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(54) **PLASMA-ASSISTED SINTERING**

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(60) Provisional application No. 60/378,693, filed on May 8, 2002. Provisional application No. 60/430,677, filed on Dec. 4, 2002. Provisional application No. 60/435,278, filed on Dec. 23, 2002.

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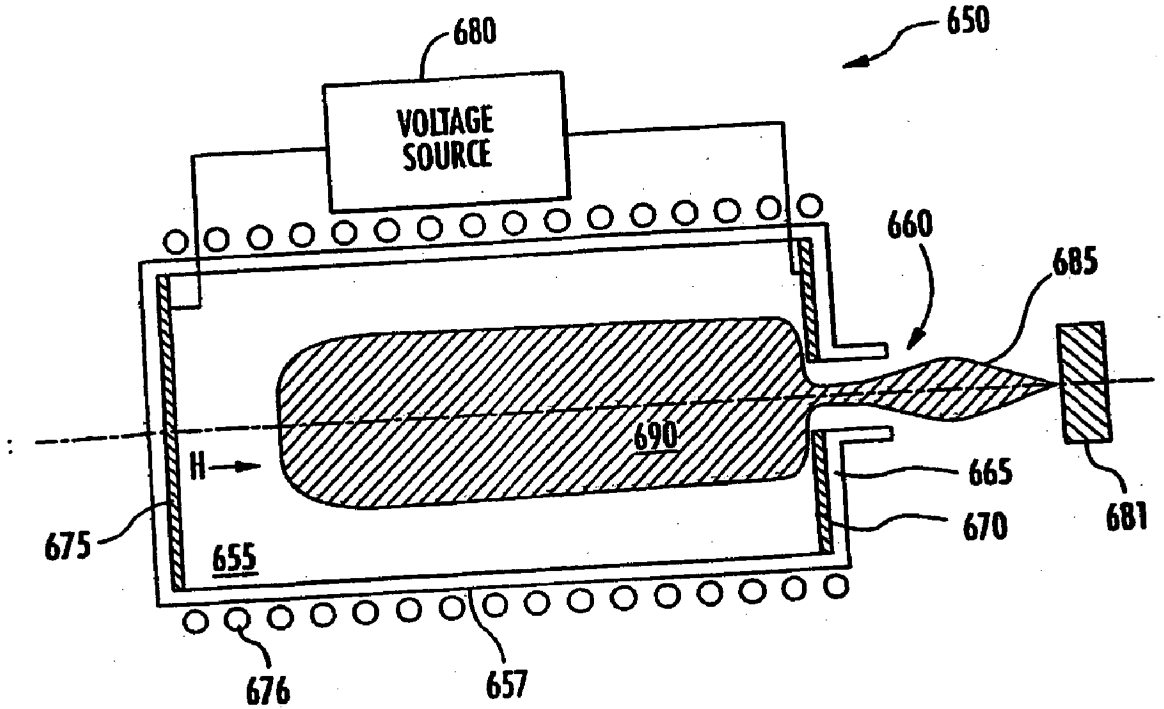
(57) **ABSTRACT**

Methods and systems for plasma-assisted sintering are provided. The method can include initiating a sintering plasma with a cavity **(12)** by subjecting a gas to radiation in the presence of a plasma catalyst and exposing at least a portion of an object which can be a powdered material component to the plasma for a period of time sufficient to sinter at least a portion of the object.



