

SYSTEMS AND METHODS FOR ADDITIVE MANUFACTURING OF METAL NITRIDE CERAMICS

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] This application claims the priority benefit of U.S. Provisional Application No. 63/200,841, filed March 31, 2021, the entire disclosure of which is incorporated herein by reference.

BACKGROUND

Field

[0002] Some embodiments of the present disclosure are directed to systems and methods for additive manufacturing of metal nitride ceramics, and for metal nitride ceramic components made by additive manufacturing.

Description

[0003] Metal nitrides, such as titanium nitride, has been used in a variety of applications, including in medical implants as a protective wear resistant coating. Many current orthopedic implants made from, for example, CoCr or titanium alloys (e.g., Ti64), have poor wear resistance and require a titanium nitride coating to prevent eventual failure of the implant in the body. Titanium nitride is a ceramic with excellent wear and corrosion resistance and is compatible with human body. The coating is typically applied to implants by Chemical Vapor Deposition (CVD), where vapors of Ti are reacted with Nitrogen gas to form a titanium nitride coating. This process forms a very thin, coherent layer of titanium nitride.

[0004] With the advent of additive manufacturing (AM), however, the design of implants has also evolved. It is now possible to design implants with internal cavities that reduce the weight of the implant and provide a location for tissue growth inside the implant. However, with intricate internal cavities, coating a layer of titanium nitride evenly on the surfaces inside the implant has become challenging. Printing the entire implant with titanium nitride would eliminate the expensive, time consuming and extra processing (CVD) of the implants and reduce the lead time for manufacturing. Due to the wear and corrosion resistance

of titanium nitride, no other coating will be needed for such implant. However, previously, AM of metal ceramics has not been possible due to the material properties of such material and the requirements for input materials of AM processes.

[0005] Thus, novel systems and methods of producing metal nitrides for AM processes, and AM processes for producing metal nitride components, and metal nitride components made by additive manufacturing, are needed.

SUMMARY

[0006] For purposes of this summary, certain aspects, advantages, and novel features of the invention are described herein. It is to be understood that not all such advantages necessarily may be achieved in accordance with any particular embodiment of the invention. Thus, for example, those skilled in the art will recognize that the invention may be embodied or carried out in a manner that achieves one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

[0007] Some embodiments herein are directed to a metal nitride ceramic component produced using an additive manufacturing process, the additive manufacturing process comprising: a powder bed diffusion process comprising: directing a laser beam or an electron beam to a metal nitride powder.

[0008] In some embodiments, the powder bed diffusion process comprises electron beam melting (EBM) or selective laser melting (SLM). In some embodiments, the metal nitride powder comprises a particle size range between about 15-45 microns, about 20-63 microns, or about 45-106 microns. In some embodiments, the metal nitride component has a density percent of 95% or higher under an optical microscope. In some embodiments, the metal nitride ceramic component consists essentially of metal nitride. In some embodiments, the metal nitride comprises titanium nitride. In some embodiments, the metal nitride powder comprises titanium nitride powder. In some embodiments, the metal nitride powder is formed by reacting a metal powder and a nitrogen-containing gas within a microwave plasma. In some embodiments, the nitrogen-containing gas comprises hydrogen or argon. In some embodiments, the laser beam or electron beam is directed to the metal

nitride powder within a process chamber, wherein the process chamber is maintained at a temperature of 1,200 °C or less throughout the process.

[0009] Some embodiments herein are directed to a process for producing a metal nitride ceramic component, the process comprising: directing a laser beam or an electron beam to a metal nitride powder.

[0010] In some embodiments, the process comprises electron beam melting (EBM) or selective laser melting (SLM) of the metal nitride powder. In some embodiments, the metal nitride powder comprises a particle size range between about 15-45 microns, about 20-63 microns, or about 45-106 microns. In some embodiments, the metal nitride component has a density percent of 95% or higher under an optical microscope. In some embodiments, the laser beam or electron beam is directed to the metal nitride powder within a process chamber, wherein the process chamber is maintained at a temperature of 1,200 °C or less throughout the process. In some embodiments, the metal nitride ceramic component consists essentially of metal nitride. In some embodiments, the metal nitride comprises titanium nitride. In some embodiments, the metal nitride powder comprises titanium nitride powder. In some embodiments, the metal nitride powder is formed by reacting a metal powder and a nitrogen-containing gas within a microwave plasma. In some embodiments, the nitrogen-containing gas comprises hydrogen or argon. Some embodiments herein are directed to a printed titanium nitride component. In some embodiments, the printed titanium nitride component comprises a density percent of 95% or higher under an optical microscope. In some embodiments, the printed titanium nitride component comprises a density of about 4.72 g/cc to 4.90 g/cc. In some embodiments, the printed titanium nitride component comprises a stoichiometry of $\text{TiN}_{0.54}$. In some embodiments, the printed titanium nitride component comprises phases of αTi , TiN and Ti_2N . In some embodiments, the printed titanium nitride component comprises 13 to 14 wt.% nitrogen. In some embodiments, the printed titanium component consists essentially of titanium nitride. In some embodiments, the printed titanium nitride component is entirely printed using additive manufacturing. In some embodiments, the printed titanium nitride component comprises a cluster of printed cubes. In some embodiments, the printed titanium nitride component is a medical implant.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The drawings are provided to illustrate example embodiments and are not intended to limit the scope of the disclosure. A better understanding of the systems and methods described herein will be appreciated upon reference to the following description in conjunction with the accompanying drawings, wherein:

[0012] FIG. 1 illustrates an example morphology of titanium nitride powder usable for additive manufacturing according to some embodiments herein.

[0013] FIG. 2 illustrates an example microstructure of titanium nitride powder usable for additive manufacturing according to some embodiments herein.

[0014] FIG. 3 illustrates an example X-ray powder diffraction of a titanium powder usable for additive manufacturing according to some embodiments herein.

[0015] FIG. 4 illustrates an example particle size distribution of a titanium powder usable for additive manufacturing according to some embodiments herein.

[0016] FIG. 5A and 5B illustrate example images of titanium nitride cubes printed using AM according to some embodiments described herein.

[0017] FIG. 6 illustrates sample table of chemical and phase analysis of TiN powders and printed parts according to some embodiments herein.

[0018] FIG. 7 an example X-ray diffraction of TiN powders and printed parts according to some embodiments herein.

[0019] FIG. 8 illustrates a Ti-N phase diagram of a material according to some embodiments herein.

[0020] FIGS. 9A-9E illustrate example scanning electron microscope images of TiN powder used for AM according to some embodiments herein.

[0021] FIGS. 10A-10G illustrate example scanning electron microscope and back-scatter detector images of TiN intermediate parts produced by AM according to some embodiments herein.

[0022] FIGS. 11A-11H illustrate example scanning electron microscope and back-scatter detector images of TiN final parts produced by AM according to some embodiments herein.

[0023] FIG. 12 illustrates an embodiment of a microwave plasma torch that can be used in the production of materials according to some embodiments herein.

[0024] FIGS. 13A-13B illustrate an exemplary microwave plasma torch that includes a side feeding hopper according to some embodiments herein.

DETAILED DESCRIPTION

[0025] Although certain preferred embodiments and examples are disclosed below, inventive subject matter extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses and to modifications and equivalents thereof. Thus, the scope of the claims appended hereto is not limited by any of the particular embodiments described below. For example, in any method or process disclosed herein, the acts or operations of the method or process may be performed in any suitable sequence and are not necessarily limited to any particular disclosed sequence. Various operations may be described as multiple discrete operations in turn, in a manner that may be helpful in understanding certain embodiments; however, the order of description should not be construed to imply that these operations are order dependent. Additionally, the structures, systems, and/or devices described herein may be embodied as integrated components or as separate components. For purposes of comparing various embodiments, certain aspects and advantages of these embodiments are described. Not necessarily all such aspects or advantages are achieved by any particular embodiment. Thus, for example, various embodiments may be carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other aspects or advantages as may also be taught or suggested herein.

[0026] Certain exemplary embodiments will now be described to provide an overall understanding of the principles of the structure, function, manufacture, and use of the devices and methods disclosed herein. One or more examples of these embodiments are illustrated in the accompanying drawings. Those skilled in the art will understand that the devices and methods specifically described herein and illustrated in the accompanying drawings are non-limiting exemplary embodiments and that the scope of the present invention is defined solely by the claims. The features illustrated or described in connection with one exemplary embodiment may be combined with the features of other embodiments.

Such modifications and variations are intended to be included within the scope of the present technology.

[0027] Described herein are embodiments directed to additive manufacturing (AM), including three-dimensional (3D) printing, of metal nitride ceramics. In some embodiments herein, AM may comprise powder bed fusion (PBF) techniques such as electron beam melting (EBM), selective laser melting (SLM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS), among others. As used herein, AM may include various technologies for processing materials into higher complexity components by joining or adding consecutive layers of material to form an object, guided by computer aided design (CAD) data. PBF systems use lasers, electron beams or thermal print heads to melt or partially melt ultra-fine layers of material in a three-dimensional space. As the process concludes, excess powder is blasted away from the object.

[0028] Previously, because of the material properties of metal nitride ceramics produced by high temperature processing such as casting, pressing, powder metallurgy, or otherwise, such materials were incompatible for use in AM processes. For example, without being limited by theory, it is postulated that the high melting point, high hardness, brittleness, and density of such previously produced metal nitride ceramics made those materials incompatible with AM processes. Titanium nitride, for example, has a melting point of about 2,930 °C, while typical AM process chambers may only reach about 1,200 °C. However, the embodiments herein include synthesized metal nitride ceramics powders capable of being used in AM processes, as well as methods and systems for synthesizing such AM-compatible metal nitride ceramics. Furthermore, the embodiments herein include methods for local melting of high-temperature refractory metal nitride ceramics and controlled solidification of such ceramics to avoid cracking and yield full density materials. In some embodiments, the AM methods and systems herein may comprise printing of metal nitride ceramics, such as titanium nitride, without altering the stoichiometry of metal or nitrogen content in the precursor materials.

