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(71) Applicant: **ARCONIC INC.** [US/US]; 201 Isabella Street, Pittsburgh, Pennsylvania 15212-5858 (US).

(72) Inventors: **RUAN, Yimin**; 4045 Impala Drive, Pittsburgh, Pennsylvania 15239 (US). **TRAVIS, Adam R.**; 1823 Parkview Boulevard, Apt. 204, Pittsburgh, Pennsylvania 15217 (US). **ZARANDI, Faramarz MH**; 444-5250 Liberty Avenue, Pittsburgh, Pennsylvania 15224 (US).

(74) Agent: **BRIGGS, Heath, J.** et al.; Arconic INC., c/o Greenberg Traurig, LLP, 500 Campus Drive, Suite 400, Florham Park, New Jersey 07932 (US).

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(54) **Title:** SYSTEMS AND METHODS FOR CONTROLLING GRAIN STRUCTURE IN ADDITIVELY-MANUFACTURED METAL-BASED PRODUCTS

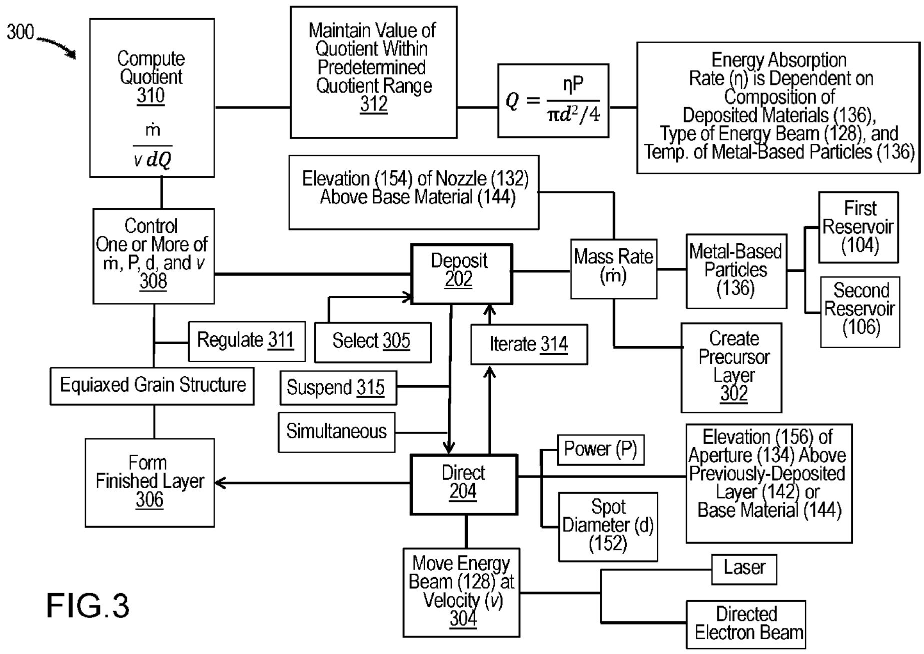

FIG.3

(57) **Abstract:** A method for controlling the grain structure of additively-manufactured metal-based products includes depositing, at a mass rate, metal-based particles on a base material, thereby creating a precursor layer, and directing an energy beam from an energy source toward the precursor layer to form a finished layer. Characteristics of the energy beam include a power and a spot diameter. The directing step includes moving the energy beam at a velocity relative to the base material, and controlling one or more of the mass rate, the power, the spot diameter and the velocity to facilitate forming the finished layer having an equiaxed and/or near-equiaxed grain structure.

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SYSTEMS AND METHODS FOR CONTROLLING GRAIN STRUCTURE IN ADDITIVELY-MANUFACTURED METAL-BASED PRODUCTS

BACKGROUND

[001] Additively-manufactured metal-based products may be produced by depositing metals in layers having one or more grain structures. Physical properties of the resulting additively-manufactured metal-based products may be influenced by the grain structure(s) of these deposited layers.