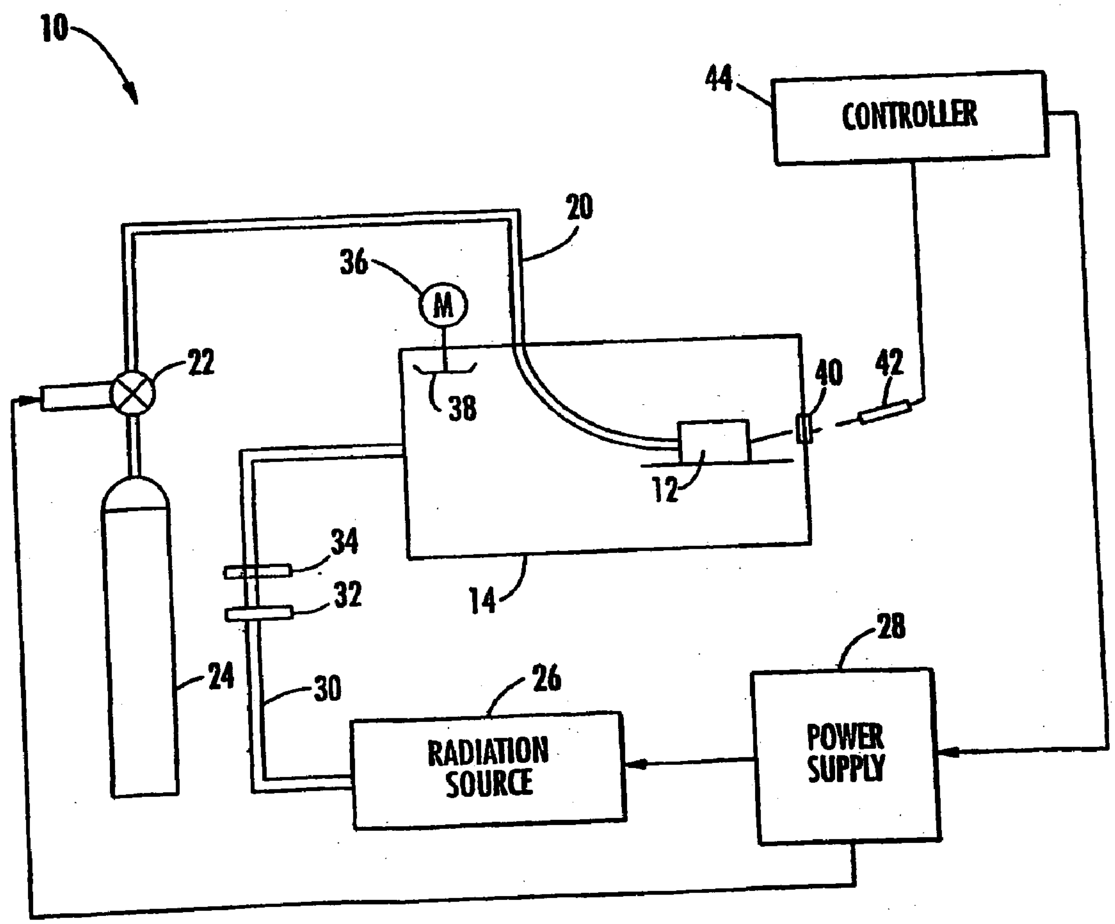

10
44
CONTROLLER
20
36
M
22
40
42
38
12
34
32
14
28
24
30
26
RADIATION SOURCE
POWER SUPPLY

FIG. 1

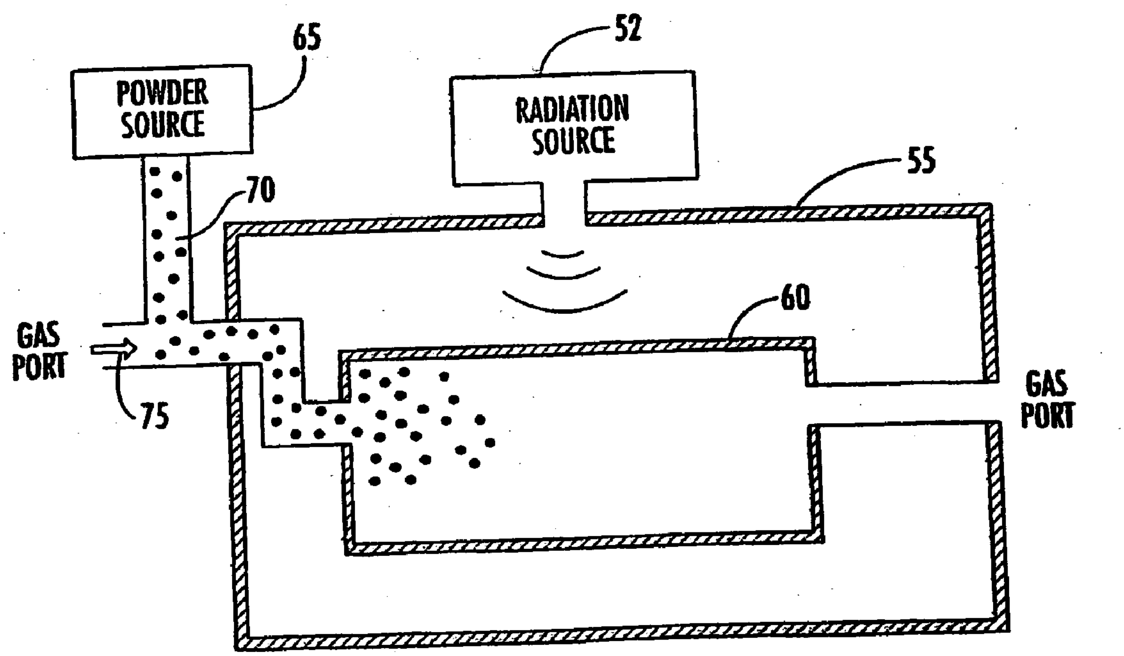

65
POWDER SOURCE
52
RADIATION SOURCE
55
70
60
GAS PORT
75
GAS PORT

FIG. 1A

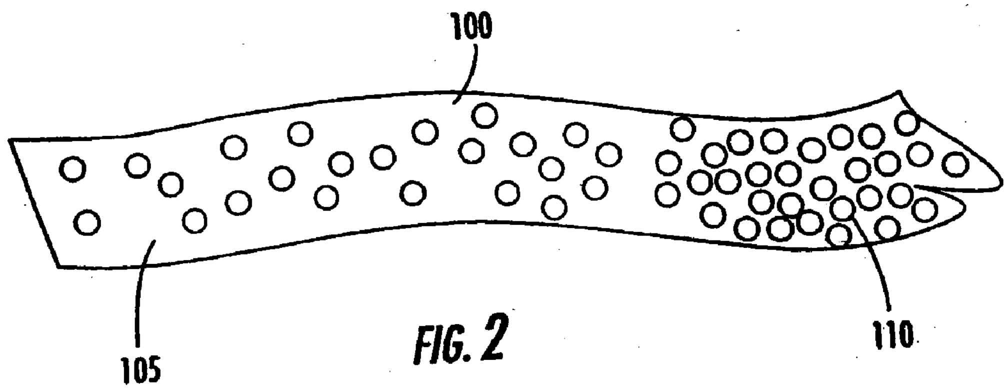


FIG. 2

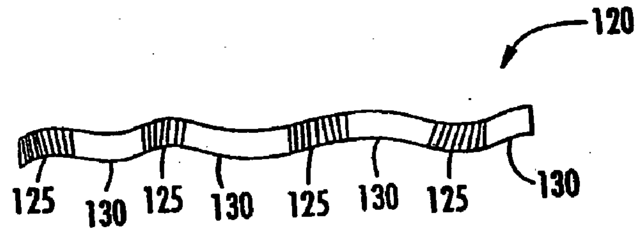


FIG. 3

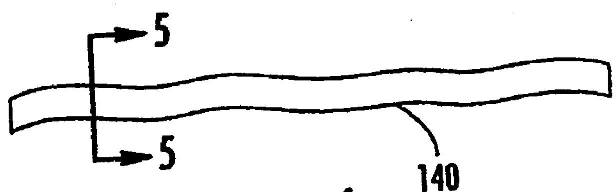


FIG. 4

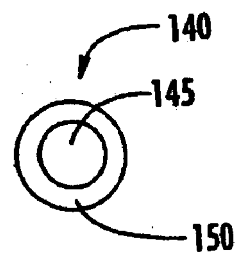


FIG. 5

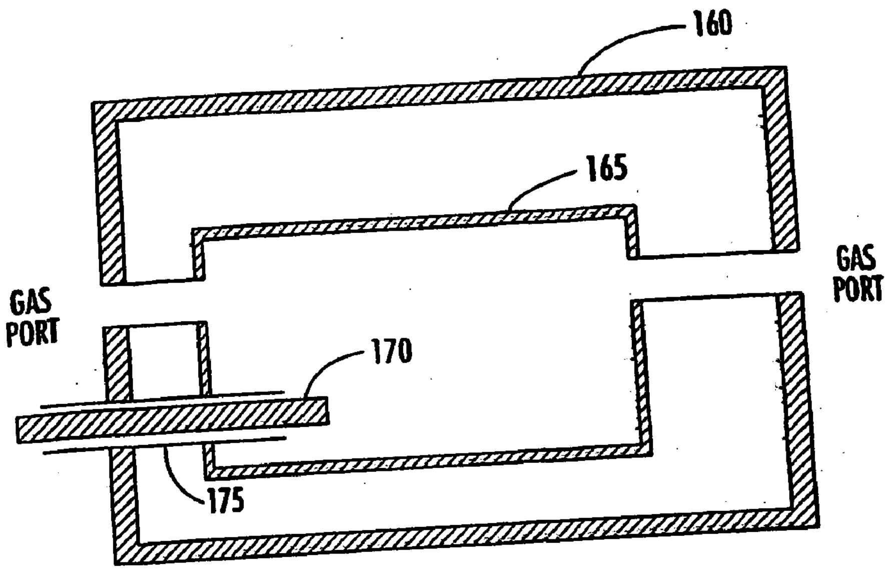


FIG. 6

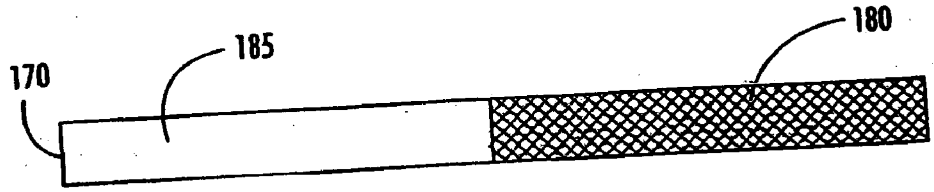


FIG. 7

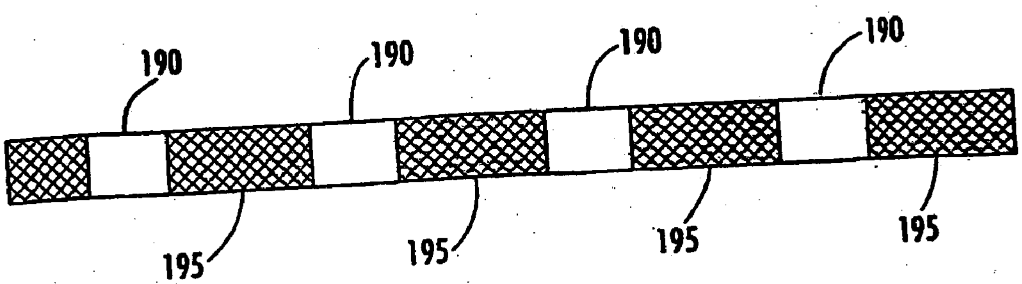


FIG. 8

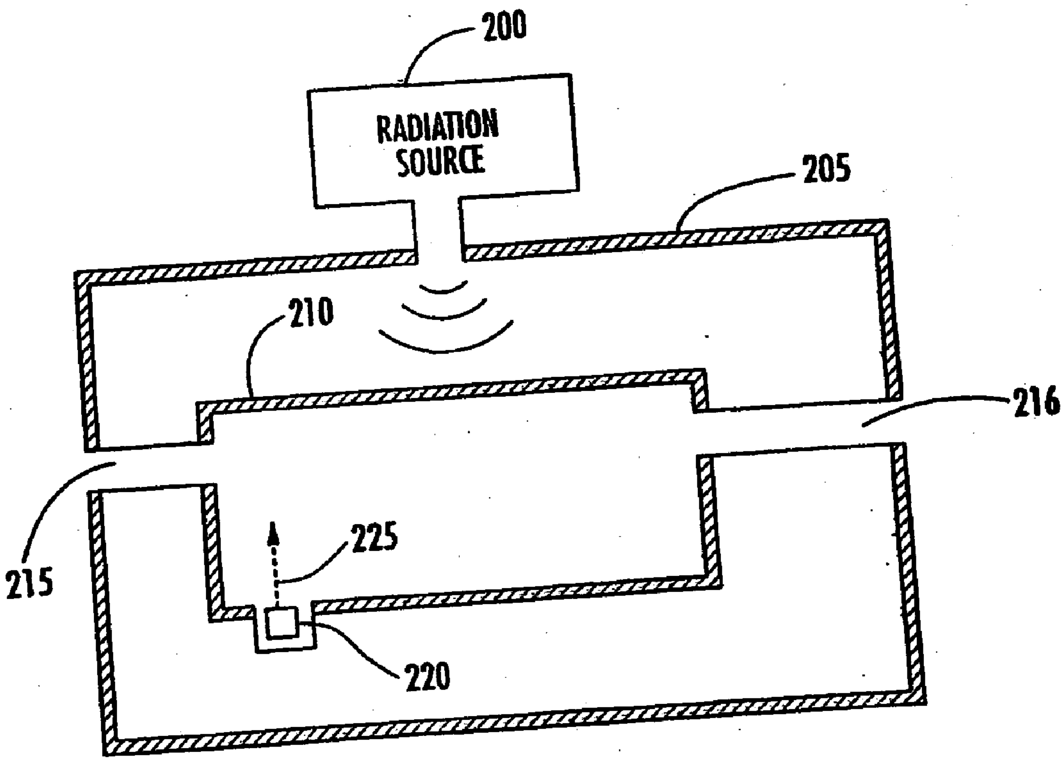


FIG. 9

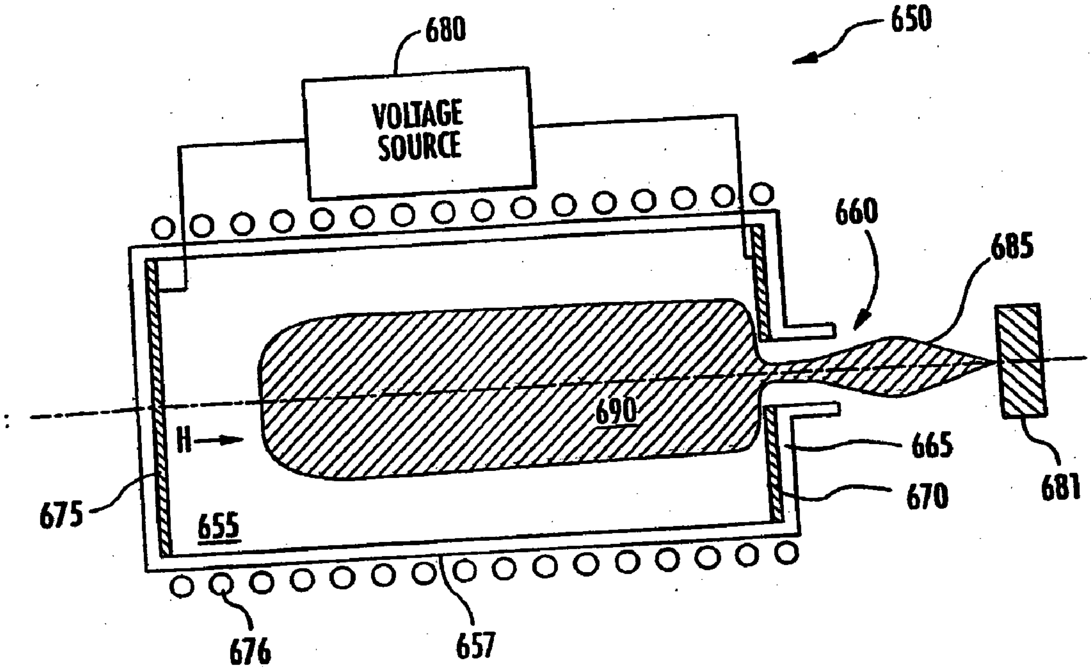

680
650
VOLTAGE SOURCE
660
685
690
H
665
670
675
655
681
676
657

FIG. 10

PLASMA-ASSISTED SINTERING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Priority is claimed to U.S. Provisional Patent Application No. 60/378,693, filed May 8, 2002, No. 60/430,677, filed Dec. 4, 2002, and No. 60/435,278, filed Dec. 23, 2002, all of which are fully incorporated herein by reference.

