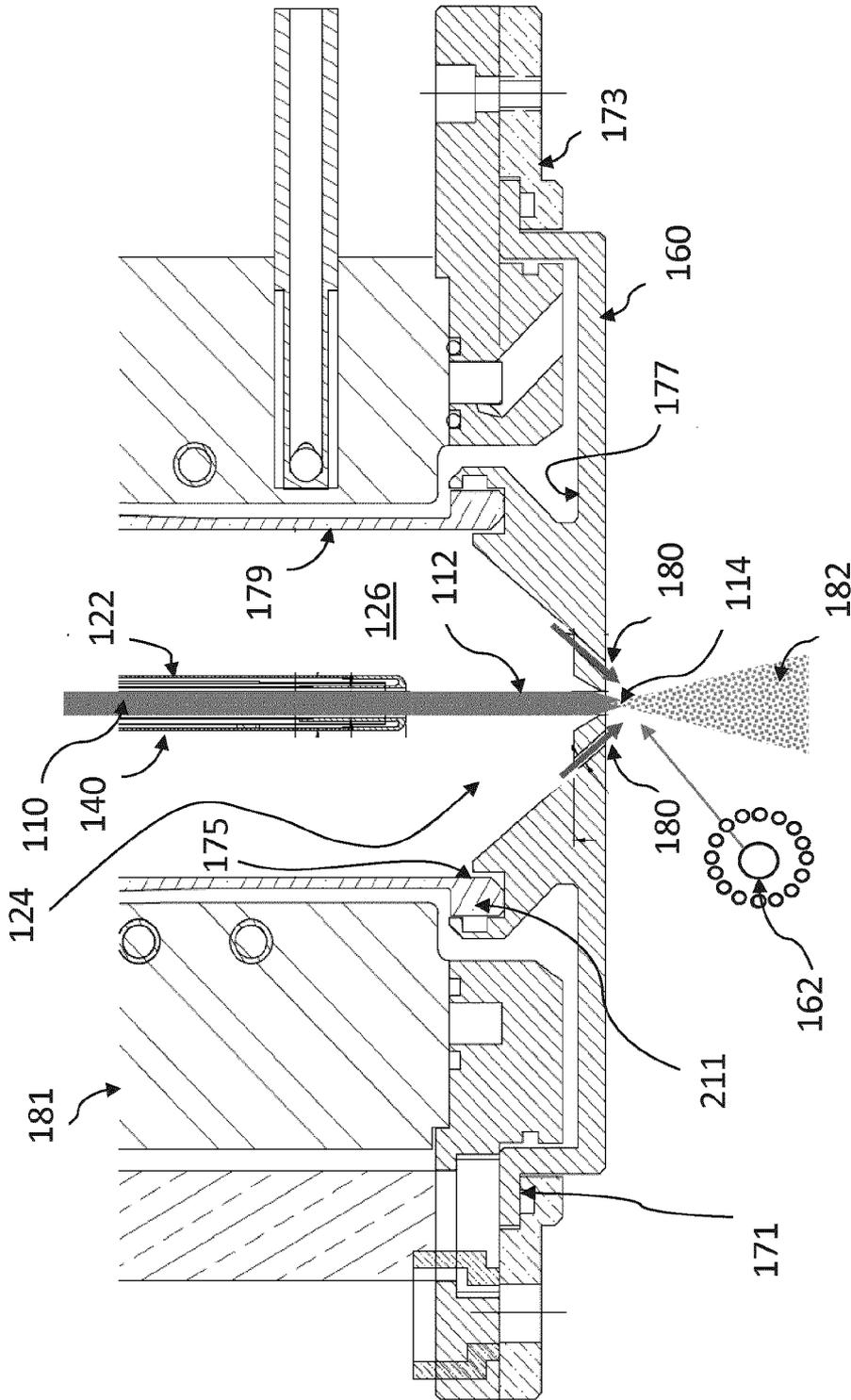


Figure 2a



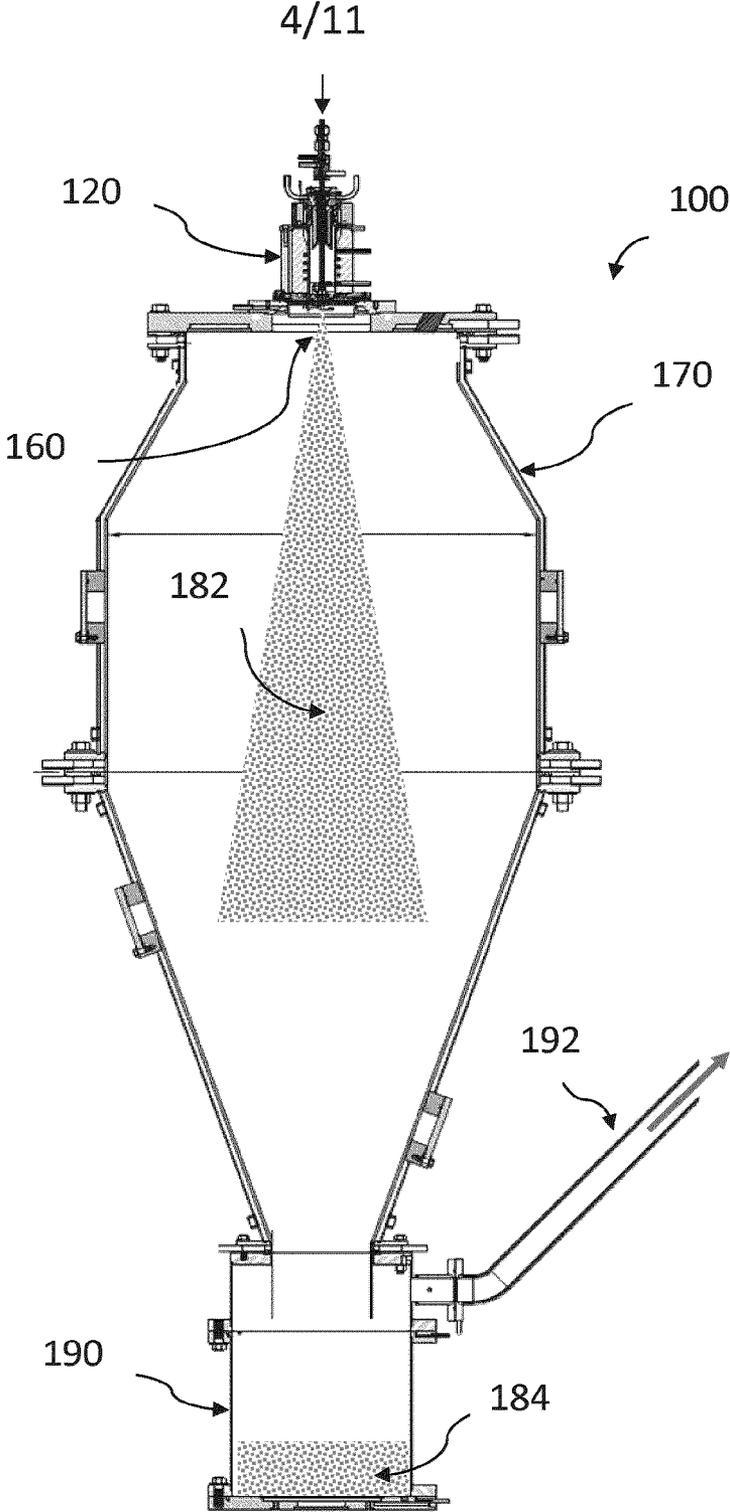


Figure 3

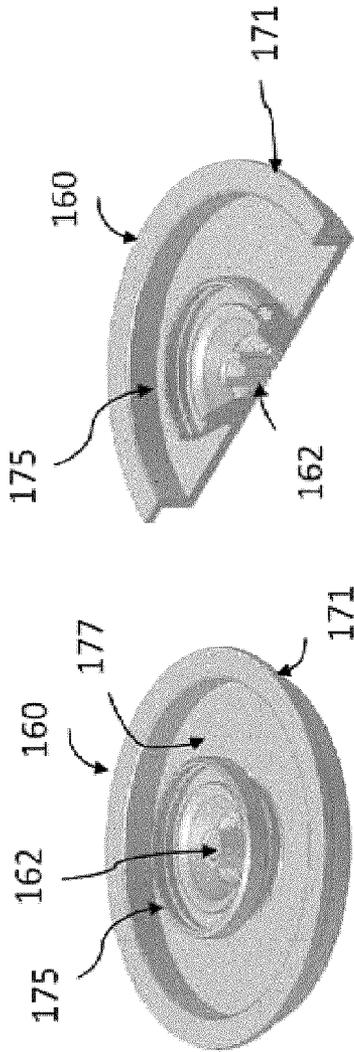


