and heat treatment sequence is described in United States Patent No. 6,416,564, which is hereby incorporated by reference into this specification.

[0037] Notwithstanding, powder metallurgy techniques may be used to produce premium quality alloy products such as large diameter nickel-base superalloy ingots. Spray forming is one powder metallurgy technique for producing large diameter superalloy ingots. During spray forming, a stream of molten alloy is atomized to form a spray of fine molten alloy droplets or particles. The molten particles are then directed to a collector where they coalesce and solidify into a coherent, near-fully-dense preform. In various applications, controlled movement of the collector and atomizer, along with control of the molten metal transport process, allows high quality large preforms to be produced. The spray forming process is capable of producing fine-grained homogeneous microstructures with equiaxed grains and more than 98 percent theoretical density for a wide range of alloys. However, conventional spray forming generally employs fluid impingement atomization techniques, which present a number of drawbacks.

[0038] In fluid impingement atomization techniques, either a gas or a liquid is impinged on a stream of a molten metallic material. Impingement using liquid or gases may introduce contaminants into the atomized material. Given that fluid impingement does not occur in a vacuum environment, even impingement techniques using inert gases can introduce significant levels of impurities into the atomized material. Various non-fluid impingement atomization techniques that may be conducted in a vacuum environment have been developed. These techniques include, for example, the atomization techniques described in U.S. Patent No. 6,772,961 (referred to is this specification as "US-6,722,961"), which is hereby incorporated by reference into this specification.

[0039] US-6,722,961 describes techniques wherein molten alloy droplets or a molten alloy stream produced by a melting device coupled with a controlled dispensing device are rapidly electrostatically charged by applying a high voltage to the droplets at a high rise rate. The electrostatic forces set up within the charged droplets

cause the droplets to break up or atomize into smaller secondary particles. In one technique described in US-6,722,961, primary molten droplets produced by the nozzle of a dispensing device are treated by an electric field from a ring-shaped electrode adjacent to and downstream of the nozzle. Electrostatic forces developed within the primary droplets exceed the surface tension forces of the particles and result in formation of smaller secondary particles. Additional ring-shaped field-producing electrodes may be provided downstream to treat the secondary particles in the same way, producing yet smaller molten particles.

[0040] Electron beam atomization is another non-fluid impingement technique for atomizing molten material that is conducted in a vacuum. In general, the technique involves using an electron beam to inject a charge into a region of a molten alloy stream and/or a series of molten alloy droplets. Once the region or droplet accumulates sufficient charge exceeding the Rayleigh limit, the region or droplet becomes unstable and is disrupted into fine particles (*i.e.*, atomizes). An electron beam atomization technique is described in U.S. Patent Nos. 6,772,961; 7,578,960; 7,803,212; and 7,803,211; which are hereby incorporated by reference into this specification.

[0041] US-6,722,961 also discloses techniques using electrostatic and/or electromagnetic fields to control the acceleration, speed, and/or direction of molten alloy particles formed by atomization in the process of producing spray formed preforms or powders. As described in US-6,722,961, such techniques provide substantial downstream control of atomized molten material and can reduce overspray and other material wastage, improve quality, and enhance the density of solid preforms made by spray forming techniques.

[0042] Methods of collecting atomized molten materials as unitary preforms include spray forming and nucleated casting. With respect to nucleated casting, specific reference is drawn to U.S. Patent Nos. 5,381,847; 6,264,717; and 6,496,529, which are hereby incorporated by reference into this specification. In general, nucleated casting involves atomizing a molten alloy stream and then directing

longitudinal axis of the cylinder may be oriented in the general direction of travel of molten alloy material through the atomizing assembly. The minimum length of the cylinder (along the longitudinal axis) required for complete atomization will depend on the velocity of the molten alloy material traveling through the atomization assembly and the energy and intensity of the electron field within the assembly. Non-cylindrical electron field shapes also may be used, such as, for example, fields having a transverse cross-section (transverse to the molten alloy material's general direction of travel through the atomizing assembly) that is rectangular, triangular, or some other polygonal or otherwise bounded shape. More generally, fields of any combination of energy, intensity, and three-dimensional shape capable of suitably atomizing molten alloy material may be used. Various non-limiting embodiments of an electron beam atomizing assembly for an apparatus constructed according to the present disclosure are discussed below.

[0065] In various non-limiting embodiments, an atomizing assembly may comprise a heated tungsten filament electron source. Electrons thermo-ionically emitted from a heated tungsten filament may be manipulated using electrostatic and/or electromagnetic fields to form a rectangular-shaped beam of electrons. The rectangular-shaped beam may be projected into an atomizing chamber as a generally block-shaped three-dimensional field across the path of travel of molten alloy material through the atomizing assembly. Figure 2 schematically illustrates an atomizing assembly 210 including a tungsten filament 212 that is heated by flow of current from a power supply 214. The heated filament 212 produces free electrons 216. The electrons 216 may be produced, for example, by a thermo-ionic electron beam emitter.

[0066] The electrons 216 are shaped by an electrostatic field produced by plates 220 to form a three-dimensional electron beam 222 having a generally rectangular-shaped cross-section. The electron beam 222 is projected into the interior of the atomizing assembly 210 to produce a generally block-shaped three-dimensional electron field 226. Molten alloy droplets 230 dispensed an the upstream melting assembly 232 travel through the electron field 226 and are atomized to smaller particles

cooling the molten alloy particles to a temperature that is no greater than a solidus temperature of the molten alloy particles so that the molten alloy particles solidify while accelerating;

impacting the solid alloy particles onto a substrate, wherein the impacting particles deform and metallurgically bond to the substrate to produce a solid alloy preform.

20. A system comprising:

a melting assembly configured to produce at least one of a stream of molten alloy and a series of droplets of molten alloy;

producing at least one of a stream of molten alloy and a series of droplets of molten alloy;

an atomizing assembly configured to produce electrically-charged particles of the molten alloy by impinging electrons on at least one of the stream of molten alloy and the series of droplets of molten alloy to atomize the molten alloy;

a field producing assembly configured to produce an electrostatic field to accelerate the electrically-charged molten alloy particles;

a thermal control zone configured to cool the molten alloy particles to a temperature that is no greater than a solidus temperature of the molten alloy particles so that the molten alloy particles solidify while accelerating; and

a substrate comprising an alloy that is the same alloy as that forming the alloy particles, wherein the electrostatic field is configured to accelerate the alloy particles so that solid alloy particles impact the substrate, deform, and metallurgically bond to the substrate to produce a solid alloy preform.

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a thermal control zone configured to cool the molten alloy particles to a temperature that is no greater than a solidus temperature of the molten alloy particles so that the molten alloy particles solidify while accelerating; and

a substrate comprising an alloy that is the same alloy as that forming the alloy particles, wherein the electrostatic field is configured to accelerate the alloy particles so that solid alloy particles impact the substrate, deform, and metallurgically bond to the substrate to produce a solid alloy preform.