

MECHANICALLY ALLOYED POWDER FEEDSTOCK

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] This application claims benefit to U.S. Provisional Patent Application Ser. No. 62/840,607 entitled “MECHANICALLY ALLOYED POWDER FEEDSTOCK,” filed on April 30, 2019, the contents of which is hereby incorporated by reference in its entirety.

BACKGROUND

Field

[0002] The present disclosure is generally directed in some embodiments towards producing metal spherical or spheroidal powder products that include properties achieved by mechanical alloying.

Description of the Related Art

[0003] Metal powders are being used industrially for certain applications. Recently there is an increased interest in metal powders for use in additive manufacturing. Metal alloy powders are generally manufactured by various atomizing techniques – water atomizing, gas atomizing, or thermochemical methods. The morphology of powders produced can depend on the method of manufacture of the powders. Further, different morphologies can be suitable for different consolidation methods or uses of powders. For example, additive manufacturing (AM), especially laser-based AM systems such as powder bed fusion, may benefit from spherical powders due to their excellent flowability, spreadability, and packing density.

SUMMARY

[0004] Disclosed herein are embodiments of a method for manufacturing a spheroidized powder from a mechanically-alloyed feedstock, the method comprising preparing a mechanically-alloyed powder feedstock by mechanically milling at least five elemental powders to mechanically alloy the at least five elemental powders, introducing the mechanically-alloyed powder feedstock into a microwave plasma torch, a plasma plume of

the microwave plasma torch, and/or an exhaust of the microwave plasma torch, and at least partially melting and spheroidizing the mechanically-alloyed powder feedstock within the microwave plasma torch, the plasma plume of the microwave plasma torch, and/or the exhaust of the microwave plasma torch to form spheroidized powder.

[0005] Also disclosed herein are embodiments of a method for manufacturing a spheroidized powder from a mechanically alloyed feedstock, the method comprising preparing a mechanically-alloyed powder feedstock by mechanically milling one or more precursors to form a high entropy alloy, introducing the mechanically-alloyed powder feedstock into a microwave plasma torch, a plasma plume of the microwave plasma torch, and/or an exhaust of the microwave plasma torch, and at least partially melting and spheroidizing the mechanically-alloyed powder feedstock within the microwave plasma torch, the plasma plume of the microwave plasma torch, and/or the exhaust of the microwave plasma torch to form spheroidized powder.

[0006] Further disclosed herein are embodiments of a method for manufacturing a spheroidized powder from a mechanically-alloyed feedstock, the method comprising introducing a mechanically-alloyed powder feedstock into a microwave plasma torch, a plasma plume of the microwave plasma torch, and/or an exhaust of the microwave plasma torch, wherein the mechanically-alloyed powder feedstock is prepared by mechanically milling at least five elemental powders to mechanically alloy the at least five elemental powders, and melting and spheroidizing the mechanically-alloyed powder feedstock within the microwave plasma torch, the plasma plume of the microwave plasma torch, and/or the exhaust of the microwave plasma torch to form spheroidized powder.

[0007] In some embodiments, the spheroidized powder can be melted and spheroidized for use in metal injection molding processes. In some embodiments, the spheroidized powder can be melted and spheroidized for use in hot isostatic processing. In some embodiments, the spheroidized powder can be melted and spheroidized for use in additive manufacturing.

[0008] In some embodiments, the mechanically-alloyed powder feedstock can be mechanically milled by ball milling. In some embodiments, the melting the mechanically-alloyed powder feedstock can be performed in less than 1 second. In some embodiments, the

melting the mechanically-alloyed powder feedstock can be performed in less than 500 milliseconds.

[0009] In some embodiments, the mechanically-alloyed powder feedstock can comprise TiZrNbTaFe. In some embodiments, the mechanically-alloyed powder feedstock can comprise AlFeVSi. In some embodiments, the mechanically-alloyed powder feedstock can comprise FeCoNiCrTi. In some embodiments, the mechanically-alloyed powder feedstock can comprise FeCoNiCrAl. In some embodiments, the mechanically-alloyed powder feedstock can comprise FeCoNiCrCu. In some embodiments, the mechanically-alloyed powder feedstock can have a microstructure, and wherein the spheroidized powder maintains the microstructure.

[0010] A spheroidized powder formed from the method of embodiments of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] **Figure 1** illustrates a transition of an arbitrary feedstock powder with time.

[0012] **Figure 2** illustrates an XRD spectra of powders pre and post microwave plasma processing.

[0013] **Figure 3** illustrates an example embodiment of a method of producing powders according to the present disclosure.

[0014] **Figure 4** illustrates an embodiment of a microwave plasma torch that can be used in the production of powders, according to embodiments of the present disclosure.

[0015] **Figures 5A-5B** illustrate embodiments of a microwave plasma torch that can be used in the production of powders, according to a side feeding hopper embodiment of the present disclosure.

[0016] **Figure 6** illustrates an embodiment of a mechanical alloying process.

DETAILED DESCRIPTION

[0017] Disclosed herein are embodiments of methods, devices, and assemblies for utilizing mechanically alloyed materials (such as powders) as feedstock, in particular for microwave plasma processing and powders and products produced from the same. It has been

extremely difficult to prepare such powders from the mechanically alloyed feedstock, an unexpected properties have been achieved based on embodiments of this disclosure.