Figure 4b

Figure 4a

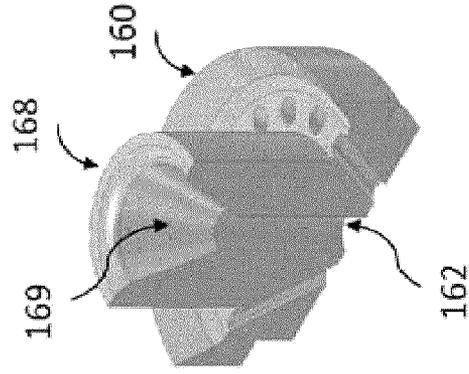


Figure 4e

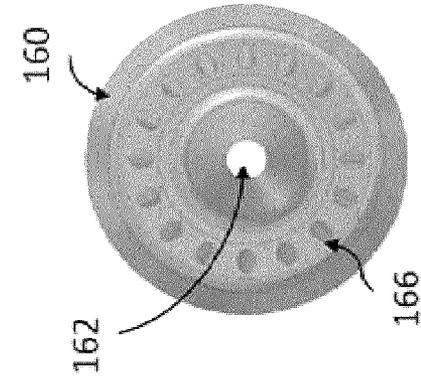


Figure 4d

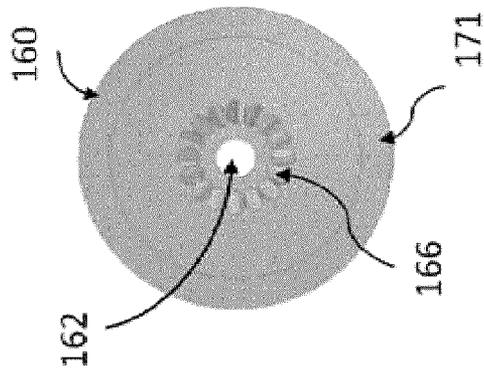


Figure 4c

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