SUMMARY

[002] Disclosed herein are systems and methods for controlling the grain structure of additively-manufactured metal-based products (AMMPs). In one embodiment, the disclosed method (e.g., as implemented by one embodiment of the disclosed system), includes (a) depositing, at a mass rate ($\dot{m}$), metal-based particles on a base material, thereby creating a precursor layer of an AMMP. In the embodiment, the method includes (b) directing an energy beam from an energy source toward the precursor layer, thereby forming a finished layer. In the embodiment, characteristics of the energy beam include a power (P) and a spot diameter (d). In the embodiment, the directing step (b) includes (i) moving the energy beam at a velocity (v) relative to the base material. In the embodiment, the directing step (b) includes (ii) controlling one or more of $\dot{m}$, P, d, and v to facilitate forming the finished layer of the AMMP having a predetermined grain structure (GS). In the embodiment, the controlling step includes maintaining a value of a quotient $\left(\frac{\dot{m}}{v d Q}\right)$ within a predetermined quotient range, where Q is an average effective heat flux of the energy beam defined as $\frac{\eta P}{\pi d^2/4}$, and where η is an energy absorption rate of the precursor layer.

[003] In one embodiment, the disclosed method includes selecting, before the depositing step (a), the predetermined GS.

[004] In one embodiment of the disclosed method, the predetermined GS is an equiaxed GS. In another embodiment, the predetermined GS is a near-equiaxed GS. In yet another embodiment, the predetermined GS is a non-equiaxed GS. In still another embodiment, the predetermined GS is a columnar GS. In another embodiment, the predetermined GS is a combination of two or more of the equiaxed GS, the near-equiaxed GS, the non-equiaxed GS, and the columnar GS.

[005] In one embodiment of the disclosed method, a type of the energy beam used during the directing step (b) is a laser beam.

[006] In one embodiment of the disclosed method, the predetermined quotient range is dependent on the type of the energy beam used during the directing step (b).

[007] In one embodiment of the disclosed method, the energy absorption rate (η) is dependent on the type of the energy beam used during the directing step (b).

[008] In one embodiment of the disclosed method, the predetermined quotient range is dependent on a composition of the metal-based particles.

[009] In one embodiment of the disclosed method, the energy absorption rate (η) is dependent on the composition of the metal-based particles.

[0010] In one embodiment of the disclosed method, the deposited precursor layer has a thickness, the thickness is dependent on the mass rate ($\dot{m}$), and the controlling step (b)(ii) includes controlling the mass rate ($\dot{m}$) to facilitate maintaining the thickness within a predetermined thickness tolerance during the depositing step (a).

[0011] In one embodiment of the disclosed method, the depositing step (a) includes depositing the metal-based particles from at least one nozzle of an additive system, where the at least one nozzle is spaced from the base material by a first distance (E1). In the embodiment, the controlling step (b)(ii) comprises maintaining the value of the first distance (E1) within a first predetermined distance tolerance to facilitate controlling the mass rate ($\dot{m}$).

[0012] In one embodiment of the disclosed method, the directing step (b) includes directing the energy beam from an aperture of an additive system, where the aperture is spaced from the base material by a second distance (E2). In the embodiment, the controlling step (b)(ii) includes maintaining the value of the second distance (E2) within a second predetermined distance tolerance to facilitate controlling the spot diameter (d).

[0013] In one embodiment of the disclosed method, the depositing step (a) comprises depositing the metal-based particles from at least one nozzle of an additive system, where the at least one nozzle is spaced from the base material. In the embodiment, the directing step (b) includes directing the energy beam from an aperture of the additive system, where the aperture is spaced from the base material. In the embodiment, the moving step (b)(i) includes moving the aperture and the at least one nozzle at the same velocity (v).

[0014] In one embodiment of the disclosed method, the additive system is a powder-fed additive system.