[0029] The basic material requirement for additive manufacturing is metal alloy powders in spherical form and in specified particle size, usually in a certain micron range (15-45 microns, 20-63 microns, 45-106 microns, etc.). Some nitride powders, such as

titanium nitride powder, matching these requirements are not currently known, and ultimately, AM of titanium nitride is not known. The embodiments herein enable the manufacturing of titanium nitride powders within the specification of AM and at scale.

[0030] The embodiments herein include methods of AM processing of micron-sized metal nitride powders into fully dense, solid components using innovative AM parameters and strategy. This innovative approach is capable of producing AM fabricated solids from metal nitride powders. The systems and methods herein are critical to melting and solidifying the metal nitride powder input without cracking during solidification. In some embodiments, the AM processing may comprise fully melting refractory metal nitride and performing a controlled solidification to produce a crack-free, solid component. In some embodiments, the methods herein further prevent decomposition of metal nitrides, such as titanium nitride, into the constituent metal and nitrogen, preserving the stoichiometry of the titanium nitride powders. In some embodiments, the strong Ti-H bond in titanium nitride may help preservation of the stoichiometry. In some embodiments, the methods herein represent the first successful 3D printing of metal nitride ceramics using a powder bed fusion technique with either an electron beam or a laser beam.

[0031] In some embodiments, the metal nitride 3D printed components produced using the systems and methods herein may potentially replace traditional CoCr alloys used for medical implants. CoCr implants may cause Cr and Co ions released in the blood stream of a patient, which can cause cytotoxic and apoptotic effects in some cases. Currently, metal nitride is used in medical applications as a protective wear resistant coating for CoCr and Ti64 implants and is on the list of FDA approved materials. However, 3D printing of metal nitrides, such as TiN, which was previously impossible, will allow for production of biocompatible metal nitride implants with controlled porosity, such that the manufacture of osteoconductive implants for faster bone tissue growth and faster recovery will be possible.

[0032] Some embodiments herein comprise methods for producing a metal nitride powders compatible with AM process. In some embodiments, the method comprises using commercially pure titanium (cPTi) powder, or other metal powder, as a precursor and nitrogen-containing gas as a reactive plasma gas to synthesize metal nitride.

[0033] Some metals, such as Ti, have a great affinity towards interstitials such as nitrogen, hydrogen, carbon, and oxygen. When present in plasma gas, such species may

exist in an ionized state and are considered more “reactive”. By carefully choosing the reactive plasma gas composition, which at least contain nitrogen and may contain varying amounts of other gases such as hydrogen or argon, among others, and passing the feed powder through it instantaneously, nitrogen in the plasma gas reacts with Ti to produce titanium nitride. By controlling the amount of nitrogen in the reactive plasma and the residence time of the Ti powder particles in the reactive plasma, it may be possible to control the stoichiometry (e.g., % of N in the compound) and phases of titanium nitride produced.

[0034] In some embodiments, the basic material requirement for additive manufacturing is metal alloy, metal carbide, metal oxide or metal nitride powders in spherical form and within a specified particle size, usually in the micron range. Particle size distribution has a direct influence on powder flowability, spreadability and the ability to provide a uniform, powder bed density. This in turn determines the energy input needed to melt or sinter the powder particles and also affects the surface finish. For example, a spheroidized powder suitable in AM process may have a particle size distribution between about 15-45 microns, about 20-63 microns, about 45-106 microns, or about 45-150 microns. In some embodiments, the particle size distribution may comprise the D50 particle size distribution. However, according to the methods and systems described herein, a spheroidized powder may comprise a particle size distribution in the nanometer range to the millimeter range. For example, a spheroidized powder according to the embodiments herein may comprise a particle size distribution between about 0.1 microns to about 1000 microns. In some embodiments, a spheroidized powder according to the embodiments herein may comprise a particle size distribution between about 0.1 microns and about 1 micron, between about 1 micron and 15 microns, between about 15 microns and about 45 microns, between about 20 microns and 63 microns, between about 45 microns and about 106 microns, between about 106 microns and about 200 microns, between about 200 microns and 300 microns, between about 300 microns and about 400 microns, between about 400 microns and about 500 microns, between about 500 microns and about 600 microns, between about 600 microns and about 700 microns, between about 700 microns and about 800 microns, between about 800 microns and about 900 microns, and between about 900 microns and about 1000 microns, or between any of the aforementioned ranges.