[0018] In some embodiments, materials can be milled together to form a desired composition of particles of a powder, thereby creating mechanically milled alloys. Other methods of alloying can be used as well, and the disclosure is not limited to mechanical milling.

[0019] In some embodiments the mechanically milled alloys can be high entropy alloys (HEAs) or can be complex concentrated alloys (CCAs), or can be modified alloys from existing alloys. HEAs are alloys that primarily contain 5 or more elements in equi-atomic or non equi-atomic percent. The powder, or other components, can then be used as a feedstock (such as a powder feedstock) for a microwave plasma process to form a final spheroidized powder, which can then be used in different processes, such as additive manufacturing processes.

[0020] There is a need to develop novel alloys, such as high entropy alloys (HEA) that yield superior properties when processed with additive manufacturing methods.

[0021] Further, with the advent of additive manufacturing (AM), there is ever increasing need to develop novel alloys that could be processed with AM and could push the envelope of the properties obtained by conventional or existing alloys.

[0022] In some embodiments, HEAs may be alloys that are formed by mixing equal or relatively large proportions of a relatively large number of elements. In some embodiments, the number of elements within a HEA may be 3 or more, 4 or more, 5 or more, or 6 or more, 7 or more, 8 or more. In some embodiments, the relative proportions by atomic percentage may be equal or close to equal. In some embodiments HEAs may be alloys with high entropy of mixing, e.g., greater than 1.67R (or greater than about 1.67R), such as described in *JOM*, by Z. Li and D. Raabe, 2017, DOES: 10.1007/s11837-017-2540-2, hereby incorporated by reference.

[0023] HEAs may have advantageous properties, or combinations of properties, such as high elevated temperature strength, high temperature oxidation resistance, high corrosion resistance and high strength to weight ratio as compared with conventional alloys in use. Due to limited solubility of elements in each other, most compositions of HEAs,

especially non-equi atomic HEAs, are difficult or impossible to manufacture by traditional methods such as arc melting and induction melting. Further, the vast differences in the melting points of the alloying elements in HEAs limit their processing by conventional methods.

[0024] Such elements could be alloyed in solid state by mechanical alloying techniques, such as where the elemental powders, pre-alloyed powders, or master alloy powders are ball milled until a homogeneous alloy is formed. In ball milling, the alloys are mechanically forced to combine into an alloy. This alloying can then be homogenized with milling time. The homogenization of the alloy is often monitored by x-ray diffraction (XRD), where the initial individual elemental peaks of the alloying elements gradually disappear, and new peaks of alloyed phase or phases appear.

[0025] With proper ball mill parameters, such as, for example, ball-to-metal ratio, rotation speed, and/or ball size, different processes can occur during the alloying. For example, the resulting powder may have undergone agglomeration, mechanical alloying, mixing, blending, or milling. Some or all of which may occur during the process.

[0026] The resulting powder, however, is of irregular and flake like morphology limiting further processing/consolidation techniques such as spark plasma sintering. Embodiments of this disclosure describe manufacturing of spherical HEA powders processed by mechanical alloying and treated with microwave plasma spheroidization. Spherical powders then could be used for a range of industrial powder consolidation processes such as Additive Manufacturing, Metal Injection Molding, Hot Isostatic Processing and Powder Forging

[0027] Mechanical alloying is a solid-state powder metallurgy process where elemental or pre-alloyed powder particles are milled with a high energy ball mill. Powder particles during this process are subjected to repeated cold welding, fracturing and re-welding. Transfer of mechanical energy to the powder particles introduces strain into powder by generating dislocations, which act as fast diffusion paths. **Figure 6** illustrates an example of such a method. As shown, the elemental powders (left) can be mechanically milled (middle) to produce a feedstock (right).

[0028] Further, diffusion distances are reduced due to grain refinement. Thus, an alloy can be manufactured by this process with different phases and different microstructure than that of the base powders. The actual milling time can vary depending on the feed material and alloy. For example, greater than 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 hours (or about 1, about 2, about 3, about 4, about 5, about 6, about 7, about 8, about 9, or about 10 hours). In some embodiments, the milling can last less than 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 hours (or about 1, about 2, about 3, about 4, about 5, about 6, about 7, about 8, about 9, or about 10 hours). In some embodiments, the milling can continue until a partial or complete homogenization is attained, such as by monitoring XRD patterns and following the disappearance of the individual elemental peaks.

[0029] Advantageously, mechanical alloying may increase the homogenization of the particles because the elements are mechanically forced into each other reducing the diffusion paths between the alloying elements. This homogenization also can be enhanced with increased milling time.

[0030] Microwave assisted plasma technology can provide for a continuous and sustainable plasma plume with the temperatures reaching on the order of 6000K. By adjusting the plasma plume characteristics, such as plume length and plume density, it is possible to spheroidize and homogenize mechanically alloyed highly irregular or flaky HEA or mechanically-alloyed powders. Further, by adjusting where the feedstock enters the plasma plume, plasma afterglow, or plasma exhaust of the microwave plasma torch may be used to adjust the temperature the feedstock is subjected to.