FIELD OF THE INVENTION

[0002] This invention relates to sintering systems and methods. More specifically, the invention relates to systems and methods for igniting, modulating, and sustaining plasmas from gases using electromagnetic radiation in the presence of plasma catalysts and for using the plasmas in sintering processes.

BACKGROUND

[0003] Various sintering methods are known. These methods can involve the thermal treatment of a powder at a temperature below its melting point. This thermal treatment can bond the powder particles together to increase the strength of the resulting sintered material.

[0004] Prior to some sintering processes, for example, the powder (e.g., a metal, ceramic, or other) can be compressed in a die under a large pressure to form a desired shape. Compaction of the powdered material may produce an object known as a compact. Prior to sintering, this compact is often referred to as a green part, and its density can depend on factors such as compaction pressure, dimensions of the compact, and powder hardness. Compacts generally have a low strength and a high porosity compared to their sintered counterparts. Sintering of the compacts may promote grain growth by solid-state diffusion and bonding between the powder particles of the compact.

[0005] While some sintering methods have reported acceptable results, some of these methods include several disadvantages. For example, some reported methods employ traditional furnaces for heating the materials to be sintered. It may difficult, however, to precisely control the temperature of the material using these furnaces. For example, for a particular rate of increase in temperature within the furnace, there may be a corresponding lag in the temperature of the material. This lag may be significant, and in certain sintering processes, not all of the material to be sintered may achieve a desired processing temperature or satisfy a desired time-temperature profile. This can lead to incomplete sintering of the material, and as a result, the sintered material may be less dense than predicted or desired.

[0006] Further, some sintering methods using conventional furnaces may not be suited for sintering objects with non-standard profiles or shapes, such as, for example, reentrant features, multiple thicknesses, thin or small features, and variable cross sections. For example, small or thin features may heat faster than the bulk of the object. As a result, these features may exhibit physical properties (e.g., porosity, density, etc.) upon sintering that are different from the bulk of the object. Moreover, atmospheric sintering furnaces may be slow in heating and may lack the ability to precisely control the temperature of the object.

[0007] Plasma-assisted sintering has also been reported. While plasma sintering methods may offer potential increases in heating rates over traditional furnace sintering methods, these plasma sintering methods normally involve the use of costly vacuum equipment. Further, generation of the sintering plasma may also depend upon the use of large electrical potentials of several hundred volts.

SUMMARY OF THE INVENTION

[0008] One aspect of the invention may provide a plasma-assisted method of sintering an object that includes at least one powdered material component. The method can include initiating a sintering plasma by subjecting a gas to electromagnetic radiation (e.g., microwave radiation) in the presence of a plasma catalyst. The method may further include exposing at least a portion of the object to the plasma for a period of time sufficient to sinter at least a portion of the at least one powdered material component.

[0009] Another aspect of the invention provides a system for plasma-assisted sintering of an object. The system can include a plasma catalyst, a vessel in which a cavity is formed and in which a plasma can be initiated by subjecting a gas to radiation in the presence of the plasma catalyst, a radiation source connected to the cavity for supplying radiation into the cavity, a gas source coupled to the cavity such that a gas can flow into the cavity during sintering.

[0010] A number of plasma catalysts are also provided for plasma-assisted sintering consistent with this invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Further aspects of the invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

[0012] **FIG. 1** shows a schematic diagram of an illustrative plasma-assisted sintering system consistent with this invention;

[0013] **FIG. 1A** shows an illustrative embodiment of a portion of a plasma-assisted sintering system for adding a powder plasma catalyst to a plasma cavity for igniting, modulating, or sustaining a plasma in a cavity consistent with this invention;

[0014] **FIG. 2** shows an illustrative plasma catalyst fiber with at least one component having a concentration gradient along its length consistent with this invention;

[0015] **FIG. 3** shows an illustrative plasma catalyst fiber with multiple components at a ratio that varies along its length consistent with this invention;

[0016] **FIG. 4** shows another illustrative plasma catalyst fiber that includes a core underlayer and a coating consistent with this invention;

[0017] **FIG. 5** shows a cross-sectional view of the plasma catalyst fiber of **FIG. 4**, taken from line **5-5** of **FIG. 4**, consistent with this invention;

[0018] **FIG. 6** shows an illustrative embodiment of another portion of a plasma system including an elongated plasma catalyst that extends through ignition port consistent with this invention;

[0019] FIG. 7 shows an illustrative embodiment of an elongated plasma catalyst that can be used in the system of FIG. 6 consistent with this invention;

[0020] FIG. 8 shows another illustrative embodiment of an elongated plasma catalyst that can be used in the system of FIG. 6 consistent with this invention;

[0021] FIG. 9 shows an illustrative embodiment of a portion of a plasma sintering system for directing radiation into a plasma chamber consistent with this invention; and

[0022] FIG. 10 shows an illustrative plasma-jet apparatus consistent with this invention.

DETAILED DESCRIPTION OF THE INVENTION

[0023] Methods and apparatus for plasma-assisted sintering may be provided consistent with this invention. The plasmas can be ignited, as well as modulated and sustained, with a plasma catalyst consistent with this invention.

[0024] The following commonly owned, concurrently filed U.S. patent applications are hereby incorporated by reference in their entireties: U.S. patent application Ser. No. 10/______ (Atty. Docket No. 1837.0008), Ser. No. 10/______ (Atty. Docket No. 1837.0009), Ser. No. 10/______ (Atty. Docket No. 1837.0010), Ser. No. 10/______ (Atty. Docket No. 1837.0011), Ser. No. 10/______ (Atty. Docket No. 1837.0013), Ser. No. 10/______ (Atty. Docket No. 1837.0015), Ser. No. 10/______ (Atty. Docket No. 1837.0016), Ser. No. 10/______ (Atty. Docket No. 1837.0017), Ser. No. 10/______ (Atty. Docket No. 1837.0018), Ser. No. 10/______ (Atty. Docket No. 1837.0020), Ser. No. 10/______ (Atty. Docket No. 1837.0021), Ser. No. 10/______ (Atty. Docket No. 1837.0023), Ser. No. 10/______ (Atty. Docket No. 1837.0024), Ser. No. 10/______ (Atty. Docket No. 1837.0025), Ser. No. 10/______ (Atty. Docket No. 1837.0026), Ser. No. 10/______ (Atty. Docket No. 1837.0027), Ser. No. 10/______ (Atty. Docket No. 1837.0028), Ser. No. 10/______ (Atty. Docket No. 1837.0029), Ser. No. 10/______ (Atty. Docket No. 1837.0030), Ser. No. 10/______ (Atty. Docket No. 1837.0032), and Ser. No. 10/______ (Atty. Docket No. 1837.0033).

[0025] Illustrative Plasma-Assisted Sintering System

[0026] FIG. 1 illustrates exemplary plasma sintering system 10 consistent with one aspect of this invention. In this embodiment, cavity 12 can be formed in a vessel that is positioned inside radiation chamber (i.e., applicator) 14. In another embodiment (not shown), vessel 12 and radiation chamber 14 are the same, thereby eliminating the need for two separate components. The vessel in which cavity 12 is formed can include one or more radiation-transmissive (e.g., microwave-transmissive) insulating layers to improve its thermal insulation properties without significantly shielding cavity 12 from the radiation.

[0027] In one embodiment, cavity 12 can be formed in a vessel made of ceramic. Due to the extremely high temperatures that can be achieved with plasmas consistent with this invention, a ceramic capable of operating at a temperature greater than about 2,000 degrees Fahrenheit, such as about 3,000 degrees Fahrenheit, can be used. The ceramic material can include, by weight, 29.8% silica, 68.2% alumina, 0.4% ferric oxide, 1% titania, 0.1% lime, 0.1% magnesia, 0.4% alkalies, which is sold under Model No. LW-30 by New Castle Refractories Company, of New Castle, Pa. It will be appreciated by those of ordinary skill in the art, however, that other materials, such as quartz, and those different from the one described above, can also be used consistent with the invention. It will be appreciated that other embodiments of the invention may include materials intended to operate at temperatures below about 2,000 degrees Fahrenheit.

[0028] In one successful experiment, a plasma was formed in a partially open cavity inside a first brick and topped with a second brick. The cavity had dimensions of about 2 inches by about 2 inches by about 1.5 inches. At least two holes were also provided in the brick in communication with the cavity: one for viewing the plasma and at least one hole for providing a gas from which the plasma can be formed. The size and shape of the cavity can depend on the sintering process being performed. Also, the cavity may be configured to discourage or prevent the plasma from rising/floating away from the primary processing region.

[0029] Cavity 12 can be connected to one or more gas sources 24 (e.g., a source of argon, nitrogen, hydrogen, xenon, krypton) by line 20 and control valve 22, which may be powered by power supply 28. In certain embodiments, a plasma can be formed from one or more gases supplied by gas source 24. Line 20 may be any channel capable of conveying the gas but can be narrow enough to prevent significant radiation leakage. For example, line 20 may be tubing (e.g., having a diameter between about 1/16 inch and about 1/4 inch, such as about 1/8"). Also, if desired, a vacuum pump can be connected to the chamber to remove any undesirable fumes that may be generated during plasma processing.

[0030] A radiation leak detector (not shown) was installed near source 26 and waveguide 30 and connected to a safety interlock system to automatically turn off the radiation (e.g., microwave) power supply assisted if a leak above a predefined safety limit, such as one specified by the FCC and/or OSHA (e.g., 5 mW/cm^2), was detected.

[0031] Radiation source 26, which may be powered by electrical power supply 28, can direct radiation energy into chamber 14 through one or more waveguides 30. It will be appreciated by those of ordinary skill in the art that source 26 can be connected directly to chamber 14, thereby eliminating waveguide 30. The radiation energy entering cavity 12 can be used to ignite a plasma within the cavity. This plasma can be modulated or substantially sustained and confined to the cavity by coupling additional radiation, such as microwave radiation, with the catalyst.