[0035] Furthermore, to be useful in AM applications that require high powder flow, metal powder particles should exhibit a spherical shape, which can be achieved through the process of plasma spheroidization. This process involves the full melting, surface melting or partial melting of particles in a hot environment whereby surface tension of the liquid metal shapes each particle into a spherical geometry, followed by cooling and re-solidification.

[0036] In some embodiments, the final particles achieved by the plasma processing can be spherical, spheroidized, or spheroidal, terms which can be used interchangeably. Advantageously, by using the critical and specific disclosure relevant to each of the different metal nitride, all of the feedstocks can be transformed into the spherical powders.

[0037] Some embodiments of the present disclosure are directed to producing particles that are substantially spheroidized 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:

$$r_{ideal} = \sqrt[3]{\frac{3V}{4\pi}}$$

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

[0038] The idealized surface area can be compared with the measured surface area of the particle, $A_{s,actual}$:

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

[0039] 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.

[0040] 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.

[0041] 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%).

[0042] 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.

[0043] Titanium nitride powder that falls within the above specifications is not currently known, and therefore, AM processes using titanium nitride are not currently known. Some embodiments herein are therefore directed to systems and methods for the manufacture of metal nitride, including titanium nitride powders within the specifications required for AM. Some embodiments herein are directed to synthesizing, for example, micron sized spherical titanium nitride powder. In some embodiments, the main alloying element is nitrogen. With respect to the composition of the titanium nitride powder, at different nitrogen concentrations, different nitride phases are formed such as TiN, Ti₂N, TiN₂. These phases have different physical properties. For example, TiN is a very hard phase with high wear resistance and Ti₂N may be relatively softer phase. Thus, based on the application and the required functional properties, different compositions and ultimately different microstructures will be desired. The embodiments herein may be directed to synthesis of titanium nitride of any desired phase, which can be controlled by controlling the stoichiometry of the reactive plasma gas.

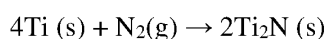
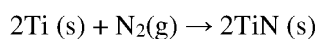
[0044] Using the metal nitride powder produced according to the above process and/or having the specifications above, and using specific AM processing techniques, a 3D printed metal nitride component may be obtained. The ability of melting or fusing the metal nitride powders by EBM may depend at least partly on the energy density received at the powder surface. For EBM, this energy density may be calculated as the current*accelerating voltage/scan speed*hatch spacing*layer thickness. The optimum parameters for powder melting may be achieved by combination of the individual parameters – current, scan time and hatch spacing being the main parameters. On the other hand, chamber temperature may help to control the cooling rate or solidification rate of the melted mass of the powder. In some embodiments, increasing the chamber temperature decreases the cooling rate of the melted mass. In some embodiments, slower cooling rates may prevent cracking of the solidified mass of the powder. The chamber temperatures in EBM machines typically could

be maintained at around 1000-1100°C. However, in some embodiments, in order to increase the chamber temperature beyond the limit of around 1100°C, a cluster of cubes can be printed so that more solid mass may be present in the chamber, wherein the cluster of cubes retains more heat surrounding the printed cube. In real world application, printing may be completed by maximizing the print area so more solid mass is present when printing. Further, for parts printing, there may be one or more support structures in the part design, which may assist in supporting overhangs from sagging, as well as heat management. This will vary from part to part based on the section thickness that is printed and the proximity of the adjacent parts being printed.

[0045] For example, printing using an EBM process generally takes place in vacuum at a chamber temperature maintained up to about 1100 °C. In some embodiments, by increasing the current of the electron beam, ultimately increasing the energy delivered to the powder bed, the powder may be melted and fused. In some embodiments, the current may be raised to a level such that melting of the metal nitride can be achieved but warping of the chamber base may not occur. For example, melting of titanium nitride used herein may be achieved at a chamber temperature of about 1,200 °C or less, despite the melting point of titanium nitride being about 2,930 °C, wherein the final part may exhibit substantially no cracking in the structure of the part. This may be achieved by printing a cluster of metal nitride cubes, such that a greater mass is present in the chamber, resulting in more heat being retained, and more uniform powder melting, and cooling may be achieved relative to melting a single metal nitride cube of lower mass. In addition to using a cluster of metal nitride cubes, the hatch spacing (overlap of two adjacent beam tracks) in the AM process may be reduced, thereby increasing the overlap of the beams, and ensuring that substantially no area of the powder bed is left untouched by the beam. Using the above AM processing techniques, metal nitride having a density of at least 95% may be produced. Density % may be measured by observation of the cross section of the printed part under microscope and density % may be calculated % of dense area observed. Otherwise, density % may be calculated by percent of cube density achieved as a function of the theoretical density of the material (e.g., titanium nitride).