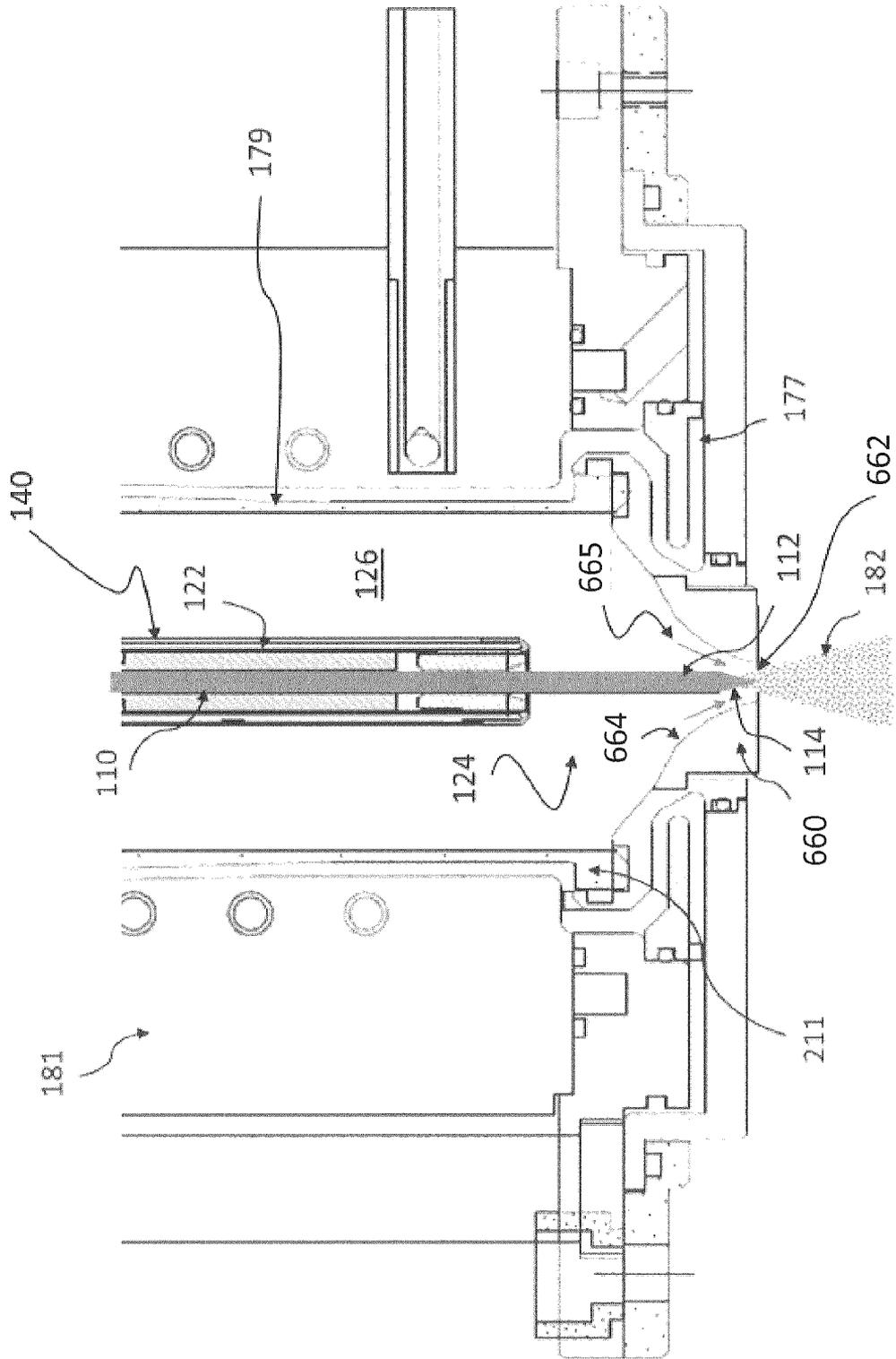


Figure 5

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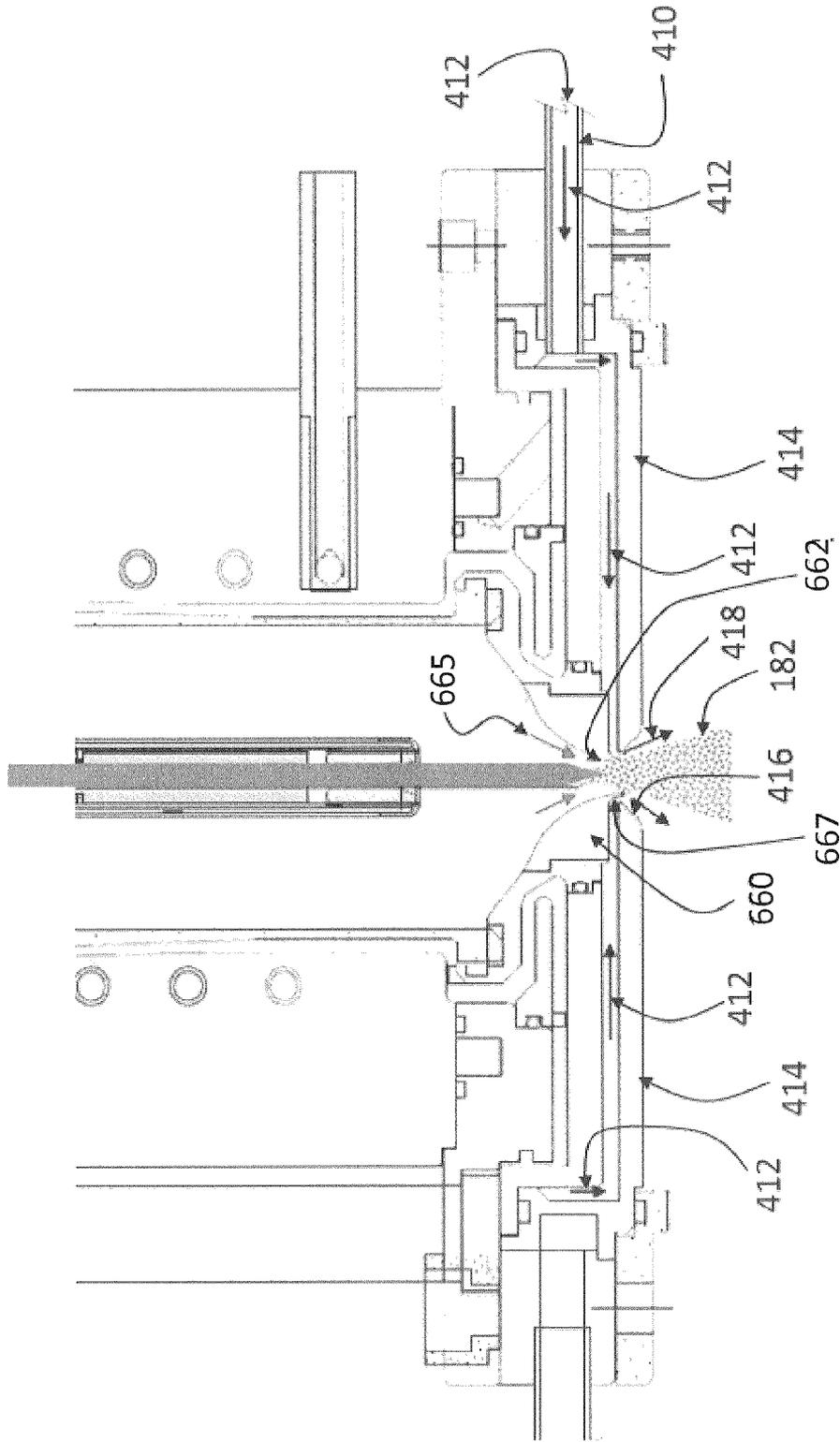