[0032] Radiation energy can be supplied through circulator 32 and tuner 34 (e.g., 3-stub tuner). Tuner 34 can be used to minimize the reflected power as a function of changing ignition or processing conditions, especially before the plasma has formed because microwave power, for example, will be strongly absorbed by the plasma.

[0033] As explained more fully below, the location of radiation-transmissive cavity 12 in chamber 14 may not be critical if chamber 14 supports multiple modes, and especially when the modes are continually or periodically mixed. For example, motor 36 can be connected to mode-mixer 38 for making the time-averaged radiation energy distribution substantially uniform throughout chamber **14**. Furthermore, window **40** (e.g., a quartz window) can be disposed in one wall of chamber **14** adjacent to cavity **12**, permitting temperature sensor **42** (e.g., an optical pyrometer) to be used to view a process inside cavity **12**. In one embodiment, the optical pyrometer has a voltage output that can vary with temperature to within a certain tracking range.

[**0034**] Sensor **42** can develop output signals as a function of the temperature or any other monitorable condition associated with a work piece (not shown) within cavity **12** and provide the signals to controller **44**. Dual temperature sensing and heating, as well as automated cooling rate and gas flow controls can also be used. Controller **44** in turn can be used to control operation of power supply **28**, which can have one output connected to radiation source **26** as described above and another output connected to valve **22** to control gas flow into radiation cavity **12**.

[**0035**] The invention has been practiced with equal success employing microwave sources at both 915 MHz and 2.45 GHz provided by Communications and Power Industries (CPI), although radiation having any frequency less than about 333 GHz can be used. The 2.45 GHz system provided continuously variable microwave power from about 0.5 kilowatts to about 5.0 kilowatts. A 3-stub tuner allowed impedance matching for maximum power transfer and a dual directional coupler (not shown in **FIG. 1**) was used to measure forward and reflected powers.

[**0036**] As mentioned above, radiation having any frequency less than about 333 GHz can be used consistent with this invention. For example, frequencies, such as power line frequencies (about 50 Hz to about 60 Hz), can be used, although the pressure of the gas from which the plasma is formed may be lowered to assist with plasma ignition. Also, any radio frequency or microwave frequency can be used consistent with this invention, including frequencies greater than about 100 kHz. In most cases, the gas pressure for such relatively high frequencies need not be lowered to ignite, modulate, or sustain a plasma, thereby enabling many plasma-processes to occur at atmospheric pressures and above.

[**0037**] The equipment was computer controlled using LabView 6i software, which provided real-time temperature monitoring and microwave power control. Noise was reduced by using sliding averages of suitable number of data points. Also, to improve speed and computational efficiency, the number of stored data points in the buffer array were limited by using shift-registers and buffer-sizing. The pyrometer measured the temperature of a sensitive area of about 1 cm^2, which was used to calculate an average temperature. The pyrometer sensed radiant intensities at two wavelengths and fit those intensities using Planck's law to determine the temperature.

[**0038**] It will be appreciated, however, that other devices and methods for monitoring and controlling temperature are also available and can be used consistent with this invention. Control software that can be used consistent with this invention is described, for example, in commonly owned, concurrently filed U.S. patent application Ser. No. 10/______ (Attorney Docket No. 1837.0033), which is hereby incorporated by reference in its entirety.

[**0039**] Chamber **14** may include several glass-covered viewing ports with microwave shields and a quartz window for pyrometer access. Several ports for connection to a vacuum pump and a gas source may also be provided, although not necessarily used.

[**0040**] System **10** may also include an optional closed-loop deionized water cooling system (not shown) with an external heat exchanger cooled by tap water. During operation, the deionized water may cool the magnetron, then the load-dump in the circulator (used to protect the magnetron), and finally the radiation chamber through water channels welded on the outer surface of the chamber.

[**0041**] Plasma Catalysts

[**0042**] A plasma catalyst consistent with this invention can include one or more different materials and may be either passive or active. A plasma catalyst can be used, among other things, to ignite, modulate, and/or sustain a plasma at a gas pressure that is less than, equal to, or greater than atmospheric pressure.

[**0043**] One method of forming a plasma consistent with this invention can include subjecting a gas in a cavity to electromagnetic radiation having a frequency of less than about 333 GHz in the presence of a passive plasma catalyst. A passive plasma catalyst consistent with this invention can include any object capable inducing a plasma by deforming a local electric field (e.g., an electromagnetic field) consistent with this invention, without necessarily adding additional energy through the catalyst, such as by applying an electric voltage to create a spark.

[**0044**] A passive plasma catalyst consistent with this invention can be, for example, a nano-particle or a nano-tube. As used herein, the term "nano-particle" can include any particle having a maximum physical dimension less than about 100 nm that is at least electrically semi-conductive. Also, both single-walled and multi-walled carbon nanotubes, doped and undoped, can be particularly effective for igniting plasmas consistent with this invention because of their exceptional electrical conductivity and elongated shape. The nanotubes can have any convenient length and can be a powder fixed to a substrate. If fixed, the nanotubes can be oriented randomly on the surface of the substrate or fixed to the substrate (e.g., at some predetermined orientation) while the plasma is ignited or sustained.

[**0045**] A passive plasma catalyst consistent with this invention can also be, for example, a powder and need not comprise nano-particles or nano-tubes. It can be formed, for example, from fibers, dust particles, flakes, sheets, etc. When in powder form, the catalyst can be suspended, at least temporarily, in a gas. By suspending the powder in the gas, the powder can be quickly dispersed throughout the cavity and more easily and uniformly consumed, if desired.

[**0046**] In one embodiment, the powder catalyst can be carried into the sintering cavity and at least temporarily suspended with a carrier gas. The carrier gas can be the same or different from the gas that forms the plasma. Also, the powder can be added to the gas prior to being introduced to the cavity. For example, as shown in **FIG. 1A**, radiation source **52** can supply radiation to cavity **55**, which includes plasma cavity **60** (e.g, where sintering may occur). Powder source **65** can provide catalytic powder **70** into gas stream **75**. In an alternative embodiment, powder **70** can be first added to cavity **60** in bulk (e.g., in a pile) and then distributed in the cavity in any number of ways, including flowing a gas through or over the bulk powder. In addition, the powder can be added to the gas for igniting, modulating, or sustaining a plasma by moving, conveying, drizzling, sprinkling, blowing, or otherwise feeding the powder into or within the cavity.

[0047] In one experiment, a plasma was ignited in a cavity by placing a pile of carbon fiber powder in a copper pipe that extended into the cavity. Although sufficient radiation was directed into the cavity, the copper pipe shielded the powder from the radiation and no plasma ignition took place. However, once a carrier gas began flowing through the pipe, forcing the powder out of the pipe and into the cavity, and thereby subjecting the powder to the radiation, a plasma was nearly instantaneously ignited in the cavity at about atmospheric pressure.

[0048] A powder plasma catalyst consistent with this invention can be substantially non-combustible, thus it need not contain oxygen or burn in the presence of oxygen. Thus, as mentioned above, the catalyst can include a metal, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nanocomposite, an organic-inorganic composite, and any combination thereof.

[0049] Also, powder catalysts can be substantially uniformly distributed in the plasma cavity (e.g., when suspended in a gas), and plasma ignition can be precisely controlled within the cavity. Uniform ignition can be important in certain applications, including those applications requiring brief plasma exposures, such as in the form of one or more bursts. Still, a certain amount of time can be required for a powder catalyst to distribute itself throughout a cavity, especially in complicated, multi-chamber cavities. Therefore, consistent with another aspect of this invention, a powder catalyst can be introduced into the cavity through a plurality of ignition ports to more rapidly obtain a more uniform catalyst distribution therein (see below).

[0050] In addition to powder, a passive plasma catalyst consistent with this invention can include, for example, one or more microscopic or macroscopic fibers, sheets, needles, threads, strands, filaments, yarns, twines, shavings, slivers, chips, woven fabrics, tape, whiskers, or any combination thereof. In these cases, the plasma catalyst can have at least one portion with one physical dimension substantially larger than another physical dimension. For example, the ratio between at least two orthogonal dimensions can be at least about 1:2, but can be greater than about 1:5, or even greater than about 1:10.

[0051] Thus, a passive plasma catalyst can include at least one portion of material that is relatively thin compared to its length. A bundle of catalysts (e.g., fibers) may also be used and can include, for example, a section of graphite tape. In one experiment, a section of tape having approximately thirty thousand strands of graphite fiber, each about 2-3 microns in diameter, was successfully used. The number of fibers in and the length of a bundle are not critical to igniting, modulating, or sustaining the plasma. For example, satisfactory results have been obtained using a section of graphite tape about one-quarter inch long. One type of carbon fiber that has been successfully used consistent wit this invention is sold under the trademark Magnamite® Model No. AS4C-GP3K, by the Hexcel Corporation, of Anderson, S.C. Also, silicon-carbide fibers have been successfully used.

[0052] A passive plasma catalyst consistent with another aspect of this invention can include one or more portions that are, for example, substantially spherical, annular, pyramidal, cubic, planar, cylindrical, rectangular or elongated.

[0053] The passive plasma catalysts discussed above can include at least one material that is at least electrically semi-conductive. In one embodiment, the material can be highly conductive. For example, a passive plasma catalyst consistent with this invention can include a metal, an inorganic material, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nanocomposite, an organic-inorganic composite, or any combination thereof. Some of the possible inorganic materials that can be included in the plasma catalyst include carbon, silicon carbide, molybdenum, platinum, tantalum, tungsten, and aluminum, although other electrically conductive inorganic materials are believed to work just as well.