[0015] In one embodiment of the disclosed method, the base material includes a previously formed finished layer, and the method includes iterating, for a plurality of iterations, through the depositing (a) and directing (b) steps to facilitate forming a plurality of finished layers having the predetermined GS.

[0016] In one embodiment of the disclosed method including the iterating step, for at least one iteration of the depositing step (a), the composition of the metal-based particles is different as compared to the composition of the metal-based particles used for at least one other iteration of the depositing step (a). In the embodiment, the controlling step (b)(ii) includes controlling the one or more of the mass rate ($\dot{m}$), the power (P), the spot diameter (d), and the velocity (v) to facilitate forming the plurality of finished layers having the predetermined GS.

[0017] In one embodiment, the disclosed method includes selecting, before the depositing step (a), the composition of the metal-based particles.

[0018] In one embodiment, the disclosed method includes maintaining a temperature of the metal-based particles within a predetermined range of temperatures during the depositing step (a).

[0019] In one embodiment, the disclosed method includes maintaining a temperature of the base material within a predetermined range of temperatures during the depositing step (a).

[0020] In one embodiment of the disclosed method, the energy absorption rate (η) is dependent on a temperature of the metal-based particles during the depositing step (a).

[0021] In one embodiment of the disclosed method, the depositing step (a) includes suspending the metal-based particles in a carrier gas stream. In one embodiment, the controlling step (b)(ii) includes controlling a flow rate of the carrier gas stream to facilitate controlling the mass rate ($\dot{m}$). In one embodiment, the controlling step (b)(ii) includes controlling a temperature of the carrier gas stream to facilitate maintaining the temperature of the metal-based particles within the predetermined range of temperatures during the depositing step (a). In one embodiment, the controlling step (b)(ii) includes controlling the temperature of the carrier gas stream to facilitate maintaining the temperature of the base material within the predetermined range of temperatures during the depositing step (a).

[0022] In one embodiment, the depositing (a) and directing (b) steps are performed substantially simultaneously by the disclosed system.

[0023] In some embodiments, the methods described herein are utilized in the absence of a grain refiner (e.g., grain refining is completed via the method, rather than via a chemical addition). In some embodiments, the methods described herein are utilized with an appropriate grain refiner (e.g., grain refining is completed via a combination of the method and grain refiner chemical addition).

[0024] The figures constitute a part of this specification and include illustrative embodiments of the present disclosure and illustrate various objects and features thereof. In addition, any measurements, specifications and the like shown in the figures are intended to be illustrative, and not restrictive. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a representative basis for teaching one skilled in the art to variously employ the present invention.

[0025] Among those benefits and improvements that have been disclosed, other objects and advantages of this invention will become apparent from the following description taken in conjunction with the accompanying figures. Detailed embodiments of the present invention are disclosed herein; however, it is to be understood that the disclosed embodiments are merely illustrative of the invention that may be embodied in various forms. In addition, each of the examples given in connection with the various embodiments of the invention is intended to be illustrative, and not restrictive.

[0026] Throughout the specification and claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise. The phrases “in one embodiment” and “in some embodiments” as used herein do not necessarily refer to the same embodiment(s), though it may. Furthermore, the phrases “in another embodiment” and “in some other embodiments” as used herein do not necessarily refer to a different embodiment, although it may. Thus, as described below, various embodiments of the invention may be readily combined, without departing from the scope or spirit of the invention.

[0027] In addition, as used herein, the term "or" is an inclusive "or" operator, and is equivalent to the term "and/or," unless the context clearly dictates otherwise. The term "based on" is not exclusive and allows for being based on additional factors not described, unless the context clearly dictates otherwise. In addition, throughout the specification, the meaning of "a," "an," and "the" include plural references. The meaning of "in" includes "in" and "on".

BRIEF DESCRIPTION OF THE FIGURES

[0028] FIG. 1 is a schematic diagram of an embodiment of a process for producing additively-manufactured metal-based products (AMMPs) using a powder-fed additive system.