[0031] Irregular or flaky powders may limit the processing method to spark plasma sintering and thus it can be advantageous to spheroidize them for more expanded use across the powder consolidation methods. For example, HIP may benefit from a tap density of the powders to be more than ~60% of the theoretical density of the alloy in order to achieve full density after HIP. Other powder processing methods may benefit from high flowability and/or spreadability of the powder, such as during additive manufacturing. Irregular and flaky powders have poor flow properties making them difficult or impossible to process. Thus, microwave plasma processing may transform irregular and flaky powders into spherical powder which may be used for various manufacturing processes.

[0032] Due to less residence time in a microwave plasma process, estimated to be up to few hundred milliseconds, at high temperatures, the powders are partially melted, which will increase the homogenization of the mechanically alloyed powders.

[0033] Accelerated processing through microwave plasma processing of mechanically alloyed particles with heat increases diffusion of the alloying elements into the bulk of the particle, hence increasing homogeneity. After plasma processing, the spherical HEA powders then can be processed with various industrial powder consolidation methods such as, but not limited to, additive manufacturing (AM), metal injection molding (MIM), powder forging and hot isostatic pressing (HIP) bringing HEA to mainstream industrial processing.

[0034] After feedstock is created from mechanical alloying, the feedstock includes a certain material composition. The set of process parameters for microwave plasma processing may be selected based on the material composition. The process parameters may be tailored to allow for varying homogeneous alloying and/or spheroidization.

[0035] This set of process parameters may include microwave power, plasma gas flows, gas types, plasma plume length, plasma plume diameter, plasma jet velocity, exhaust chamber pressure, quench gases, exhaust gas velocity, feedstock velocity vis-à-vis plasma jet velocity, feed gas flow, and feedstock feed-rates, or a combination thereof. This set of process parameters may further include the portion of the plasma, plasma plume, and/or plasma exhaust the feedstock enters into. For example, the feedstock may be fed in an area of the plasma exhaust that is cooler if a cooler temperature is desired.

[0036] As disclosed herein, melting can include fully melting, partially melting, or melting a surface of a particular feedstock.

Feedstock

[0037] The feedstock for the microwave plasma processing can be developed by mechanical alloying. Advantageously, mechanical alloying may develop alloys which are otherwise difficult or impossible to manufacture by other alloying methods such as arc melting and induction melting. The unique alloys that can be formed with mechanical

alloying include HEAs which, on laboratory scale have demonstrated unique properties over conventional alloys.

[0038] In mechanical alloying, the feedstock can be milled mechanically to achieve homogenization, which can be measured/monitored using XRD techniques. As the time for mechanical alloying increases, different peaks appear on the XRD spectra indicating the formation of alloyed phases. The milling is continued until a stable XRD spectra is obtained, the stable XRD spectra being a spectra which does not change with increased milling time, thereby indicating a chemically stable alloy.

[0039] The resultant powder is highly irregular and flaky due to intensive mechanical milling. For example, an irregular powder can be particles having an irregular or angular morphology, such as in water atomized powders. On the other hand, flaky powder may have relatively large aspect ratios and are thin, having very low apparent density and packing density, which makes them difficult to flow, spread, and process. Both irregular and flaky powders are unsuitable for industrial powder consolidation methods.

[0040] However, the resultant powder from mechanical milling has been demonstrated to be an ideal feedstock for microwave plasma processing. Microwave plasma processing can spheroidize the machined powder which is in irregular or flaky form. **Figure 1** depicts the transition of an example feedstock powder with time during the milling process. Illustrated are XRD scans performed on powder that has been mechanically milled for 1 hour, 4 hours, 8 hours, and 17 hours. As illustrated, as time increases, several peaks in the XRD scans attenuate or substantially disappear. Further, new peaks are enhanced or appear indicating the formation or increase of alloyed phases.

[0041] HEAs due to their extraordinary properties are of interest to several applications. For example, for medical implants TiZrNbTaFe HEAs have shown much improved corrosion resistance compared to Ti-6Al-4V alloys currently being used. AlFeVSi alloys may have high strength and high thermal stability making them of interest to aerospace industry by potential structural weight reduction. Similarly FeCoNiCrTi or FeCoNiCrAl HEAs have been shown to achieve extraordinary tensile properties at room temperature making them attractive for many industrial applications. In some embodiments, FeCoCrNiCu HEAs can be used.

[0042] The mechanically alloyed powder when spheroidized with microwave plasma processing yields highly spherical powder. This spherical powder then can be used as feedstock material for various industrial consolidation methods like additive manufacturing, metal injection molding, powder forging and hot isostatic pressing. Advantageously, the microstructure (or nanostructure) of the mechanically milled powders can be maintained throughout the processing, such as after the plasma processing.

[0043] **Figure 2** shows the XRD spectra of an example powder (having an example composition including 25Fe-17Co-17Cr-17Ni-16Cu before and after microwave plasma processing spheroidization. Other example compositions include Fe-25, Ni-19, Cr-13, Co-0.45, Ti-2.5, Mo-2.4, Nb-.4, Cu-0.2, Re. The line 202 illustrates an XRD plot of a powder feedstock after 17 hours of mechanical alloying but before microwave plasma processing. The line 204 illustrates an XRD plot of the powder feedstock after microwave plasma processing.