Examples

[0046] Titanium nitride powder was synthesized from cpTi powder. The titanium nitride powder exhibited a 45–106-micron particle-size distribution (PSD) and was synthesized using a microwave plasma generated using a nitrogen containing gas (N₂) as a plasma gas. The cpTi, which was made by the hydride-dehydride (HDH) method, was treated in a reactive plasma comprising a mixture of nitrogen (N₂) and hydrogen (H₂). A small amount of hydrogen (~10%) was introduced in the reactive nitrogen gas to prevent oxidation of the cpTi powder during the plasma treatment. The plasma treatment transformed the irregular shaped HDH cpTi powder into a spherical titanium nitride powder. During spheroidization, due to the high temperatures and the contact between ionized nitrogen species in the plasma with fully melted, surface melted or partially melted cpTi particles, a reaction between Ti and N was initiated, resulting in titanium nitride, Ti_xN_y. Example reactions are shown below:



[0047] The titanium nitride synthesized had the following elemental composition: nitrogen at 12% by weight, oxygen at 0.34% by weight, iron at 0.034% by weight, carbon at 0.0068% by weight, and titanium at 85.9% by weight. The titanium nitride synthesized had a particle size distribution wherein D₁₀ was 50.35 microns, D₅₀ was 68.5 microns, and D₉₀ was 97.73 microns. The synthesized titanium nitride had the following physical properties: Hall Flow of 27 s/50 g, apparent density (AD) of 2.54 g/cubic cm, true density of 4.9 g/cubic cm, and tapped density (TD) of 2.91 g/cubic cm. Titanium nitride powder may be synthesized through microwave plasma processing. In some embodiments, within the plasma, plasma plume, or exhaust, 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%).

[0048] FIG. 1 illustrates an example morphology of titanium nitride powder usable with AM process according to some embodiments herein.

[0049] FIG. 2 illustrates an example microstructure of titanium nitride powder usable with AM process according to some embodiments herein. In some embodiments, the

microstructure of the titanium nitride powder may comprise one or more separate phases. For example, in some embodiments, phases may include α -Ti, TiN, Ti₂N, and/or TiN₂. In some embodiments, titanium nitride shell will be formed with cP-Ti core.

[0050] FIG. 3. illustrates an example X-ray powder diffraction of a titanium nitride powder usable with AM process according to some embodiments herein.

[0051] FIG. 4 illustrates an example particle size distribution of a titanium nitride powder usable with AM process according to some embodiments herein. In some embodiments, a titanium nitride powder may comprise a particle size distribution between about 15 microns and about 150 microns.

[0052] FIG. 5A and 5B illustrate example images of titanium nitride cubes printed using AM according to some embodiments described herein. An EBM printer was used to print titanium nitride powder to produce 15 x 15 mm squares to a height of about 8.6 mm. A EBM chamber temperature was maintained at about 1100°C throughout the duration of the build. The structures were built directly on a stainless-steel plate with no support structure. With optimized parameters, a density of about 4.72 g/cc to 4.90 g/cc was achieved on the printed structures. The theoretical density for TiN phase is 5.4 g/cc and the theoretical density of Ti₂N phase is 4.88 g/cc.

[0053] FIG. 6 illustrates sample table of chemical and phase analysis of TiN powders and printed parts according to some embodiments herein. The table illustrates properties of a metal nitride powder according to the embodiments herein and a reference powder formed by previous methods. In some embodiments, a final printed part according to some embodiments herein may comprise a stoichiometry of TiN_{0.54} (Ti₂N is equivalent to TiN_{0.5}).

[0054] FIG. 7 illustrates an example X-ray diffraction of TiN powders and printed parts according to some embodiments herein.

[0055] FIG. 8 illustrates a Ti-N phase diagram. As seen from Ti-N phase diagram, Ti₂N is a narrow phase region from with about 12 to 13 wt.% N. TiN has broad range from about 13 to 25 wt.% N. The XRD of FIG. 7 shows the powder according to some embodiments herein has three phases: α Ti+TiN+Ti₂N. Similarly, the final Printed solid also has 3 phases: α Ti+TiN+Ti₂N, although with different proportions. The % N is effectively

unchanged from powder to printed solid. Thus, in some embodiments, EBM print conditions may diffuse Nitrogen and transform TiN to Ti₂N.

[0056] FIGS. 9A-9E illustrate example scanning electron microscope images of TiN powder used for AM according to some embodiments herein. The spheroidized powder particles show recrystallized layers and the particle cross-sections show homogenous chemistry.

[0057] FIGS. 10A-10G illustrate example scanning electron microscope and back-scatter detector images of TiN intermediate parts produced by AM according to some embodiments herein. The intermediate print solids show high porosity and iron rich regions are observed in the microstructure, possibly picked up from the chamber base plate.

[0058] FIGS. 11A-11H illustrate example scanning electron microscope and back-scatter detector images of TiN final parts produced by AM according to some embodiments herein. The final print solids show less porosity and higher density compared to intermediate parts. Iron rich regions are observed in the microstructure, possibly picked up from the chamber base plate.