Figure 6

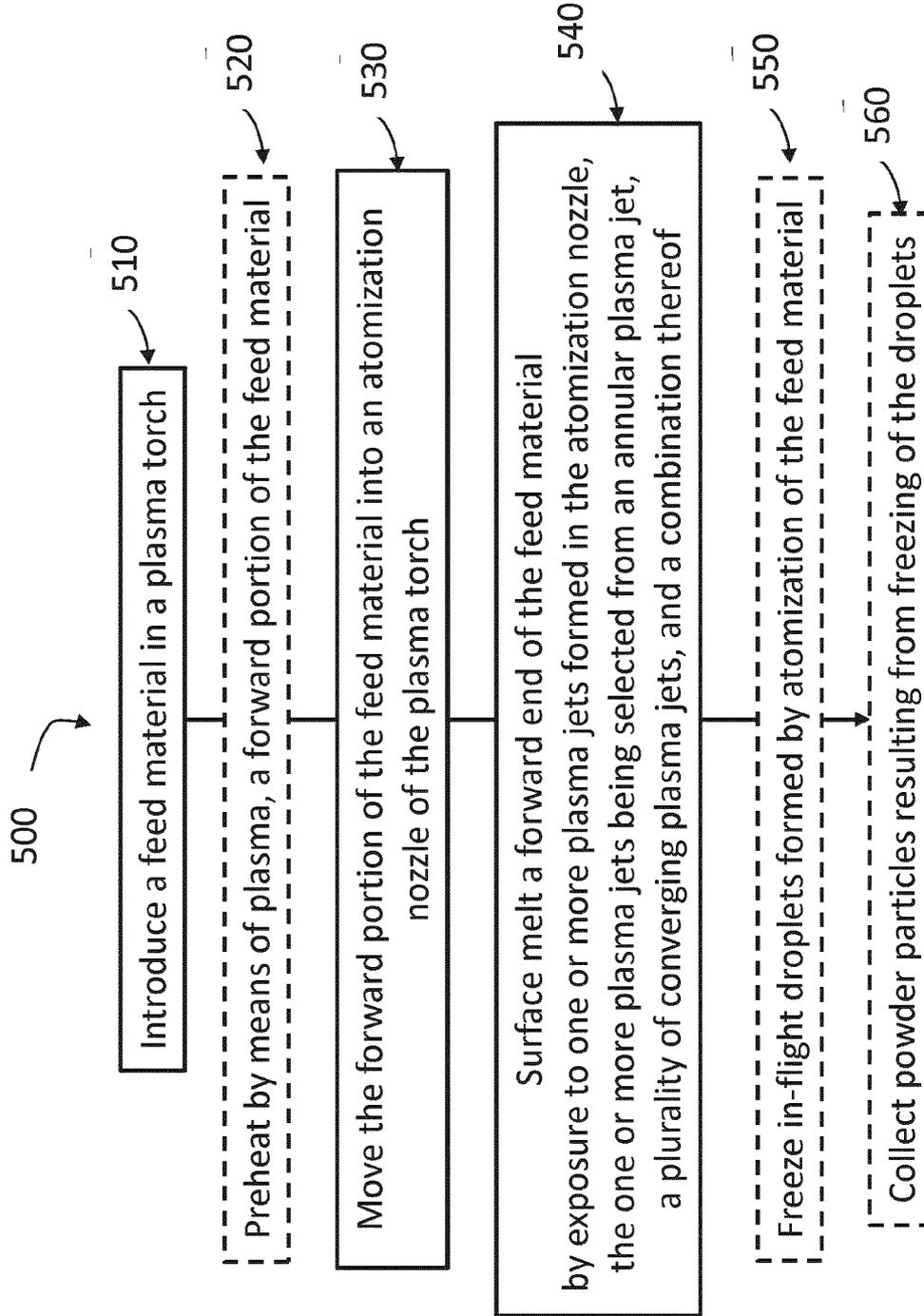


Figure 7