[0029] FIG. 2 is a flow chart illustrating an embodiment of a method for controlling grain structure in AMMPs.

[0030] FIG. 3 is a flow chart illustrating embodiments of the depositing and directing steps of FIG. 2.

[0031] FIG. 4 is a micro-section of an Inconel 718 (IN718) AMMP produced using a powder-fed additive system in accordance with a known method.

[0032] FIG. 5 is a plot of quotient values versus mass rate in accordance with the embodiments disclosed in methods of FIGS. 2 and 3.

[0033] FIG. 6A is a micro-section of an IN718 AMMP produced using the additive system of FIG. 1 in accordance with the embodiment(s) of disclosed methods of FIGS. 2 and 3, and with a quotient value of 0.466, as shown in FIG. 5.

[0034] FIG. 6B is a micro-section of an IN718 AMMP produced using the additive system of FIG. 1 in accordance with the embodiment(s) of disclosed methods of FIGS. 2 and 3, and with a first quotient value of 0.466 for a lower portion of the micro-section, and then a second quotient value of 0 for an upper portion of the micro-section.

[0035] FIG. 6C is a micro-section of an IN718 AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed methods of FIGS. 2 and 3, and with a quotient value of 0.121, as shown in FIG. 5.

[0036] FIG. 6D is a micro-section of an IN718 AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed methods of FIGS. 2 and 3, and with a quotient value of 0.118, as shown in FIG. 5.

[0037] FIG. 7A is a micro-section of a stainless steel 316 (SS316) AMMP produced using the additive system of FIG. 1 in accordance with the embodiment(s) of disclosed methods of FIGS. 2 and 3, and with a quotient value of 0.060, as shown in FIG. 5.

[0038] FIG. 7B is a micro-section of an SS316 AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed method(s) of FIGS. 2 and 3, and with a quotient value of 0.018, as shown in FIG. 5.

[0039] FIG. 8A is a micro-section of a Ti-6Al-4V AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed method(s) of FIGS. 2 and 3, and with a quotient value of 0.081, as shown in FIG. 5.

[0040] FIG. 8B is a micro-section of a Ti-6Al-4V AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed method(s) of FIGS. 2 and 3, and with a quotient value of 0.047, as shown in FIG. 5.

[0041] FIG. 8C is a micro-section of a Ti-6Al-4V AMMP produced using the additive system of FIG. 1 in accordance with the embodiments of disclosed method(s) of FIGS. 2 and 3, and with a quotient value of 0.01, as shown in FIG. 5.

DETAILED DESCRIPTION

[0042] As used herein, "metal-based particles" means particles having one or more metal elements therein.

[0043] As used herein, "metal-based powder" means a collection of metal-based particles. In some embodiments, metal-based powder is suitably sized to be utilized in one or more additive manufacturing applications. A metal-based powder may be composed of metal-based particles having a mean diameter (D_{50}) of less than 1000 μm, and typically having a D_{50} of from 5 to 200 μm, or having a D_{50} of from 40 to 180 μm. "Metal-based powders" may be used in additive manufacturing processes, as defined below.

[0044] As used herein, "additive manufacturing" means "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies," as defined in ASTM F2792-12A entitled "Standard Terminology for Additive Manufacturing Technologies." Such materials may be manufactured via any appropriate additive manufacturing technique described in ASTM F2792-12A, such as binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, or sheet lamination, among others. Additive manufacturing processes are implemented, at least in part, by "additive systems," as defined by ASTM F2792-12A.

[0045] As used herein, "directed energy deposition" means "an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited," as defined by ASTM F2792-12A. Directed energy deposition-based additive manufacturing processes include powder-fed processes, as defined below.

[0046] "Focused thermal energy" means an energy source that is focused to thermally treat the materials being deposited by an additive system.