[0054] In addition to one or more electrically conductive materials, a passive plasma catalyst consistent with this invention can include one or more additives (which need not be electrically conductive). As used herein, the additive can include any material that a user wishes to add to the plasma. For example, in sintering semiconductors and other materials, one or more dopants can be added to the plasma through the catalyst. See, e.g., commonly owned, concurrently filed U.S. patent application Ser. No. 10/______ (Atty. Docket No. 1837.0026), which is hereby incorporated by reference in its entirety. The catalyst can include the dopant itself, or it can include a precursor material that, upon decomposition, can form the dopant. Thus, the plasma catalyst can include one or more additives and one or more electrically conductive materials in any desirable ratio, depending on the ultimate desired composition of the plasma and the process using the plasma.

[0055] The ratio of the electrically conductive components to the additives in a passive plasma catalyst can vary over time while being consumed. For example, during ignition, the plasma catalyst could desirably include a relatively large percentage of electrically conductive components to improve the ignition conditions. On the other hand, if used while sustaining the plasma, the catalyst could include a relatively large percentage of additives. It will be appreciated by those of ordinary skill in the art that the component ratio of the plasma catalyst used to ignite and sustain the plasma could be the same.

[0056] In certain embodiments of the invention, a predetermined plasma catalyst ratio profile can be used. In some conventional plasma processes, the components within the plasma are added as necessary, but such addition normally requires programmable equipment to add the components according to a predetermined schedule. However, consistent with this invention, the ratio of components in the catalyst can be varied, and thus the ratio of components in the plasma itself can be automatically varied. That is, the ratio of components in the plasma at any particular time can depend on which of the catalyst portions is currently being consumed by the plasma. Thus, the catalyst component ratio can be different at different locations within the catalyst. And, the ratio of components in a plasma can depend on the portions of the catalyst currently and/or previously consumed, especially when the flow rate of a gas passing through the plasma chamber is relatively slow.

[0057] A passive plasma catalyst consistent with this invention can be homogeneous, inhomogeneous, or graded. Also, the plasma catalyst component ratio can vary continuously or discontinuously throughout the catalyst. For example, in **FIG. 2**, the component ratio can vary smoothly forming a ratio gradient along the length of catalyst **100**. Thus, catalyst **100** can include a strand of material that includes a relatively low concentration of one or more components at section **105** and a continuously increasing concentration toward section **110**.

[0058] Alternatively, as shown in **FIG. 3**, the ratio can vary discontinuously in each portion of catalyst **120**, which includes, for example, alternating sections **125** and **130** having different concentrations. It will be appreciated that catalyst **120** can have more than two section types. Thus, the catalytic component ratio being consumed by the plasma can vary in any predetermined fashion. In one embodiment, when the plasma is monitored and a particular additive is detected, further processing can be automatically commenced or terminated.

[0059] Another way to vary the ratio of components in a modulated or sustained plasma is by introducing multiple catalysts having different component ratios at different times or different rates. For example, multiple catalysts can be introduced at approximately the same location or at different locations within the cavity. When introduced at different locations, the plasma formed in the cavity can have a component concentration gradient determined by the locations of the various catalysts. Thus, an automated system can include a device by which a consumable plasma catalyst is mechanically inserted before and/or during plasma igniting, modulating, and/or sustaining a plasma.

[0060] A passive plasma catalyst consistent with this invention can also be coated. In one embodiment, a catalyst can include a substantially non-electrically conductive coating deposited on the surface of a substantially electrically conductive material. Alternatively, the catalyst can include a substantially electrically conductive coating deposited on the surface of a substantially electrically non-conductive material. **FIGS. 4 and 5**, for example, show fiber **140**, which includes underlayer **145** and coating **150**. In one embodiment, a plasma catalyst including a carbon core is coated with nickel to prevent oxidation of the carbon.

[0061] A single plasma catalyst can also include multiple coatings. If the coatings are consumed during contact with the plasma, the coatings could be introduced into the plasma sequentially, from the outer coating to the innermost coating, thereby creating a time-release mechanism. Thus, a coated plasma catalyst can include any number of materials, as long as a portion of the catalyst is at least electrically semiconductive.

[0062] Consistent with another embodiment of this invention, a plasma catalyst can be located entirely within a radiation cavity to substantially reduce or prevent radiation energy leakage via the catalyst. In this way, the plasma catalyst does not electrically or magnetically couple with the vessel containing the cavity or to any electrically conductive object outside the cavity. This prevents sparking at the ignition port and prevents radiation from leaking outside the cavity during the ignition and possibly later if the plasma is sustained. In one embodiment, the catalyst can be located at a tip of a substantially electrically nonconductive extender that extends through an ignition port.

[0063] **FIG. 6**, for example, shows radiation chamber **160** in which plasma cavity **165** is placed. Plasma catalyst **170** can be elongated and can extend through ignition port **175**. As shown in **FIG. 7**, and consistent with this invention, catalyst **170** can include electrically conductive distal portion **180** (which is placed in chamber **160** but can extend into chamber **160**) and electrically non-conductive portion **185** (which is placed substantially outside chamber **160**). This configuration prevents an electrical connection (e.g., sparking) between distal portion **180** and chamber **160**.

[0064] In another embodiment, shown in **FIG. 8**, the catalyst can be formed from a plurality of electrically conductive segments **190** separated by and mechanically connected to a plurality of electrically non-conductive segments **195**. In this embodiment, the catalyst can extend through the ignition port between a point inside the cavity ad another point outside the cavity, but the electrically discontinuous profile significantly prevents sparking and energy leakage.

[0065] As an alternative to the passive plasma catalysts described above, active plasma catalysts can be used consistent with this invention. A method of forming a sintering plasma using an active catalyst consistent with this invention can include subjecting a gas in a cavity to electromagnetic radiation having a frequency less than about 333 GHz in the presence of the active plasma catalyst, which generates or includes at least one ionizing particle or ionizing radiation. It will be appreciated that both passive and active plasma catalysts can be used in the same sintering process.

[0066] An active plasma catalyst consistent with this invention can be any particle or high energy wave packet capable of transferring a sufficient amount of energy to a gaseous atom or molecule to remove at least one electron from the gaseous atom or molecule in the presence of electromagnetic radiation. Depending on the source, the ionizing radiation and/or particles can be directed into the cavity in the form of a focused or collimated beam, or they may be sprayed, spewed, sputtered, or otherwise introduced.

[0067] For example, **FIG. 9** shows radiation source **200** directing radiation into chamber **205**. Plasma cavity **210** can be positioned inside of chamber **205** and may permit a gas to flow therethrough via ports **215** and **216**. Source **220** directs ionizing particles and/or radiation **225** into cavity **210**. Source **220** can be protected from the radiation provided by source **200** and the plasma formed thereform, for example, by a metallic screen that allows the ionizing particles to pass through but shields source **220** from the radiation. If necessary, source **220** can be water-cooled.

[0068] Examples of ionizing radiation and/or particles consistent with this invention can include x-rays, gamma radiation, alpha particles, beta particles, neutrons, protons, and any combination thereof. Thus, an ionizing particle catalyst can be charged (e.g., an ion from an ion source) or uncharged and can be the product of a radioactive fission process. In one embodiment, the vessel in which the plasma cavity is formed could be entirely or partially transmissive to the ionizing particle catalyst. Thus, when a radioactive fission source is located outside the cavity, the source can direct the fission products through the vessel to ignite the plasma. The radioactive fission source can be located inside the radiation chamber to substantially prevent the fission products (i.e., the ionizing particle catalyst) from creating a safety hazard.

[0069] In another embodiment, the ionizing particle can be a free electron, but it need not be emitted in a radioactive decay process. For example, the electron can be introduced into the cavity by energizing an electron source (such as a metal), such that the electrons have sufficient energy to escape from the source. The electron source can be located inside the cavity, adjacent the cavity, or even in the cavity wall. It will be appreciated by those of ordinary skill in the art that the any combination of electron sources is possible. A common way to produce electrons is to heat a metal, and these electrons can be further accelerated by applying an electric field.

[0070] In addition to electrons, free energetic protons can also be used to catalyze a plasma. In one embodiment, a free proton can be generated by-ionizing hydrogen and, optionally, accelerated with an electric field.

[0071] Multi-Mode Radiation Cavities

[0072] A radiation waveguide, cavity, or chamber can be designed to support or facilitate propagation of at least one electromagnetic radiation mode. As used herein, the term "mode" refers to a particular pattern of any standing or propagating electromagnetic wave that satisfies Maxwell's equations and the applicable boundary conditions (e.g., of the cavity). In a waveguide or cavity, the mode can be any one of the various possible patterns of propagating or standing electromagnetic fields. Each mode is characterized by its frequency and polarization of the electric field and/or the magnetic field vectors. The electromagnetic field pattern of a mode depends on the frequency, refractive indices or dielectric constants, and waveguide or cavity geometry.

[0073] A transverse electric (TE) mode is one whose electric field vector is normal to the direction of propagation. Similarly, a transverse magnetic (TM) mode is one whose magnetic field vector is normal to the direction of propagation. A transverse electric and magnetic (TEM) mode is one whose electric and magnetic field vectors are both normal to the direction of propagation. A hollow metallic waveguide does not typically support a normal TEM mode of radiation propagation. Even though radiation appears to travel along the length of a waveguide, it may do so only by reflecting off the inner walls of the waveguide at some angle. Hence, depending upon the propagation mode, the radiation (e.g., microwave radiation) may have either some electric field component or some magnetic field component along the axis of the waveguide (often referred to as the z-axis).

[0074] The actual field distribution inside a cavity or waveguide is a superposition of the modes therein. Each of the modes can be identified with one or more subscripts (e.g., TE_{10} ("tee ee one zero")). The subscripts normally specify how many "half waves" at the guide wavelength are contained in the x and y directions. It will be appreciated by those skilled in the art that the guide wavelength can be different from the free space wavelength because radiation propagates inside the waveguide by reflecting at some angle from the inner walls of the waveguide. In some cases, a third subscript can be added to define the number of half waves in the standing wave pattern along the z-axis.

[0075] For a given radiation frequency, the size of the waveguide can be selected to be small enough so that it can support a single propagation mode. In such a case, the system is called a single-mode system (i.e., a single-mode applicator). The TE_{10} mode is usually dominant in a rectangular single-mode waveguide.