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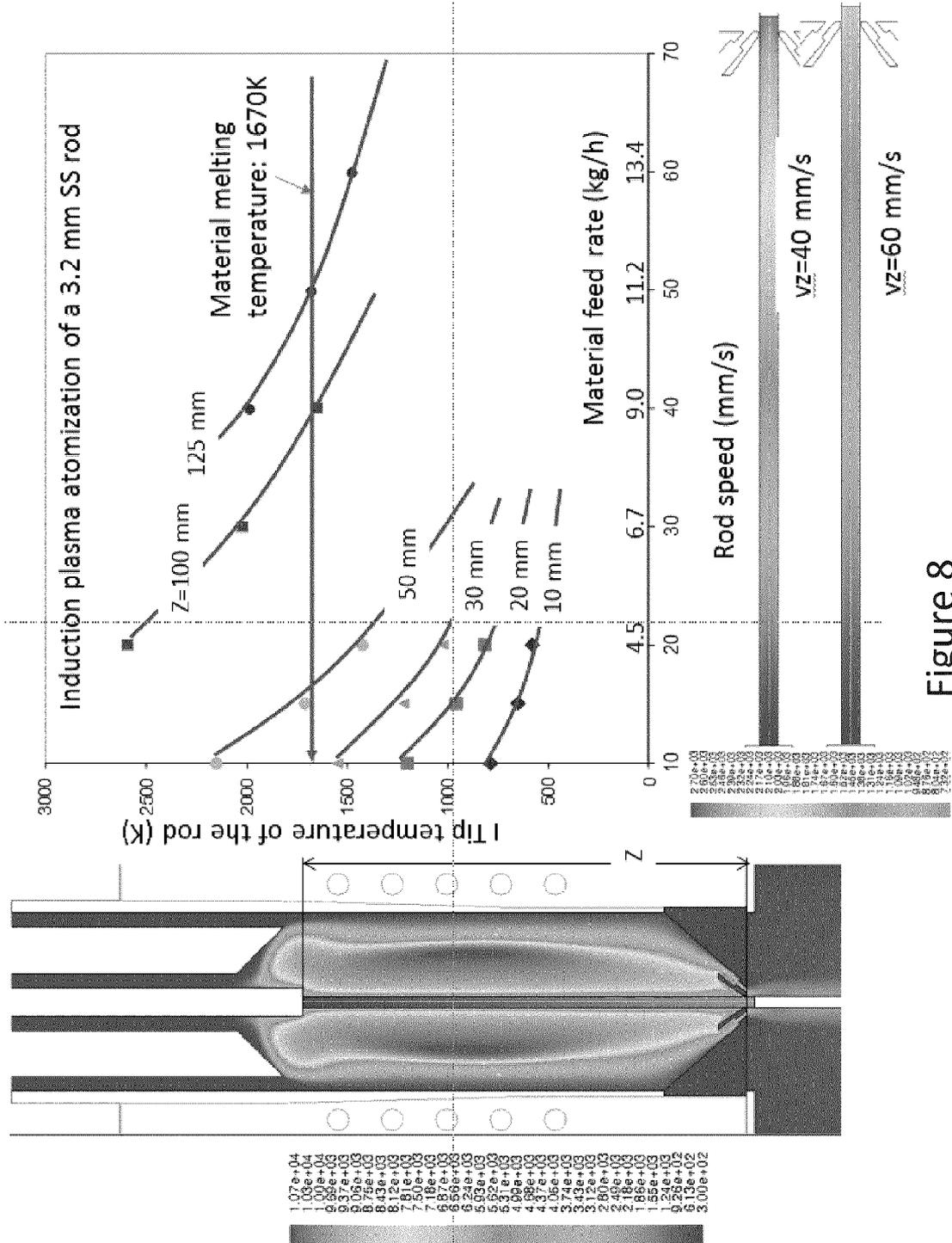