[0044] As shown, the alloy is more homogenized after the spheroidization process. Homogenizing refers to forming an alloy from the starting individual elemental powders. This can be seen from the XRD spectrum where individual peaks representing elements disappear and alloy peaks appear. After spheroidization the alloy peaks are more defined, eliminating remaining background peaks indicating enhanced homogenization of mechanically alloyed powder. Thus, the microwave plasma processing not only spheroidizes the powder feedstock but further homogenizes the feedstock.

[0045] With proper optimization, the milling time for mechanical alloying can be reduced because homogenizing can be accomplished using microwave plasma processing spheroidization. Without being limited to a single theory, since milling produces refined grains, mechanical alloying greatly reduces diffusion distances within the powder. Thus, after mechanical alloying, during microwave plasma processing, diffusion can occur rapidly at high temperatures thereby enhancing the homogenization of the alloy produced by mechanical alloying. Thus, microwave plasma processing can create similar homogenization as long periods of milling time for mechanical alloying. A milling time may be shortened when the feedstock is microwave plasma processed.

[0046] Mechanical alloying could also be used for alloys other than HEAs. Any existing alloy could be manufactured by mechanical alloying for example, stainless steels such as stainless steel type 316 and 17-4, or Ni base Inconels such as 718, 625, 738 etc. Embodiments of the disclosure can be effectively and economically used to develop new alloys or modify existing alloys to be used in emerging consolidation techniques such as Additive Manufacturing

[0047] Mechanical alloying is a solid state process. So technically any alloy could be manufactured by mechanical alloying. However, for conventional alloys or the alloys that can be manufactured in liquid state such as melting, these processes are much faster and economical than mechanical alloying. Hence they are rarely used for such alloys. Nevertheless, mechanical alloying may be used to also produce alloys that can be manufactured in liquid state such as melting.

Spheroidization

[0048] In some embodiments, the final particles achieved by the plasma processing can be spherical or spheroidal, terms which can be used interchangeably. Advantageously, by using the critical and specific disclosure relevant to each of the different feedstocks disclosed, all of the feedstocks can be transformed into the spherical powders.

[0049] Embodiments of the present disclosure are directed to producing particles that are substantially spherical or spheroidal or have undergone significant spheroidization. In some embodiments, spherical, spheroidal or spheroidized particles refer to particles having a sphericity greater than a certain threshold. Particle sphericity can be calculated by calculating the surface area of a sphere $A_{s,ideal}$ with a volume matching that of the particle, V using the following equation:

$$V_{ideal} = \frac{4}{3} \pi R^3$$

$$A_{s,ideal} = 4 \pi R_{ideal}^2$$

and then comparing that idealized surface area with the measured surface area of the particle, $A_{s,actual}$:

$$Sphericity = \frac{A_{s,ideal}}{A_{s,actual}}$$

[0050] In some embodiments, particles can have a sphericity of greater than 0.5, 0.6, 0.7, 0.75, 0.8, 0.9, 0.91, 0.95, or 0.99 (or greater than about 0.5, about 0.6, about 0.7, about 0.75, about 0.8, about 0.8, about 0.91, about 0.95, or about 0.99). In some embodiments, particles can have a sphericity of 0.75 or greater or 0.91 or greater (or about 0.75 or greater or about 0.91 or greater). In some embodiments, particles can have a sphericity of less than 0.5, 0.6, 0.7, 0.75, 0.8, 0.9, 0.91, 0.95, or 0.99 (or less than about 0.5, about 0.6, about 0.7, about 0.75, about 0.8, about 0.8, about 0.91, about 0.95, or about 0.99). In some embodiments, a particle is considered to be spherical, spheroidal or spheroidized if it has a sphericity at or above any of the aforementioned sphericity values, and in some preferred embodiments, a particle is considered to be spherical if its sphericity is at or about 0.75 or greater or at or about 0.91 or greater.

[0051] In some embodiments, a median sphericity of all particles within a given powder can be greater than 0.5, 0.6, 0.7, 0.75, 0.8, 0.9, 0.91, 0.95, or 0.99 (or greater than about 0.5, about 0.6, about 0.7, about 0.75, about 0.8, about 0.8, about 0.91, about 0.95, or about 0.99). In some embodiments, a median sphericity of all particles within a given powder can be less than 0.5, 0.6, 0.7, 0.75, 0.8, 0.9, 0.91, 0.95, or 0.99 (or less than about 0.5, about 0.6, about 0.7, about 0.75, about 0.8, about 0.8, about 0.91, about 0.95, or about 0.99). In some embodiments, a powder is considered to be spheroidized if all or a threshold percentage (as described by any of the fractions below) of the particles measured for the given powder have a median sphericity greater than or equal to any of the aforementioned sphericity values, and in some preferred embodiments, a powder is considered to be spheroidized if all or a threshold percentage of the particles have a median sphericity at or about 0.75 or greater or at or about 0.91 or greater.

[0052] In some embodiments, the fraction of particles within a powder that can be above a given sphericity threshold, such as described above, can be greater than 50%, 60%, 70%, 80%, 90%, 95%, or 99% (or greater than about 50%, about 60%, about 70%, about 80%, about 90%, about 95%, or about 99%). In some embodiments, the fraction of particles within a powder that can be above a given sphericity threshold, such as described above, can

be less than 50%, 60%, 70%, 80%, 90%, 95%, or 99% (or less than about 50%, about 60%, about 70%, about 80%, about 90%, about 95%, or about 99%).