[0059] In summary, according to some embodiments herein, synthesized titanium nitride powder may be rich in TiN phase with Ti₂N and α Ti phases. Using the TiN powders produced according to the methods described herein, 95% dense prints using EBM were formed. The printed solids were rich in Ti₂N phase with TiN and α Ti phases. The nitrogen content was consistent at about 13 -14 wt.% from powder to print. The printed solids appeared gray in color in contrast to golden color of powder. Some studies show a change of color as a function of Ti : N stoichiometry with the TiN phase appearing golden and Ti₂N appearing silvery gray.

Plasma Processing

[0060] FIG. 12 illustrates an embodiment of a microwave plasma torch 1200 that can be used in the production of titanium nitride AM materials according to some embodiments herein. In some embodiments, a feedstock can be introduced, via one or more feedstock inlets 1202, into a microwave plasma 1204. In some embodiments, an entrainment gas flow and/or a sheath flow may be injected into the microwave plasma applicator 1205 to create flow conditions within the plasma applicator prior to ignition of the plasma 1204 via

microwave radiation source 1206. In some embodiments, the entrainment flow and sheath flow are both axis-symmetric and laminar, while in other embodiments the gas flows are swirling. In some embodiments, the feedstock may be introduced into the microwave plasma torch 1200, where the feedstock may be entrained by a gas flow that directs the materials toward the plasma 1204.

[0061] The gas flows can comprise nitrogen and/or a noble gas column of the periodic table, such as helium, neon, argon, etc. Although the gases described above may be used, it is to be understood that a variety of gases can be used depending on the desired material and processing conditions. In some embodiments, within the microwave plasma 1204, the feedstock may undergo a physical and/or chemical transformation. Inlets 1202 can be used to introduce process gases to entrain and accelerate the feedstock towards plasma 1204. In some embodiments, a second gas flow can be created to provide sheathing for the inside wall of a plasma applicator 1204 and a reaction chamber 1210 to protect those structures from melting due to heat radiation from plasma 1204.

[0062] Various parameters of the microwave plasma 1204, as created by the plasma applicator 1205, may be adjusted manually or automatically in order to achieve a desired material. These parameters may include, for example, power, plasma gas flow rates, type of plasma gas, presence of an extension tube, extension tube material, level of insulation of the reactor chamber or the extension tube, level of coating of the extension tube, geometry of the extension tube (e.g. tapered/stepped), feed material size, feed material insertion rate, feed material inlet location, feed material inlet orientation, number of feed material inlets, plasma temperature, residence time and cooling rates. The resulting material may exit the plasma into a sealed chamber 1212 where the material is quenched then collected.

[0063] In some embodiments, the feedstock is injected after the microwave plasma 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 core tube 1208, or further downstream. In some embodiments, adjustable downstream feeding allows engaging the feedstock with the plasma plume downstream at a temperature suitable for optimal melting of feedstock through precise targeting of temperature level and residence time. Adjusting the inlet location and plasma characteristics may allow for further customization of material characteristics. Furthermore, in some embodiments, by adjusting

power, gas flow rates, pressure, and equipment configuration (e.g., introducing an extension tube), the length of the plasma plume may be adjusted.

[0064] In some embodiments, feeding configurations may include one or more individual feeding nozzles surrounding the plasma plume. The feedstock may enter the plasma from any direction and can be fed in 360° around the plasma depending on the placement and orientation of the inlets 1202. Furthermore, the feedstock may enter the plasma at a specific position along the length of the plasma 1204 by adjusting placement of the inlets 1202, where a specific temperature has been measured and a residence time estimated for providing the desirable characteristics of the resulting material.

[0065] In some embodiments, the angle of the inlets 1202 relative to the plasma 1204 may be adjusted, such that the feedstock can be injected at any angle relative to the plasma 1204. For example, the inlets 1202 may be adjusted, such that the feedstock may be injected into the plasma at an angle of about 0 degrees, about 5 degrees, about 10 degrees, about 15 degrees, about 20 degrees, about 25 degrees, about 30 degrees, about 35 degrees, about 40 degrees, about 45 degrees, about 50 degrees, about 55 degrees, about 60 degrees, about 65 degrees, about 70 degrees, about 75 degrees, about 80 degrees, about 85 degrees, or about 90 degrees relative to the direction of the plasma 1204, or between any of the aforementioned values.

[0066] In some embodiments, implementation of the downstream injection method may use a downstream swirl or quenching. A downstream swirl refers to an additional swirl component that can be introduced downstream from the plasma applicator to keep the powder from the walls of the applicator 1205, the reactor chamber 1210, and/or an extension tube 1214.