[0076] As the size of the waveguide (or the cavity to which the waveguide is connected) increases, the waveguide or applicator can sometimes support additional higher order modes forming a multi-mode system. When many modes are capable of being supported simultaneously, the system is often referred to as highly moded.

[0077] A simple, single-mode system has a field distribution that includes at least one maximum and/or minimum. The magnitude of a maximum largely depends on the amount of radiation supplied to the system. Thus, the field distribution of a single mode system is strongly varying and substantially non-uniform.

[0078] Unlike a single-mode cavity, a multi-mode cavity can support several propagation modes simultaneously, which, when superimposed, results in a complex field distribution pattern. In such a pattern, the fields tend to spatially smear and, thus, the field distribution usually does not show the same types of strong minima and maxima field values within the cavity. In addition, as explained more fully below, a mode-mixer can be used to "stir" or "redistribute" modes (e.g., by mechanical movement of a radiation reflector). This redistribution desirably provides a more uniform time-averaged field distribution within the cavity.

[0079] A multi-mode sintering processing cavity consistent with this invention can support at least two modes, and may support many more than two modes. Each mode has a maximum electric field vector. Although there may be two or more modes, one mode may be dominant and may have a maximum electric field vector magnitude that is larger than the other modes. As used herein, a multi-mode cavity may be any cavity in which the ratio between the first and second mode magnitudes is less than about 1:10, or less than about 1:5, or even less than about 1:2. It will be appreciated by those of ordinary skill in the art that the smaller the ratio, the more distributed the electric field energy between the modes, and hence the more distributed the radiation energy is in the cavity.

[0080] The distribution of plasma within a sintering processing cavity may strongly depend on the distribution of the applied radiation. For example, in a pure single mode system, there may only be a single location at which the electric field is a maximum. Therefore, a strong plasma may only form at that single location. In many applications, such a strongly localized plasma could undesirably lead to non-uniform plasma treatment or heating (i.e., localized overheating and underheating).

[0081] Whether or not a single or multi-mode sintering processing cavity is used consistent with this invention, it will be appreciated by those of ordinary skill in the art that the cavity in which the plasma is formed can be completely dosed or partially open. For example, in certain applications, such as in plasma-assisted furnaces, the cavity could be entirely closed. See, for example, commonly owned, concurrently filed U.S. patent application Ser. No. 10/______ (Attorney Docket No. 1837.0020), which is fully incorporated herein by reference. In other applications, however, it may be desirable to flow a gas through the cavity, and therefore the cavity must be open to some degree. In this way, the flow, type, and pressure of the flowing gas can be varied over time. This may be desirable because certain gases that facilitate formation of plasma, such as argon, for example, are easier to ignite but may not be needed during subsequent plasma processing.

[0082] Mode-Mixing

[0083] For many sintering applications, a cavity containing a substantially uniform plasma is desirable. Therefore, consistent with one aspect of this invention, the radiation modes in a multi-mode cavity can be mixed, or redistributed, over a period of time to provide a more uniform radiation field distribution. Because the field distribution within the cavity must satisfy all of the boundary conditions set by the inner surface of the cavity, those field distributions can be changed by changing the position of any portion of that inner surface.

[0084] In one embodiment consistent with this invention, a movable reflective surface can be located inside the sintering cavity. The shape and motion of the reflective surface can change the reflective properties of the inner surface of the cavity, as a whole, during motion. For example, an "L" shaped metallic object (i.e., "mode-mixer") when rotated about any axis will change the location or the orientation of the reflective surfaces in the cavity and therefore change the radiation distribution therein. Any other asymmetrically shaped object can also be used (when rotated), but symmetrically shaped objects can also work, as long as the relative motion (e.g., rotation, translation, or a combination of both) causes some change in the location or orientation of the reflective surfaces. In one embodiment, a mode-mixer can be a cylinder that is rotatable about an axis that is not the cylinder's longitudinal axis.

[0085] Each mode of a multi-mode sintering cavity may have at least one maximum electric field vector, but each of these vectors could occur periodically across the inner dimension of the cavity. Normally, these maxima are fixed, assuming that the frequency of the radiation does not change. However, by moving a mode-mixer such that it interacts with the radiation, it is possible to move the positions of the maxima. For example, mode-mixer **38** can be used to optimize the field distribution within sintering cavity **12** such that the plasma ignition conditions and/or the plasma sustaining conditions are optimized. Thus, once a plasma is excited, the position of the mode-mixer can be changed to move the position of the maxima for a uniform time-averaged plasma process (e.g., sintering).

[0086] Thus, consistent with this invention, mode-mixing can be useful during plasma ignition. For example, when an electrically conductive fiber is used as a plasma catalyst, it is known that the fiber's orientation can strongly affect the minimum plasma-ignition conditions. When such a fiber is oriented at an angle that is greater than 60° to the electric field, for example, the catalyst does little to improve, or relax, these conditions. By moving a reflective surface either in or near the sintering cavity, however, the electric field distribution can be significantly changed.

[0087] Mode-mixing can also be achieved by launching the radiation into the applicator chamber through, for example, a rotating waveguide joint that can be mounted inside the applicator chamber. The rotary joint can be mechanically moved (e.g., rotated) to effectively launch the radiation in different directions in the radiation chamber. As a result, a changing field pattern can be generated inside the applicator chamber.

[0088] Mode-mixing can also be achieved by launching radiation in the radiation chamber through a flexible waveguide. In one embodiment, the waveguide can be mounted inside the chamber. In another embodiment, the waveguide can extend into the chamber. The position of the end portion of the flexible waveguide can be continually or periodically moved (e.g., bent) in any suitable manner to launch the radiation (e.g., microwave radiation) into the chamber at different directions and/or locations. This movement can also result in mode-mixing and facilitate more uniform plasma processing (e.g., sintering) on a time-averaged basis. Alternatively, this movement can be used to optimize the location of a plasma for ignition or other plasma-assisted process.

[0089] If the flexible waveguide is rectangular, for example, a simple twisting of the open end of the waveguide will rotate the orientation of the electric and the magnetic field vectors in the radiation inside the applicator chamber. Then, a periodic twisting of the waveguide can result in mode-mixing as well as rotating the electric field, which can be used to assist ignition, modulation, or sustaining of a plasma.

[0090] Thus, even if the initial orientation of the catalyst is perpendicular to the electric field, the redirection of the electric field vectors can change the ineffective orientation to a more effective one. Those skilled in the art will appreciate that mode-mixing can be continuous, periodic, or preprogrammed.

[0091] In addition to plasma ignition, mode-mixing can be useful during subsequent sintering processes and other types of plasma processing to reduce or create (e.g., tune) "hot spots" in the chamber. When a cavity only supports a small number of modes (e.g., less than 5), one or more localized electric field maxima can lead to "hot spots" (e.g., within cavity **12**). In one embodiment, these hot spots could be configured to coincide with one or more separate, but simultaneous, plasma ignitions or sintering events. Thus, the plasma catalyst can be located at one or more of those ignition or subsequent plasma processing positions.

[0092] Multi-Location Ignition

[0093] A sintering plasma can be ignited using multiple plasma catalysts at different locations. In one embodiment, multiple fibers can be used to ignite the plasma at different points within the cavity. Such multi-point ignition can be especially beneficial when a uniform plasma ignition is desired. For example, when a plasma is modulated at a high frequency (i.e., tens of Hertz and higher), or ignited in a relatively large volume, or both, substantially uniform instantaneous striking and restriking of the plasma can be improved. Alternatively, when plasma catalysts are used at multiple points, they can be used to sequentially ignite a sintering plasma at different locations within a plasma chamber by selectively introducing the catalyst at those different locations. In this way, a sintering plasma ignition gradient can be controllably formed within the cavity, if desired.

[0094] Also, in a multi-mode sintering cavity, random distribution of the catalyst throughout multiple locations in the cavity can increase the likelihood that at least one of the fibers, or any other passive plasma catalyst consistent with this invention, is optimally oriented with the electric field lines. Still, even where the catalyst is not optimally oriented (not substantially aligned with the electric field lines), the ignition conditions are improved.

[0095] Furthermore, because a catalytic powder can be suspended in a gas, it is believed that each powder particle may have the effect of being placed at a different physical location within the cavity, thereby improving ignition uniformity within the sintering cavity.

[0096] Dual-Cavity Plasma Igniting/Sustaining

[0097] A dual-cavity arrangement can be used to ignite and sustain a plasma consistent with this invention. In one embodiment, a system includes at least an ignition cavity and a sintering cavity in fluid communication with the ignition cavity. To ignite a plasma, a gas in the ignition cavity can be subjected to electromagnetic radiation having a frequency less than about 333 GHz, optionally in the presence of a plasma catalyst. In this way, the proximity of the ignition and sintering cavities may permit a plasma formed in the ignition cavity to ignite a sintering plasma in the sintering cavity, which may be modulated or sustained with additional electromagnetic radiation.

[0098] In one embodiment of this invention, the ignition cavity can be very small and designed primarily, or solely, for plasma ignition. In this way, very little microwave energy may be required to ignite the plasma, permitting easier ignition, especially when a plasma catalyst is used consistent with this invention.

[0099] In one embodiment, the ignition cavity may be a substantially single mode cavity and the sintering cavity may be a multi-mode cavity. When the ignition cavity only supports a single mode, the electric field distribution may strongly vary within the cavity, forming one or more precisely located electric field maxima. Such maxima are normally the first locations at which plasmas ignite, making them ideal points for placing plasma catalysts. It will be appreciated, however, that when a plasma catalyst is used, it need not be placed in the electric field maximum and, many cases, need not be oriented in any particular direction.

[0100] Illustrative Sintering Processes

[0101] Consistent with the invention, there may be provided a method of sintering an object (e.g., a compact or other powder metallurgy part) that includes at least one powdered material component. In an illustrative embodiment of the invention, a sintering plasma may be initiated within a cavity, as described above, by subjecting a gas (e.g., supplied by gas source **24** of **FIG. 1**) to radiation (e.g., supplied by radiation source **26** of **FIG. 1**) in the presence of a plasma catalyst. Plasma ignition may occur within cavity **12**, which may be formed in a vessel positioned inside chamber (i.e., applicator) **14**. The plasma source gas may be supplied to the cavity substantially simultaneously or at different times with the radiation used to initiate the plasma.