[0053] Particle size distribution and sphericity may be determined by any suitable known technique such as by SEM, optical microscopy, dynamic light scattering, laser diffraction, manual measurement of dimensions using an image analysis software, for example from about 15-30 measures per image over at least three images of the same material section or sample, and any other techniques.

Microwave Plasma Processing

[0054] The process parameters can be optimized to obtain maximum spheroidization depending on the powder initial condition. For each feedstock powder characteristic, process parameters can be optimized for a particular outcome. U.S. Pat. Pub. No. 2018/0297122, U.S. Pat. No. 8,748,785, and U.S. Pat. No. 9,932,673 disclose certain processing techniques that can be used in the disclosed process, specifically for microwave plasma processing. Accordingly, U.S. Pat. Pub. No. 2018/0297122, U.S. Pat. No. 8,748,785, and U.S. Pat. No. 9,932,673 are incorporated by reference in its entirety and the techniques describes should be considered to be applicable to the feedstock described herein.

[0055] One aspect of the present disclosure involves a process of spheroidization of metals and metal alloys using a microwave generated plasma. The powder feedstock is entrained in inert and/or reducing and/or oxidizing gas environment and injected into the microwave plasma environment. Upon injection into a hot plasma, the feedstock is spheroidized and released into a chamber filled with an inert gas and directed into hermetically sealed drums where is it stored. This process can be carried out at atmospheric pressure, in a partial vacuum, or at a slightly higher pressure than atmospheric pressure. In alternative embodiments, the process can be carried out in a low, medium, or high vacuum environment. The process can run continuously and the drums are replaced as they fill up with spheroidized metal or metal alloy particles.

[0056] The rate of cooling of the spheroidized metal and metal alloys can be controlled to strategically influence the microstructure of the powder. By controlling the process parameters such as cooling gas flow rate, residence time, cooling gas composition

etc., microstructure of the metal and metal alloys can be controlled. The precise cooling rates required to form these structures is largely a function of the type and quantity of the alloying elements within the material.

[0057] The rate of cooling, especially when combined with the consistent and uniform heating capabilities of a microwave plasma plume, allow for control over the final microstructure. As a result, the above methods can be applied to processing metal (e.g., mechanical alloying and/or HEA) feedstock.

[0058] Cooling processing parameters include, but are not limited to, cooling gas flow rate, residence time of the spheroidized particles in the hot zone, and the composition or make of the cooling gas. For example, the cooling rate or quenching rate of the particles can be increased by increasing the rate of flow of the cooling gas. The faster the cooling gas is flowed past the spheroidized particles exiting the plasma, the higher the quenching rate—thereby allowing certain desired microstructures to be locked-in. Residence time of the particles within the hot zone of the plasma can also be adjusted to provide control over the resulting microstructure. That is, the length of time the particles are exposed to the plasma determines the extent of melting of the particle (i.e., surface of the particle melted as compared to the inner most portion or core of the particle).

[0059] Consequently, the extent of melting effects the extent of cooling needed for solidification and thus it is a cooling process parameter. Microstructural changes can be incorporated throughout the entire particle or just a portion thereof depending upon the extent of particle melting. Residence time can be adjusted by adjusting such operating variables of particle injection rate and flow rate (and conditions, such as laminar flow or turbulent flow) within the hot zone. Equipment changes can also be used to adjust residence time. For example, residence time can be adjusted by changing the cross-sectional area of the hot zone.

[0060] Another cooling processing parameter that can be varied or controlled is the composition of the cooling gas. Certain cooling gases are more thermally conductive than others. For example helium is considered to be a highly thermally conductive gas. The higher the thermal conductivity of the cooling gas, the faster the spheroidized particles can be cooled/quenched. By controlling the composition of the cooling gas (e.g., controlling the

quantity or ratio of high thermally conductive gasses to lesser thermally conductive gases) the cooling rate can be controlled.

[0061] As is known in metallurgy, the microstructure of a metal is determined by the composition of the metal and heating and cooling /quenching of the material. In the present technology, by selecting (or knowing) the composition of the feedstock material, and then exposing the feedstock to a plasma that has the uniform temperature profile and control there over as provided by the microwave plasma torch, followed by selecting and controlling the cooling parameters control over the microstructure of the spheroidized metallic particle is achieved. In addition, the phase of the metallic material depends upon the compositions of the feed stock material (e.g., purity, composition of alloying elements, etc.) as well thermal processing.

[0062] In one exemplary embodiment, inert gas is continually purged surrounding a powdered metal feed to remove oxygen within a powder-feed hopper. A continuous volume of powder feed is then entrained within an inert gas and fed into the microwave generated plasma for dehydrogenation or for composition/maintaining purity of the spheroidized particles. In one example, the microwave generated plasma may be generated using a microwave plasma torch, as described in U.S. Patent Publication No. US 2013/0270261, and/or U.S. Patent Nos. 8,748,785, 9,023,259, 9,206,085, 9,242,224, and 10,477,665, each of which is hereby incorporated by reference in its entirety.