[0047] As used herein, "powder-fed processes" means a type of directed energy deposition-based process in which metal-based powder is conveyed through a nozzle or other appropriate apparatus onto the build surface. The focused thermal energy is used to melt a layer or more of the powder into the shaped desired. This process may be repeated to create a solid three dimensional component. The two dominant types of powder-fed processes are (e.g. non-limiting examples): 1) the work piece remains stationary, and the nozzle of a deposition head moves, and 2) the deposition head remains stationary, and the work piece is moved.

[0048] As used herein, "additively-manufactured metal-based product" means a product formed using an additive manufacturing process.

[0049] As used herein, "precursor layer" means a layer of metal-based particles deposited onto a build surface by an additive system. In one embodiment, the additive system is a powder-fed-based additive system. The precursor layer may be deposited prior to or concomitant with exposure to focused thermal energy as a fully solid material, or it may be deposited onto the build surface as an at least partially melted material.

[0050] As used herein, "finished layer" means the layer formed due to exposure of the precursor layer to focused thermal energy.

[0051] As used herein, "base material" and "build surface" both mean a surface upon which the precursor layer is deposited, and which provides mechanical and thermal support to the material being deposited by the additive system.

[0052] As used herein, "grain structure" means the collective arrangement of the grains in an additively-manufactured metal-based product, with each grain having a particular crystal structure and boundary which separates it from neighboring grain(s). Grain structure is characterized by the sizes, shapes, aspect ratios, and crystallographic orientations of the grains, and how the grains are connected to each at their boundaries.

[0053] As used herein, "equiaxed grain structure" means a grain having an aspect ratio (in the x,z plane) of less than 1.5.

[0054] As used herein, "near-equiaxed grain structure" means a grain having an aspect ratio (in the x,z plane) of from 1.5 to 3.0.

[0055] As used herein, "non-equiaxed grain structure" means a grain having an aspect ratio (in the x,z plane) of greater than 3.0.

[0056] As used herein, "columnar grain structure" means a grain having a non-equiaxed grain structure and with a generally columnar morphology.

[0057] Broadly, the present disclosure relates to systems and methods for controlling the grain structure of additively-manufactured metal-based products (AMMPs). In particular, and referring to FIGS. 1-3, a method (200) may be implemented, at least in part, via an additive manufacturing (AM) process. In one embodiment, the AM process may be a powder-fed AM process (100). Process (100) may employ a powder-fed additive system (102) having hardware and software directed to performing the disclosed steps of method (200). System (102) may include a first reservoir (104) configured to contain metal-based particles (136) having a first composition. In one embodiment, system (102) may include a second reservoir (104) configured to contain metal-based particles (136) having a second composition.

[0058] In one embodiment, the composition of the metal-based particles (136) contained in the first reservoir (104) is the same as the composition of the metal-based particles (136) contained in the second reservoir (106). In another embodiment, the composition of the metal-based particles (136) contained in the first reservoir (104) is different from the composition of the metal-based particles (136) contained in the second reservoir (106). In one embodiment, system (102) may have greater than two reservoirs for containing metal-based particles (136) having either the same or different compositions as compared to metal-based particles (136) contained in the first (104) and/or second (106) reservoir(s).

[0059] System (102) may include a gas supply (108) configured to supply a carrier gas for use in process (100). System (102) may include one or more pump(s) (110) and/or one or more valve(s) (112). When present in system (102), the pump(s) (110) and/or the valve(s) (112) may be configured to regulate (311) a flow of the metal-based particles (136) and/or the carrier gas to and between components of system (102) for use in process (100). System (102) may include one or more temperature maintenance subsystem devices such as a heater/cooler (113). When present in system (102), the heater/cooler (113) may be configured to regulate (311) a temperature of components of system (102) for use in process (100). In one embodiment, the heater/cooler (113) may regulate (311) the operating temperature of the first (104) and/or the second (106) reservoir(s) (and the metal-based particles (136) contained therein). In one embodiment, the heater/cooler (113) may regulate (311) the operating temperature of the gas supply (108) (and the carrier gas contained therein). In one embodiment, the heater/cooler (113) may regulate (311) the operating temperature(s) of other hardware component(s) of system (102) which may require temperature regulation (311) during their operation in process (100).