[0067] In some embodiments, the length of a reaction chamber 1210 of a microwave plasma apparatus may be about 1 foot, about 2 feet, about 3 feet, about 4 feet, about 5 feet, about 6 feet, about 7 feet, about 8 feet, about 9 feet, about 10 feet, about 11 feet, about 12 feet, about 13 feet, about 14 feet, about 15 feet, about 16 feet, about 17 feet, about 18 feet, about 19 feet, about 20 feet, about 21 feet, about 22 feet, about 23 feet, about 24 feet, about 25 feet, about 26 feet, about 27 feet, about 28 feet, about 29 feet, or about 30 feet, or any value between the aforementioned values.

[0068] In some embodiments, the length of the plasma 1204, which may be extended by adjusting various processing conditions and equipment configurations, may be about 1 foot, about 2 feet, about 3 feet, about 4 feet, about 5 feet, about 6 feet, about 7 feet, about 8 feet, about 9 feet, about 10 feet, about 11 feet, about 12 feet, about 13 feet, about 14 feet, about 15 feet, about 16 feet, about 17 feet, about 18 feet, about 19 feet, about 20 feet, about 21 feet, about 22 feet, about 23 feet, about 24 feet, about 25 feet, about 26 feet, about 27 feet, about 28 feet, about 29 feet, or about 30 feet, or any value between the aforementioned values.

[0069] FIGS. 13A-13B illustrate an exemplary microwave plasma torch that includes a side feeding hopper. 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. 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.

[0070] 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 8748785 B2 and US 9932673 B2. Both FIG. 13A and FIG. 13B 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. Other feeding configurations may include one or several individual feeding nozzles surrounding the plasma plume.

[0071] 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. In alternative embodiments, the feedstock can be injected along the longitudinal axis of the plasma torch.

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 FIG. 12, the embodiments of FIGS. 13A-13B are understood to use similar features and conditions to the embodiment of FIG. 12.

Additional Embodiments

[0072] In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than restrictive sense.

[0073] Indeed, although this invention has been disclosed in the context of certain embodiments and examples, it will be understood by those skilled in the art that the invention extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses of the invention and obvious modifications and equivalents thereof. In addition, while several variations of the embodiments of the invention have been shown and described in detail, other modifications, which are within the scope of this invention, will be readily apparent to those of skill in the art based upon this disclosure. It is also contemplated that various combinations or sub-combinations of the specific features and aspects of the embodiments may be made and still fall within the scope of the invention. It should be understood that various features and aspects of the disclosed embodiments can be combined with, or substituted for, one another in order to form varying modes of the embodiments of the disclosed invention. Any methods disclosed herein need not be performed in the order recited. Thus, it is intended that the scope of the invention herein disclosed should not be limited by the particular embodiments described above.

[0074] It will be appreciated that the systems and methods of the disclosure each have several innovative aspects, no single one of which is solely responsible or required for the desirable attributes disclosed herein. The various features and processes described above may be used independently of one another or may be combined in various ways. All possible combinations and subcombinations are intended to fall within the scope of this disclosure.

[0075] Certain features that are described in this specification in the context of separate embodiments also may be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment also may be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination may in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination. No single feature or group of features is necessary or indispensable to each and every embodiment.

[0076] It will also be appreciated that conditional language used herein, such as, among others, “can,” “could,” “might,” “may,” “e.g.,” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments 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 or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or steps are included or are to be performed in any particular embodiment. The terms “comprising,” “including,” “having,” and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. In addition, the term “or” is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term “or” means one, some, or all of the elements in the list. In addition, the articles “a,” “an,” and “the” as used in this application and the appended claims are to be construed to mean “one or more” or “at least one” unless specified otherwise. Similarly, while operations may be depicted in the drawings in a particular order, it is to be recognized that such operations need not be performed in the

particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Further, the drawings may schematically depict one more example processes in the form of a flowchart. However, other operations that are not depicted may be incorporated in the example methods and processes that are schematically illustrated. For example, one or more additional operations may be performed before, after, simultaneously, or between any of the illustrated operations. Additionally, the operations may be rearranged or reordered in other embodiments. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems may generally be integrated together in a single software product or packaged into multiple software products. Additionally, other embodiments are within the scope of the following claims. In some cases, the actions recited in the claims may be performed in a different order and still achieve desirable results.

[0077] Further, while the methods and devices described herein may be susceptible to various modifications and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms or methods disclosed, but, to the contrary, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the various implementations described and the appended claims. Further, the disclosure herein of any particular feature, aspect, method, property, characteristic, quality, attribute, element, or the like in connection with an implementation or embodiment can be used in all other implementations or embodiments set forth herein. Any methods disclosed herein need not be performed in the order recited. The methods disclosed herein may include certain actions taken by a practitioner; however, the methods can also include any third-party instruction of those actions, either expressly or by implication. The ranges disclosed herein also encompass any and all overlap, sub-ranges, and combinations thereof. Language such as “up to,” “at least,” “greater than,” “less than,” “between,” and the like includes the number recited. Numbers preceded by a term such as “about” or “approximately” include the recited numbers and should be interpreted based on the circumstances (e.g., as accurate as reasonably possible under the circumstances, for example

$\pm 5\%$, $\pm 10\%$, $\pm 15\%$, etc.). For example, “about 3.5 mm” includes “3.5 mm.” Phrases preceded by a term such as “substantially” include the recited phrase and should be interpreted based on the circumstances (e.g., as much as reasonably possible under the circumstances). For example, “substantially constant” includes “constant.” Unless stated otherwise, all measurements are at standard conditions including temperature and pressure.