[0063] In some embodiments, the particles are exposed to a uniform temperature profile at between 4,000 and 8,000 K within the microwave generated plasma. In some embodiments, the particles are exposed to a uniform temperature profile at between 3,000 and 8,000 K within the microwave generated plasma. Within the plasma torch, the powder particles are rapidly heated and melted. Liquid convection accelerates H₂ diffusion throughout the melted particle, continuously bringing hydrogen (H₂) to the surface of the liquid metal hydride where it leaves the particle, reducing the time each particle is required to be within the process environment relative to solid-state processes. As the particles within the process are entrained within an inert gas, such as argon, generally contact between particles is minimal, greatly reducing the occurrence of particle agglomeration. The need for post-process sifting is thus greatly reduced or eliminated, and the resulting particle size

distribution could be practically the same as the particle size distribution of the input feed materials. In exemplary embodiments, the particle size distribution of the feed materials is maintained in the end products.

[0064] Within the plasma, the melted metals are inherently spheroidized due to liquid surface tension. As the microwave generated plasma exhibits a substantially uniform temperature profile, more than 90% spheroidization of particles could be achieved (e.g., 91%, 93%, 95%, 97%, 99%, 100%). After exiting the plasma, the particles are cooled before entering collection bins. When the collection bins fill, they can be removed and replaced with an empty bin as needed without stopping the process.

[0065] **Figure 3** is a flow chart illustrating an exemplary method (250) for producing spherical powders, according to an embodiment of the present disclosure. In this embodiment, the process (250) begins by introducing a feed material into a plasma torch (255). In some embodiments, the plasma torch is a microwave generated plasma torch or an RF plasma torch. Within the plasma torch, the feed materials are exposed to a plasma causing the materials to melt, as described above (260). The melted materials are spheroidized by surface tension, as discussed above (260b). After exiting the plasma, the products cool and solidify, locking in the spherical shape and are then collected (265).

[0066] In some embodiments, the environment and/or sealing requirements of the bins are carefully controlled. That is, to prevent contamination or potential oxidation of the powders, the environment and or seals of the bins are tailored to the application. In one embodiment, the bins are under a vacuum. In one embodiment, the bins are hermetically sealed after being filled with powder generated in accordance with the present technology. In one embodiment, the bins are back filled with an inert gas, such as, for example argon. Because of the continuous nature of the process, once a bin is filled, it can be removed and replaced with an empty bin as needed without stopping the plasma process.

[0067] The methods and processes in accordance with the disclosure can be used to make powders, such as spherical powders.

[0068] In some embodiments, the processing discussed herein, such as the microwave plasma processing, can be controlled to prevent and/or minimize certain elements

for escaping the feedstock during the melt, which can maintain the desired composition/microstructure.

[0069] **Figure 4** illustrates an exemplary microwave plasma torch that can be used in the production of powders, according to embodiments of the present disclosure. As discussed above, feed materials 9, 10 can be introduced into a microwave plasma torch 3, which sustains a microwave generated plasma 11. In one example embodiment, an entrainment gas flow and a sheath flow (downward arrows) may be injected through inlets 5 to create flow conditions within the plasma torch prior to ignition of the plasma 11 via microwave radiation source 1.

[0070] In some embodiments, the entrainment flow and sheath flow are both axis-symmetric and laminar, while in other embodiments the gas flows are swirling. The feed materials 9 are introduced axially into the microwave plasma torch, where they are entrained by a gas flow that directs the materials toward the plasma. As discussed above, the gas flows can consist of a noble gas column of the periodic table, such as helium, neon, argon, etc. Within the microwave generated plasma, the feed materials are melted in order to spheroidize the materials. Inlets 5 can be used to introduce process gases to entrain and accelerate particles 9, 10 along axis 12 towards plasma 11. First, particles 9 are accelerated by entrainment using a core laminar gas flow (upper set of arrows) created through an annular gap within the plasma torch. A second laminar flow (lower set of arrows) can be created through a second annular gap to provide laminar sheathing for the inside wall of dielectric torch 3 to protect it from melting due to heat radiation from plasma 11. In exemplary embodiments, the laminar flows direct particles 9, 10 toward the plasma 11 along a path as close as possible to axis 12, exposing them to a substantially uniform temperature within the plasma.

[0071] In some embodiments, suitable flow conditions are present to keep particles 10 from reaching the inner wall of the plasma torch 3 where plasma attachment could take place. Particles 9, 10 are guided by the gas flows towards microwave plasma 11 where each undergoes homogeneous thermal treatment. Various parameters of the microwave generated plasma, as well as particle parameters, may be adjusted in order to achieve desired results. These parameters may include microwave power, feed material size, feed material

insertion rate, gas flow rates, plasma temperature, residence time and cooling rates. In some embodiments, the cooling or quenching rate is not less than 10^{+3} degrees C/sec upon exiting plasma 11. As discussed above, in this particular embodiment, the gas flows are laminar; however, in alternative embodiments, swirl flows or turbulent flows may be used to direct the feed materials toward the plasma.