Figure 8

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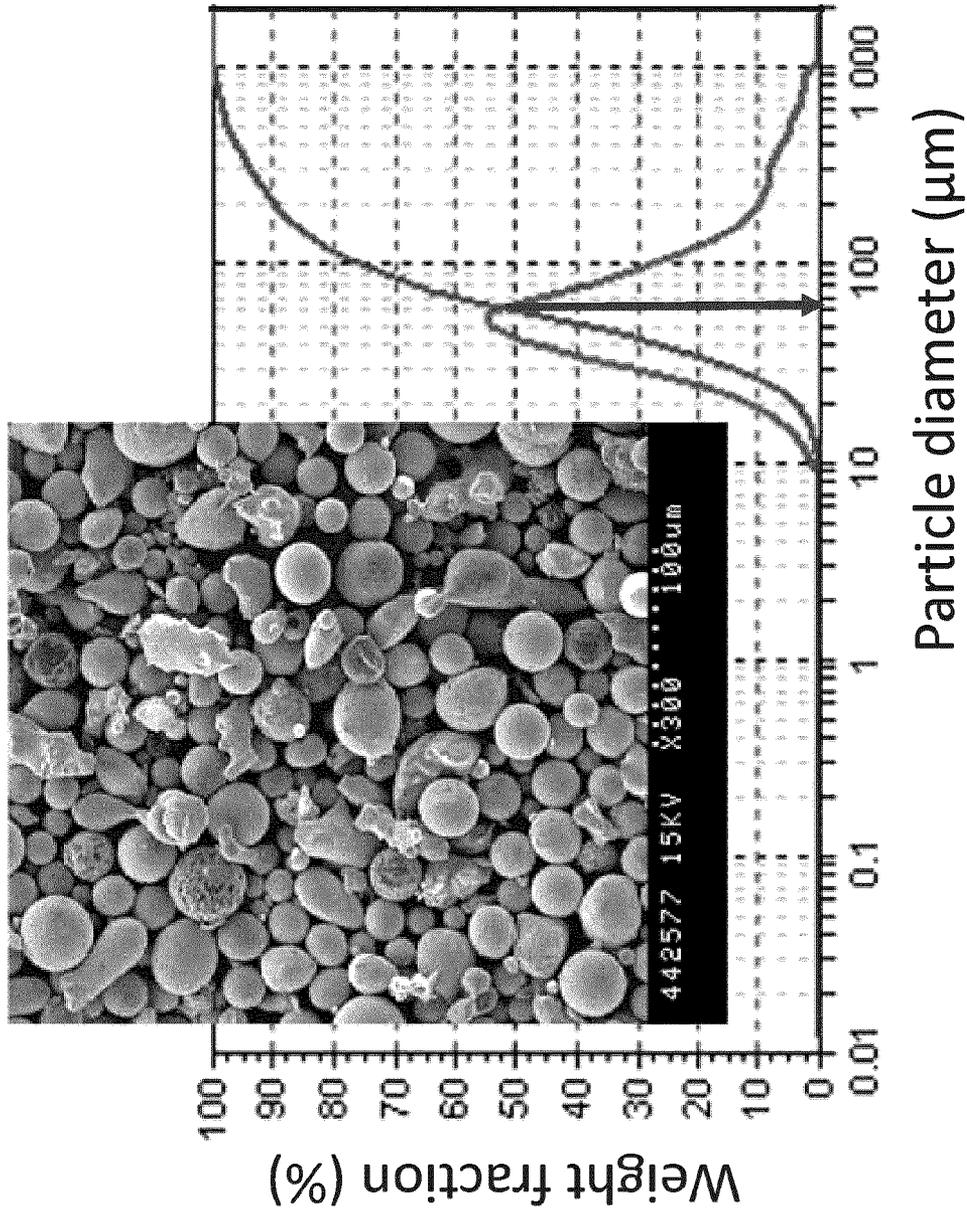
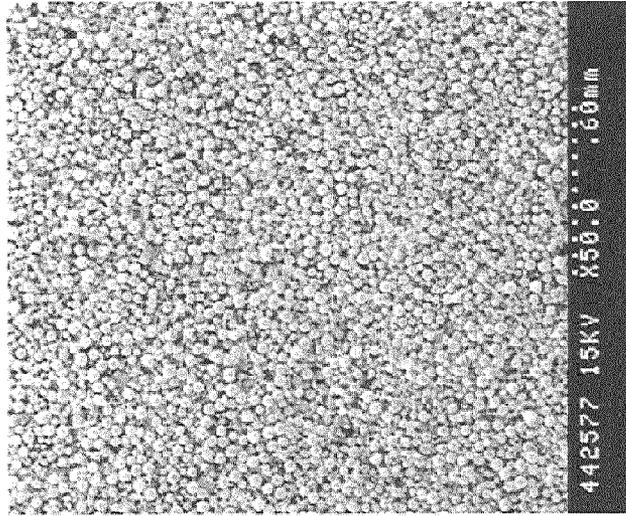