[0102] Thus, a sintering plasma consistent with the invention may be initiated using a plasma catalyst. While a sintering plasma may be initiated without the use of a plasma catalyst, the presence of a passive or active plasma catalyst consistent with this invention may reduce the radiation energy density needed to ignite, modulate, or sustain the sintering plasma. This reduction may allow a plasma to be generated in a controlled manner with a relatively low amount of radiation energy, which can be especially useful when sensitive portions of an object are exposed to the sintering plasma. In one embodiment, a sintering plasma may be ignited using a time-averaged radiation energy (e.g., microwave energy) density below about 10 W/cm^3, or below about 5 W/cm^3. Advantageously, plasma ignition can be achieved at these relatively low energy densities without the use of vacuum equipment.

[0103] In addition to ignition, the use of a plasma catalyst may facilitate control over any portion of the plasma-assisted sintering process. Specifically, because plasma can be an efficient absorber of electromagnetic radiation, including microwave radiation, any radiation used to initiate the sintering plasma may be mostly and immediately absorbed by the plasma. Therefore, the radiation energy directed into a sintering cavity may be less subject to reflection at the early stages of generating the plasma. As a result, a plasma catalyst may be used to increase control over the heating rate of an object exposed to the plasma, the temperature of an object, or any other plasma-assisted process.

[0104] The use of a plasma catalyst may also enable initiation of a sintering plasma over a broad range of pressures including pressures less than, equal to, or greater than atmospheric pressure. Thus, a sintering plasma consistent with the invention may be ignited, modulated, and sustained not only in vacuum environments, where the total pressure is less than atmospheric pressure, but also at pressures at or above atmospheric pressure.

[0105] The temperature of catalyzed plasmas may be precisely controlled consistent with the invention. For example, the temperature can be controlled by varying the amount of radiation supplied to the plasma. Because heat from the plasma may be efficiently transferred to objects, the temperature of an object to be sintered may be accurately varied by controlling the temperature of the plasma and the exposure level between the object and the plasma. For example, in a sintering process consistent with the invention, the plasma may be used to adjust the temperature of an object to a predetermined sintering temperature, such as by varying the position of a mode-mixer or varying the rate at which gas flows through the sintering cavity.

[0106] Energy can be transferred from the plasma to an object at any desirable rate. For example, the heating rate of an object may reduced by reducing the power level of the radiation supplied to the plasma and/or by limiting the amount of exposure between the object and the plasma (e.g., via mode-mixing, modulating, etc.). By increasing the radiation power level and/or the amount of plasma exposure, however, the rate of increase of the temperature of an object may be increased. For example, in certain embodiments, at least a portion of an object exposed to the plasma may be heated at a rate of at least 400 degrees Celsius per minute.

[0107] The temperature of the object also may be controlled by adjusting the percentage of the total surface area of the object exposed to the plasma. Exposure of the object to the plasma may be sustained for any period of time sufficient to sinter at least a portion of the powdered material component of the object. The exposure time may be varied to affect the properties of the sintered object. For example, longer exposure times may promote more complete sintering and, therefore, more dense objects.

[0108] Plasma-assisted sintering of the present invention can also be used to sinter an object that includes more than one powdered material component. Such an object can be sintered by exposing the object to the sintering plasma until its temperature approaches the melting temperature of any one of the powdered material components. In certain embodiments, an object may be liquid phase sintered by heating the object to a temperature above the melting temperature of at least one of the powdered material components of the object. Thus, the presence of a liquid phase from the melted powdered material component(s) may facilitate sintering in some embodiments. It will be appreciated that powdered material components may include metals, ceramics, ores, salts, alloys, silicon, aluminum, tungsten, carbon, iron, oxygen-containing compounds, nitrogen-containing compounds, and any combination thereof.

[0109] Consistent with the plasma-assisted sintering methods of the invention, the object may be uniformly sintered or may be subjected to a non-uniform sintering pattern. In one embodiment, the sintering cavity may include an interior surface with one or more surface features. During exposure to the plasma, a sintering pattern can be formed on the sintered object based on these surface feature(s).

[0110] For example, the surface features on the interior of the plasma sintering cavity may affect sintering by effectively masking certain areas of the object from the sintering plasma. As previously discussed, the number or order of modes of the radiation in cavity **12** may depend on the size or configuration of the cavity. The presence of an object to be sintered within cavity **12** may also affect the field distribution in the modes of radiation within the cavity. The boundary conditions for normal incidence of electromagnetic radiation on metallic objects require that the electric field at the surface be zero and the first maxima occur at a distance of a quarter wavelength from the surface of the object. Consequently, if the gap between the surface of the metallic object and the inner wall of the cavity is less than about a quarter wavelength of the radiation, little or no sintering plasma may be sustained in these areas, and the regions of the object satisfying this condition may experience little or no sintering. These "masked" surface regions may be provided through positioning of the object within cavity **12**, by configuring the walls of cavity **12**, or by any other suitable method for controlling the distance between the surface of the object and the cavity walls.

[0111] In order to generate or maintain a substantially uniform time-averaged radiation field distribution within cavity **12**, mode mixer **38** may be provided, as shown in **FIG. 1**. Alternatively, or additionally, the object may be moved with respect to the plasma while being exposed to the plasma. Such motion may provide more uniform exposure of all surface regions of the object to the plasma, which may cause more uniform heating of the object or may assist in heating certain areas of the object more rapidly than other areas.

[0112] An electric potential bias may be applied to the object during the plasma-assisted sintering processes consistent with the invention. Such a potential bias may facilitate heating of the object by attracting the charged ions in the plasma to the object. Such an attraction may encourage uniform coverage of the plasma over the object and contribute to more uniform heating of the object. The potential bias applied to the object may be, for example, an AC bias, a DC bias, or a pulsed DC bias. The magnitude of the bias may be selected according to a particular application. For example, the magnitude of the voltage may range from 0.1 volts to 100 volts, or even several hundred volts depending on the desired rate of attraction of the ionized species. Further, the bias may be either positive or negative. In addition to an electric potential bias, a magnetic field source may positioned with respect to the object to apply a magnetic field to the object during plasma-assisted sintering.

[0113] It will be appreciated by those of ordinary skill in the art that the plasma-assisted sintering methods consistent with this invention need not occur within a cavity. Rather, a sintering plasma formed in a cavity can be flowed through an aperture in the form of a plasma jet, for example, and used outside the cavity to heat an object located adjacent to the aperture.

[0114] **FIG. 10** shows illustrative apparatus **650** for forming a sintering plasma jet for sintering objects consistent with this invention. Apparatus **650** can include vessel **657**, in which cavity **655** can be formed, and a gas source (not shown) for directing a gas into cavity **655**. Cavity **655** can include at least one aperture **660** formed in cavity wall **665**. An electromagnetic radiation source for directing electromagnetic radiation into cavity **655** and a plasma catalyst for relaxing the plasma ignition, modulation, and sustaining conditions can also be included, although they are not necessary, nor are they shown in **FIG. 10** for illustrative simplicity. Additional methods and apparatus for forming a plasma jet are described in commonly owned, concurrently filed U.S. patent application Ser. No. 10/______ (Attorney Docket No. 1837.0025), which is hereby incorporated by reference in its entirety.

[0115] Consistent with this invention, cavity **655** can include electrically conductive and substantially thermally resistant inner surface **670**, which can be proximate to aperture **660**, electrically conductive surface **675**, which faces surface **670**, and voltage source **680**, which can apply a potential difference between surfaces **670** and **675**. A magnetic field H can also be applied to the plasma by passing an electric current through coil winding **676**, which can be external or internal to vessel **657**.

[0116] A method for forming plasma jet **685** at aperture **660** can also be provided. The method can include (1) flowing a gas into cavity **655**, (2) forming plasma **690** from the gas in cavity **655**, (3) allowing at least a portion of plasma **690** to pass out of cavity **655** through aperture **660** such that plasma jet **685** is formed outside cavity **655** proximate to aperture **660**, and (4) applying an electric potential between surfaces **670** and **675** and/or passing an electric current through coil **676**.

[0117] Application of an electric potential between surfaces **670** and **675** can cause plasma **690** to accelerate charged particles to move toward aperture **660**. Surfaces **670** and **675** can be disposed on, or be integral with, vessel **657**. Alternatively, surfaces **670** and **675** can be separate from the internal surface of vessel **657**. In this case, these surfaces can be plates or screens that are suspended or otherwise mounted in cavity **655**. Alternatively, surfaces **670** and **675** can be discs or rings or any other part having a convenient shape configured for use in plasma cavity **655**.

[0118] Magnetic field H can be generated by passing a current through coil **676** and applied to plasma **690**. The magnetic field can exert a deflecting force on the charged particles that try to move perpendicular to the magnetic field. Consequently, charged particles in the plasma will be less able to move radially outward (i.e., perpendicular to the longitudinal axis of coil **676**) and, as a result, the inner surface of cavity **655** close to coil **676** will be heated less. In addition, because the plasma will tend to form along the longitudinal axis of coil **676**, a hotter and more efficient plasma jet can be formed.

[0119] The potential can be applied between surfaces **670** and **675** during any time period, including before the formation of plasma **690**, during the formation of plasma **690**, and after the formation of plasma **690**, although the principal benefit may result when the potential is applied while the plasma is formed (that is, while the plasma is being modulated or sustained) in cavity **655**. Also, magnetic field H can be applied at any time, including before, during, or after plasma formation. As a result, one or more plasma characteristics (e.g., physical shape, density, etc.) can be varied by applying a potential between surfaces **670** and **675** and a current through coil **676**.

[0120] The potential difference can cause surface **670** to be more positive or more negative than surface **675**. In one embodiment, positively charged ions of atoms and molecules within plasma **690** can be attracted toward surface **670** by applying a relatively negative potential to surface **670**. Because the positive ions, which are attracted by negative surface **670**, will transfer at least some of the kinetic energy to surface **670**, surface **670** can be made from a material that can withstand relatively high temperatures (e.g., 1,000 degrees Fahrenheit and above). In one embodiment, that surface can include molybdenum, which is also electrically conductive.