[0072] **Figures 5A-B** illustrates an exemplary microwave plasma torch that includes a side feeding hopper rather than the top feeding hopper shown in the embodiment of **Figure 4**, thus allowing for downstream feeding. Thus, in this implementation the feedstock is injected after the microwave plasma torch applicator for processing in the “plume” or “exhaust” of the microwave plasma torch. Thus, the plasma of the microwave plasma torch is engaged at the exit end of the plasma torch to allow downstream feeding of the feedstock, as opposed to the top-feeding (or upstream feeding) discussed with respect to **Figure 4**. This downstream feeding can advantageously extend the lifetime of the torch as the hot zone is preserved indefinitely from any material deposits on the walls of the hot zone liner. Furthermore, it allows engaging the plasma plume downstream at temperature suitable for optimal melting of powders through precise targeting of temperature level and residence time. For example, there is the ability to dial the length of the plume using microwave powder, gas flows, and pressure in the quenching vessel that contains the plasma plume.

[0073] Generally, the downstream spheroidization method can utilize two main hardware configurations to establish a stable plasma plume which are: annular torch, such as described in U.S. Pat. Pub. No. 2018/0297122, or swirl torches described in US 8,748,785 B2 and US 9,932,673 B2. Both **Figure 5A** and **Figure 5B** show embodiments of a method that can be implemented with either an annular torch or a swirl torch. A feed system close-coupled with the plasma plume at the exit of the plasma torch is used to feed powder axisymmetrically to preserve process homogeneity.

[0074] Other feeding configurations may include one or several individual feeding nozzles surrounding the plasma plume. The feedstock powder can enter the plasma at a point from any direction and can be fed in from any direction, 360° around the plasma, into the point within the plasma. The feedstock powder can enter the plasma at a specific position along the length of the plasma plume where a specific temperature has been measured and a

residence time estimated for sufficient melting of the particles. The melted particles exit the plasma into a sealed chamber where they are quenched then collected.

[0075] The feed materials 314 can be introduced into a microwave plasma torch 302. A hopper 306 can be used to store the feed material 314 before feeding the feed material 314 into the microwave plasma torch 302, plume, or exhaust. The feed material 314 can be injected at any angle to the longitudinal direction of the plasma torch 302. 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, or 55 degrees. In some embodiments, the feedstock can be injected an angle of greater than 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, or 55 degrees. In some embodiments, the feedstock can be injected an angle of less than 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, or 55 degrees. In alternative embodiments, the feedstock can be injected along the longitudinal axis of the plasma torch.

[0076] The microwave radiation can be brought into the plasma torch through a waveguide 304. The feed material 314 is fed into a plasma chamber 310 and is placed into contact with the plasma generated by the plasma torch 302. When in contact with the plasma, plasma plume, or plasma exhaust, the feed material melts. While still in the plasma chamber 310, the feed material 314 cools and solidifies before being collected into a container 312. Alternatively, the feed material 314 can exit the plasma chamber 310 while still in a melted phase and cool and solidify outside the plasma chamber. In some embodiments, a quenching chamber may be used, which may or may not use positive pressure. While described separately from **Figure 4**, the embodiments of **Figures 5A-5B** are understood to use similar features and conditions to the embodiment of **Figure 4**.

[0077] In some embodiments, implementation of the downstream injection method may use a downstream swirl, extended spheroidization, or quenching. A downstream swirl refers to an additional swirl component that can be introduced downstream from the plasma torch to keep the powder from the walls of the tube. An extended spheroidization refers to an extended plasma chamber to give the powder longer residence time. In some implementations, it may not use a downstream swirl, extended spheroidization, or quenching. In some embodiments, it may use one of a downstream swirl, extended spheroidization, or quenching. In some embodiments, it may use two of a downstream swirl, extended spheroidization, or quenching.

[0078] Injection of powder from below may result in the reduction or elimination of plasma-tube coating in the microwave region. When the coating becomes too substantial, the microwave energy is shielded from entering the plasma hot zone and the plasma coupling is reduced. At times, the plasma may even extinguish and become unstable. Decrease of plasma intensity means decreases in spheroidization level of the powder. Thus, by feeding feedstock below the microwave region and engaging the plasma plume at the exit of the plasma torch, coating in this region is eliminated and the microwave powder to plasma coupling remains constant through the process allowing adequate spheroidization.

[0079] Thus, advantageously the downstream approach may allow for the method to run for long durations as the coating issue is reduced. Further, the downstream approach allows for the ability to inject more powder as there is no need to minimize coating.

[0080] From the foregoing description, it will be appreciated that inventive processing methods for mechanically alloyed and/or HEA powder are disclosed. While several components, techniques and aspects have been described with a certain degree of particularity, it is manifest that many changes can be made in the specific designs, constructions and methodology herein above described without departing from the spirit and scope of this disclosure.

[0081] Certain features that are described in this disclosure in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations, one or more features from a claimed combination can, in some cases, be excised from the combination, and the combination may be claimed as any subcombination or variation of any subcombination.

[0082] Moreover, while methods may be depicted in the drawings or described in the specification in a particular order, such methods need not be performed in the particular order shown or in sequential order, and that all methods need not be performed, to achieve desirable results. Other methods that are not depicted or described can be incorporated in the example methods and processes. For example, one or more additional methods can be

performed before, after, simultaneously, or between any of the described methods. Further, the methods may be rearranged or reordered in other implementations. Also, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described components and systems can generally be integrated together in a single product or packaged into multiple products. Additionally, other implementations are within the scope of this disclosure.

[0083] Conditional language, such as “can,” “could,” “might,” or “may,” unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include or do not include, certain features, elements, and/or steps. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required for one or more embodiments.