[0078] As used herein, a phrase referring to “at least one of” a list of items refers to any combination of those items, including single members. As an example, “at least one of: A, B, or C” is intended to cover: A, B, C, A and B, A and C, B and C, and A, B, and C. 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 at least one of X, Y or Z. Thus, such conjunctive language is not generally intended to imply that certain embodiments require at least one of X, at least one of Y, and at least one of Z to each be present. The headings provided herein, if any, are for convenience only and do not necessarily affect the scope or meaning of the devices and methods disclosed herein.

[0079] Accordingly, the claims are not intended to be limited to the embodiments shown herein but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein.

WHAT IS CLAIMED IS:

1. A metal nitride ceramic component produced using an additive manufacturing process, the additive manufacturing process comprising:
a powder bed diffusion process comprising:
directing a laser beam or an electron beam to a metal nitride powder.
2. The metal nitride ceramic component of Claim 1, wherein the powder bed diffusion process comprises electron beam melting (EBM) or selective laser melting (SLM).
3. The metal nitride ceramic component of Claim 1, wherein the metal nitride powder comprises a particle size range between about 15-45 microns, about 20-63 microns, or about 45-106 microns.
4. The metal nitride ceramic component of Claim 1, wherein the metal nitride component has a density percent of 95% or higher under an optical microscope.
5. The metal nitride ceramic component of Claim 1, wherein the metal nitride ceramic component consists essentially of metal nitride.
6. The metal nitride ceramic component of Claim 5, wherein the metal nitride comprises titanium nitride.
7. The metal nitride ceramic component of Claim 1, wherein the metal nitride powder comprises titanium nitride powder.
8. The metal nitride ceramic component of Claim 1, wherein the metal nitride powder is formed by reacting a metal powder and a nitrogen-containing gas within a microwave plasma.
9. The metal nitride ceramic component of Claim 8, wherein the nitrogen-containing gas comprises hydrogen or argon.
10. The metal nitride ceramic component of Claim 1, wherein the laser beam or electron beam is directed to the metal nitride powder within a process chamber, wherein the process chamber is maintained at a temperature of 1,200 °C or less throughout the process.
11. The metal nitride ceramic component of Claim 1, wherein the electron beam is directed to the metal nitride powder to form a plurality of cubes or articles forming the metal nitride ceramic component.
12. The metal nitride ceramic component of Claim 1, wherein the metal nitride powder comprises a sphericity above 90%.

13. A process for producing a metal nitride ceramic component, the process comprising:

directing a laser beam or an electron beam to a metal nitride powder within a process chamber; and

maintaining the chamber at a temperature of 1,200°C or less throughout the process.

14. The process of Claim 13, wherein the process comprises electron beam melting (EBM) or selective laser melting (SLM) of the metal nitride powder.

15. The process of Claim 13, wherein the metal nitride powder comprises a particle size range between about 15-45 microns, about 20-63 microns, or about 45-106 microns.

16. The process of Claim 13, wherein the metal nitride component has a density percent of 95% or higher under an optical microscope.

17. The process of Claim 13, wherein the metal nitride ceramic component consists essentially of metal nitride.

18. The process of Claim 17, wherein the metal nitride comprises titanium nitride.

19. The process of Claim 13, wherein the metal nitride powder comprises titanium nitride powder.

20. The process of Claim 13, wherein the metal nitride powder is formed by reacting a metal powder and a nitrogen-containing gas within a microwave plasma.

21. The process of Claim 20, wherein the nitrogen-containing gas comprises hydrogen or argon.

22. A printed titanium nitride component.

23. The printed titanium nitride component of Claim 22, comprising a density percent of 95% or higher under an optical microscope.

24. The printed titanium nitride component of Claim 22, comprising a density of about 4.72 g/cc to 4.90 g/cc.

25. The printed titanium nitride component of Claim 22, comprising a stoichiometry of $\text{TiN}_{0.54}$.

26. The printed titanium nitride component of Claim 22, comprising phases of αTi , TiN and Ti_2N .

27. The printed titanium nitride component of Claim 22, comprising 13 to 14 wt.% nitrogen.

28. The printed titanium nitride component of Claim 22, wherein the component consists essentially of titanium nitride.

29. The printed titanium nitride component of Claim 22, wherein the component is entirely printed using additive manufacturing.

30. The printed titanium nitride component of Claim 22, comprising a cluster of printed cubes.

31. The printed titanium nitride component of Claim 22, wherein the component is a medical implant.