[0121] In another embodiment, surface **670** can include two or more layers. The outer layer, which faces or contacts plasma **690** during operation, can be selected to withstand very high temperatures (although not necessarily electrically conductive). The under layer, then, can be electrically conductive, but not necessarily capable of withstanding very high temperatures. Additional layers can be used as well to enhance its heat-resistance and/or its electrical conductivity.

[0122] An electric potential can also be applied between vessel **657** and work piece **681** can be located outside cavity **655** to accelerate plasma **690** through aperture **660** toward a surface of work piece **681**. When a sufficient electric current flows through the work piece, the temperature of the work piece can be increased through a resistive heating as well as from the kinetic energy of the charged particles striking the work piece.

[0123] In addition to sintering, the plasma of the present invention may be used in processes performed either prior to, simultaneously, or subsequent to the sintering process. That is, before, during, or after the sintering process, a source of a processing material may be supplied to the plasma. By exposing an object to the plasma, the object can be subjected to a treatment using the processing material. For example, in one embodiment, the processing material can include carbon, and the treatment may comprise carburizing. During carburizing, some of the carbon supplied to the plasma may diffuse into the surface of the object. In another embodiment, the processing material can include nitrogen, and the treatment may comprise nitriding. During nitriding, some of the nitrogen supplied to the plasma may diffuse into the surface of the object. Both carburizing and nitriding can result in a hardened surface layer formed on the object.

[0124] Additionally, the plasma consistent with the invention may be used for depositing a coating on the surface of the object before, during, or after sintering. In one embodiment, a coating material may be supplied to the plasma. This material may dissociate and/or disperse within the plasma. By exposing the object to the plasma containing the coating material, some of the coating material may be deposited on the surface of the object. Coatings that may be deposited on the object may include at least one of tungsten carbide, tungsten nitride, tungsten oxide, tantalum nitride, tantalum oxide, titanium oxide, titanium nitride, silicon oxide, silicon carbide, silicon nitride, aluminum oxide, aluminum nitride, aluminum carbide, boron nitride, boron carbide, boron oxide, gallium phosphide, aluminum phosphide, chromium oxide, tin oxide, yttria, zirconia, silicon-germanium, indium tin oxide, indium gallium arsenide, aluminum gallium arsenide, boron, chromium, gallium, germanium, indium, phosphorus, magnesium, silicon, tantalum, tin, titanium, tungsten, yttrium, and zirconium.

[0125] Still other processes may be performed in conjunction with the sintering process of the invention. For example, after sintering, the plasma may be used to heat treat the object. Such a heat treatment may alter one or more properties of the sintered part (e.g., hardness, ductility, grain size, etc.).

[0126] In the foregoing described embodiments, various features are grouped together in a single embodiment for purposes of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the following claims are hereby incorporated into this Detailed Description of Embodiments, with each claim standing on its own as a separate preferred embodiment of the invention.

We claim:

1. A method of plasma-assisted sintering of an object including at least one powdered material component, the method comprising:

initiating a plasma in a first cavity by subjecting a gas in the first cavity to electromagnetic radiation having a frequency less than about 333 GHz in the presence of a plasma catalyst; and

exposing at least a portion of the object to the plasma for a period of time sufficient to sinter at least a portion of the at least one powdered material component.

2. The method of claim 1, wherein the plasma catalyst includes at least one of a passive plasma catalyst and an active plasma catalyst.

3. The method of claim 1, wherein the plasma catalyst includes at least one of powdered carbon, carbon nanotubes, carbon nanoparticles, carbon fibers, graphite, solid carbon, and any combination thereof.

4. The method of claim 1, wherein the plasma catalyst includes at least one of x-rays, gamma radiation, alpha particles, beta particles, neutrons, protons, and any combination thereof.

5. The method of claim 1, wherein the plasma catalyst includes at least one of electrons and ions.

6. The method of claim 1, wherein the plasma catalyst includes at least one of a metal, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nanocomposite, an organic-inorganic composite, and any combination thereof.

7. The method of claim 1, further comprising placing the portion of the object in a location selected from within the first cavity and adjacent an aperture in the first cavity.

8. The method of claim 7, wherein the initiating occurs in the first cavity in a gaseous environment having an initial pressure level of at least about 760 Torr.

9. The method of claim 1, wherein the exposing causes heating of the at least a portion of the object that proceeds at a rate of at least 400 degrees Celsius per minute until the portion of the object reaches a temperature no greater than about a melting temperature of the at least one powdered material component.

10. The method of claim 1, wherein the object includes multiple powder material components, and wherein the exposing causes heating of the at least a portion of the object that proceeds at a rate of at least 400° C. per minute until the portion of the object reaches a temperature up to a melting temperature for any one of the multiple powder material components.

11. The method of claim 1, further comprising flowing gas through the first cavity.

12. The method of claim 1, further comprising sustaining the plasma by directing additional radiation into the first cavity.

13. The method of claim 12, further comprising mode-mixing the additional radiation.

14. The method of claim 1, further comprising moving the object with respect to the plasma during the exposing.

15. The method of claim 1, wherein the powdered material component comprises a material selected from a group consisting of a metal, a ceramic, an ore, a salt, an alloy, silicon, aluminum, tungsten, carbon, iron, an oxygen-containing compound, a nitrogen containing compound, and any combination thereof.

16. The method of claim 1, wherein the first cavity has an interior surface with at least one surface feature, wherein the exposing comprises forming a sintering pattern on the object based on the at least one surface feature.

17. The method of claim 1, wherein the first cavity is connected to a second cavity through a conduit, the method further comprising:

placing the object in the second cavity;

sustaining the plasma in the first cavity during the exposing; and

forming a plasma jet in the second cavity at the conduit, thereby permitting the exposing to occur in the second cavity.

18. The method of claim 1, wherein the first cavity is formed in a vessel that has an aperture, the method further comprising:

placing the object outside the first cavity near the aperture;

sustaining the plasma in the first cavity during the exposing; and

forming a plasma jet at the aperture, thereby permitting the exposing to occur outside the first cavity.

19. The method of claim 1, further comprising:

supplying a source of a processing material to the plasma, and

subjecting the object to a treatment using the processing material.

20. The method of claim 19, wherein the processing material includes carbon and the treatment comprises carbunizing.

21. The method of claim 19, wherein the processing material includes nitrogen and the treatment comprises nitriding.

22. The method of claim 19, further comprising:

supplying a coating material to the plasma, and

depositing a coating on the object.

23. The method of claim 22, wherein the coating includes at least one of tungsten carbide, tungsten nitride, tungsten oxide, tantalum nitride, tantalum oxide, titanium oxide, titanium nitride, silicon oxide, silicon carbide, silicon nitride, aluminum oxide, aluminum nitride, aluminum carbide, boron nitride, boron carbide, boron oxide, gallium phosphide, aluminum phosphide, chromium oxide, tin oxide, yttria, zirconia, silicon-germanium, indium tin oxide, indium gallium arsenide, aluminum gallium arsenide, boron, chromium, gallium, germanium, indium, phosphorus, magnesium, silicon, tantalum, tin, titanium, tungsten, yttrium, and zirconium.

24. The method of claim 22, wherein at least one of the steps of subjecting the object to a treatment and depositing a coating on the object is performed in a location where the exposing at least a portion of the object to the plasma occurs.

25. A system for plasma-assisted sintering of an object including at least one powdered material component, the system comprising:

a plasma catalyst;

a vessel in which a first cavity is formed and in which a plasma can be initiated by subjecting a gas to an amount of electromagnetic radiation having a frequency less than about 333 GHz in the presence of the plasma catalyst, wherein the vessel has a shape that permits at least a portion of the object to be exposed to the plasma;

a radiation source coupled to the cavity such that the radiation source can direct radiation into the cavity; and

a gas source coupled to the cavity such that a gas can flow into the cavity during sintering.

26. The system of claim 25, wherein the cavity has an aperture at which a plasma jet can form.

27. The system of claim 25, further comprising:

a temperature sensor for monitoring a temperature of the object; and

a controller that adjusts a power level of the radiation source in response to the temperature of the object.

28. The system of claim 27, wherein the controller is programmed to control the power level of the radiation source such that the temperature of the object substantially conforms to a predetermined temperature profile.

29. The system of claim 27, further comprising an applicator that contains the vessel, where the applicator is a multi-mode applicator.

30. The system of claim 29, further comprising a mode mixer that can move relative to the applicator to make a time-averaged radiation density in a treatment zone of the applicator substantially uniform.

31. The system of claim 27, further comprising an electrical bias source configured to be connected to the object during sintering.

32. The system of claim 31, wherein the electrical bias-source generates an AC bias.

33. The system of claim 31, wherein the electrical bias source generates a DC bias.

34. The system of claim 31, wherein the electrical bias source generates a pulsed DC bias.

35. The system of claim 27, further comprising a magnetic field source positioned to apply a magnetic field to the portion of the object during sintering.

36. The system of claim 29, wherein the applicator includes an outer housing comprising a material that is substantially opaque to the radiation.

37. The system of claim 36, wherein the applicator includes the vessel, which comprises a material that is substantially transmissive to the radiation.

38. The system of claim 25, wherein the plasma catalyst includes at least one of a passive plasma catalyst and an active plasma catalyst.

39. The system of claim 25, wherein the plasma catalyst includes at least one of powdered carbon, carbon nanotubes, carbon nanoparticles, carbon fibers, graphite, solid carbon, and any combination thereof.

40. The system of claim 25, wherein the plasma catalyst includes at least one of x-rays, gamma radiation, alpha particles, beta particles, neutrons, protons, and any combination thereof.

41. The system of claim 25, wherein the plasma catalyst includes at least one of electrons and ions.

42. The system of claim 25, wherein the plasma catalyst includes at least one of a metal, carbon, a carbon-based alloy, a carbon-based composite, an electrically conductive polymer, a conductive silicone elastomer, a polymer nanocomposite, an organic-inorganic composite, and any combination thereof.

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