[0084] Conjunctive language such as the phrase “at least one of X, Y, and Z,” unless specifically stated otherwise, is otherwise understood with the context as used in general to convey that an item, term, etc. may be either X, Y, or Z. Thus, such conjunctive language is not generally intended to imply that certain embodiments require the presence of at least one of X, at least one of Y, and at least one of Z.

[0085] Language of degree used herein, such as the terms “approximately,” “about,” “generally,” and “substantially” as used herein represent a value, amount, or characteristic close to the stated value, amount, or characteristic that still performs a desired function or achieves a desired result. For example, the terms “approximately,” “about,” “generally,” and “substantially” may refer to an amount that is within less than or equal to 10% of, within less than or equal to 5% of, within less than or equal to 1% of, within less than or equal to 0.1% of, and within less than or equal to 0.01% of the stated amount. If the stated amount is 0 (e.g., none, having no), the above recited ranges can be specific ranges, and not within a particular % of the value. For example, within less than or equal to 10 wt./vol. % of, within less than or equal to 5 wt./vol. % of, within less than or equal to 1 wt./vol. % of, within less than or equal to 0.1 wt./vol. % of, and within less than or equal to 0.01 wt./vol. % of the stated amount.

[0086] The disclosure herein of any particular feature, aspect, method, property, characteristic, quality, attribute, element, or the like in connection with various embodiments can be used in all other embodiments set forth herein. Additionally, it will be recognized that any methods described herein may be practiced using any device suitable for performing the recited steps.

[0087] While a number of embodiments and variations thereof have been described in detail, other modifications and methods of using the same will be apparent to those of skill in the art. Accordingly, it should be understood that various applications, modifications, materials, and substitutions can be made of equivalents without departing from the unique and inventive disclosure herein or the scope of the claims.

WHAT IS CLAIMED IS:

1. A method for manufacturing a spheroidized powder from a mechanically-alloyed feedstock, the method comprising:

preparing a mechanically-alloyed powder feedstock by mechanically milling at least five elemental powders to mechanically alloy the at least five elemental powders;

introducing the mechanically-alloyed powder feedstock into a microwave plasma torch, a plasma plume of the microwave plasma torch, and/or an exhaust of the microwave plasma torch; and

at least partially melting and spheroidizing the mechanically-alloyed powder feedstock within the microwave plasma torch, the plasma plume of the microwave plasma torch, and/or the exhaust of the microwave plasma torch to form spheroidized powder.

2. The method of Claim 1, wherein the spheroidized powder is at least partially melted and spheroidized for use in metal injection molding processes, hot isostatic processing, and/or additive manufacturing.

3. The method of Claim 1, wherein the spheroidized powder is at least partially melted and spheroidized for use in hot isostatic processing.

4. The method of Claim 1, wherein the spheroidized powder is at least partially melted and spheroidized for use in additive manufacturing.

5. The method of any one of Claims 1-4, wherein the mechanically-alloyed powder feedstock is mechanically milled by ball milling.

6. The method of any one of Claims 1-5, wherein the mechanically-alloyed powder feedstock comprises TiZrNbTaFe.

7. The method of any one of Claims 1-5, wherein the mechanically-alloyed powder feedstock comprises AlFeVSi.

8. The method of any one of Claims 1-5, wherein the mechanically-alloyed powder feedstock comprises FeCoNiCrTi.

9. The method of any one of Claims 1-5, wherein the mechanically-alloyed powder feedstock comprises FeCoNiCrAl.

10. The method of any one of Claims 1-5, wherein the mechanically-alloyed powder feedstock comprises FeCoNiCrCu.

11. The method of any one of Claims 1-10, wherein the mechanically-alloyed powder feedstock comprises a microstructure, and wherein the spheroidized powder maintains the microstructure.

12. A method for manufacturing a spheroidized powder from a mechanically alloyed feedstock, the method comprising:

preparing a mechanically-alloyed powder feedstock by mechanically milling one or more precursor powders to form a high entropy alloy;

introducing the mechanically-alloyed powder feedstock into a microwave plasma torch, a plasma plume of the microwave plasma torch, and/or an exhaust of the microwave plasma torch; and

at least partially melting and spheroidizing the mechanically-alloyed powder feedstock within the microwave plasma torch, the plasma plume of the microwave plasma torch, and/or the exhaust of the microwave plasma torch to form spheroidized powder.

13. The method of Claim 12, wherein the spheroidized powder is at least partially melted and spheroidized for use in metal injection molding processes.

14. The method of Claim 12, wherein the spheroidized powder is at least partially melted and spheroidized for use in hot isostatic processing.

15. The method of Claim 12, wherein the spheroidized powder is at least partially melted and spheroidized for use in additive manufacturing.

16. The method of any one of Claims 12-15, wherein the mechanically-alloyed powder feedstock is mechanically milled by ball milling.

17. The method of any one of Claims 12-16, wherein the mechanically-alloyed powder feedstock comprises TiZrNbTaFe.

18. The method of any one of Claims 12-16, wherein the mechanically-alloyed powder feedstock comprises AlFeVSi.

19. The method of any one of Claims 12-16, wherein the mechanically-alloyed powder feedstock comprises FeCoNiCrTi.

20. The method of any one of Claims 12-16, wherein the mechanically-alloyed powder feedstock comprises FeCoNiCrAl.