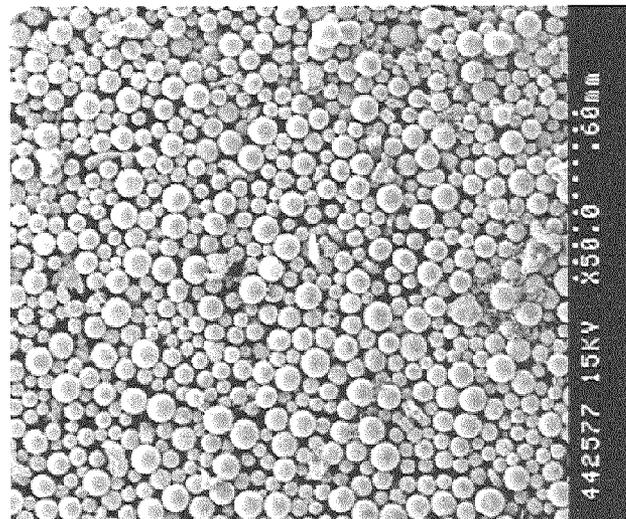
Figure 9

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-45  $\mu\text{m}$



-105 + 45  $\mu\text{m}$



-150 + 105  $\mu\text{m}$

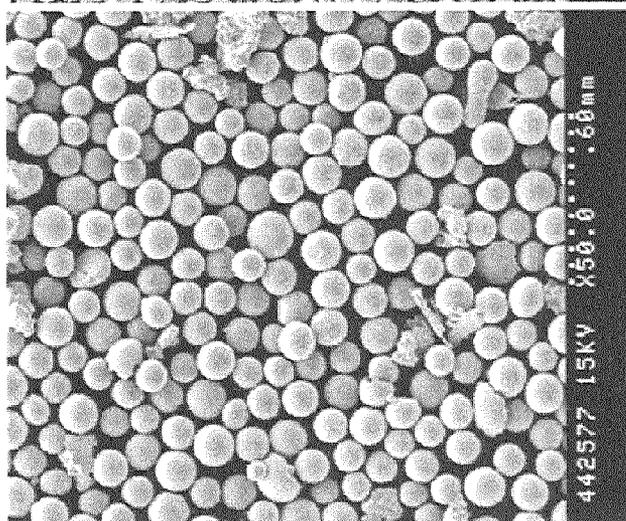


Figure 10