[0060] System (102) may include an energy beam generator (116) configured to produce an energy beam (128) and purposefully direct it distally from the energy beam generator (116) through an aperture (134) in a controlled manner. In one embodiment, the energy beam (128) is a beam of focused thermal energy. In one embodiment, the energy beam (128) is a laser beam. In one embodiment, the energy beam generator (116) is a laser beam generator.

[0061] System (102) may include a lens (118) positioned proximate the aperture (134). The lens (118) may be configured to focus the energy beam (128) and/or facilitate directing (204) the energy beam (128) in a desired direction distally from the energy beam generator (116).

[0062] System (102) may include a beam shield (130) configured to contain at least a portion of the energy beam (128) and provide increased safety to a user (131) of system (102) in process (100). The beam shield (130) may include one or more conduit(s) (132). In one embodiment, the conduit(s) (132) may be configured to allow a flow of metal-based particles (136) (e.g., as regulated (311) by pump(s) (110) and/or valve(s) (112)) from the first (104) and/or second (106) reservoirs to at least one nozzle (133) distal the reservoir(s) (104 and/or 106). In one embodiment, the conduit(s) (132) may be configured to allow a flow of the carrier gas (e.g., as regulated (311) by pump(s) (110) and/or valve(s) (112)) from the gas supply (108) to the at least one nozzle (133). In one embodiment, the beam shield (130) and/or the conduit(s) (132) may have their operating temperature(s) regulated (311) by the heater/cooler (113) during their operation in process (100).

[0063] System (102) may include one or more motor(s) (120) configured to move at least a portion of system (102) (e.g., one or more hardware components thereof) in one or more of the x, y, and z directions in a workspace (denoted "W" in FIG. 1). In one embodiment, the positive z direction is defined as a "build direction." In one embodiment, motor(s) (120) may be configured to move two or more hardware components of system (102) independently of one another. In one embodiment, motor(s) (120) may be configured to move two or more hardware components of system (102) in tandem. In one embodiment, motor(s) (120) may be configured to move all hardware components of system (102) in tandem. In one embodiment, motor(s) (120) may be configured to actuate movement of one or more hardware components of system (102) in two or more of the x, y, and z directions at the same time. In one embodiment, motor(s) (120) may be configured to actuate movement of one or more hardware components of system (102) in one direction at a time. In one embodiment, motor(s) (120) may be configured to operate pump(s) (110). In one embodiment, motor(s) (120) may be configured to actuate valve(s) (112) (e.g., open and/or close them to varying extents).

[0064] System (102) may include at least one sensor (122). In one embodiment, sensor (122) may include a thermocouple or other temperature measurement device coupled to one or more hardware components of system (102) (e.g., reservoir(s) (104, 106), gas supply (108), energy beam generator (116), beam shield (130), and/or conduit(s) (132)). In one embodiment, sensor (122) may include encoder(s) and/or other rotational motion measuring device(s) configured to measure angular velocity of shaft(s) of motor(s) (120). In one embodiment, sensor (122) may include positional sensing device(s) configured to measure the position of at least a portion of system (102) (e.g., one or more hardware components thereof) in the x,y plane and/or the x,y,z space. In one embodiment, sensor (122) may include flowmeter(s) configured to measure flow rate(s) of at least one of the metal-based particles (136) and the carrier gas. In one embodiment, sensor (122) may include pressure transmitter(s) configured to measure operating pressures(s) of, for example, gas supply (108), valve(s) (112), and pump(s) (110), including with respect to flow of metal-based particles (136) and/or carrier gas.

[0065] System (102) may include one or more processor(s) (124). The processor(s) (124) may include a central processing unit (CPU) (125) and one or more memory device(s) (126). The memory device(s) (126) may include one or more non-transitory processor (124)-readable storage media. Prior to, during, and/or after operation of process (100), the processor(s) (124) may execute software instructions encoded in memory device(s) (126) to perform CPU (125)-mediated computations, and may direct one or more read, write, and/or delete operations for data to and/or from the memory device(s) (126). In one embodiment, the software instructions may be encoded in non-transitory processor (124)-readable media-type memory device(s) (126). In one embodiment, the software instructions may be user (131)-defined processor (124) executable program instruction data. In one embodiment, the software instructions may be stored in the memory device(s) (126) prior to the user (131) commencing the various unit operations of process (100) as described herein.

[0066] In one embodiment, the processor(s) (124) may be located on-board the system (102), and system (102) may include a general purpose computer (GPC), also located on-board the system (102). In one embodiment, the processor(s) (124) may be configured as dedicated embedded (non-GPC) processor(s) (124) located on-board the system (102), and the system (102) may include a GPC located distally from, but electrically and communicatively coupled to the remaining hardware components of system (102). In one embodiment, system (102) may include a combination of one or more GPC-based processor(s) (124) and one or more embedded processor(s) (124). In one embodiment, system (102) may include the GPC having all processor(s) (124) for system (102). Similarly, memory device(s) (126) of system (102) may be located either entirely on-board system (102), entirely external to system (102) (e.g., within a GPC), or at locations both within and/or external to system (102) (but electrically and communicatively coupled to processor(s) (124) and/or memory device(s) (126) within system (102)).

[0067] System (102) may include a human-machine interface (HMI) (129) configured to facilitate interaction, programming, monitoring, control, and/or general operational intervention(s) by user(s) (131) of system (102), including in process (100). In one embodiment, the functionality of the HMI (129) is performed, at least in part, by a GPC (e.g., monitor, keyboard, mouse, and/or other input/output (I/O) devices). In one embodiment, the functionality of the HMI (129) is performed, at least in part, by one or more I/O device(s) residing within system (102).

[0068] System (102) may include a power supply (127) configured to receive, convert, and/or regulate (311) a flow of electrical current to one or more hardware components of system (102) requiring electric power during operation of system (102), including in process (100). The various disclosed, and, if applicable, other, hardware components of system (102) are coupled to one another via one or more of wired and/or wireless electrical and/or communication lines (not shown in FIG. 2). The physical actions, outcomes, and/or implementations accomplished by the system (102) during process (100) are primarily initiated by the user (131) and may proceed via computations directed by user (131) pre-defined, processor (124)-executable software instructions (e.g., control schemes, algorithms, and/or readable, writable, and/or deletable data) stored in processor (124)-readable memory device(s) (126). At least some of the computations performed by processor(s) (124), and at least some of the physical outcomes, and/or implementations accomplished by system (102) during process (100) are accomplished substantially simultaneously and/or in near real-time, limited by, for example, non-human-based factors such as the base computation speed of CPU(s) (125), operational speeds of memory device(s) (126), and time delays for transmission of electrical and/or data signals on the wired and/or wireless communication lines of system (102).

[0069] Prior to commencing the steps of method (200) via process (100), a base material (144) is positioned in the workspace (W). In one embodiment, at least a portion of the base material (144) may form a portion of the AMMP (158) following completion of process (100). In another embodiment, at least a portion of the base material (144) may be excised from at least a portion of the AMMP (158) following completion of process (100).

[0070] In one embodiment, a user (131)-defined template model (140) is stored in the memory device(s) (126) of system (102). The model (140) is a three-dimensional (3D) map of a predetermined form that the AMMP (158) will take following completion of process (100). In one embodiment, processor(s) (124) may read the model (140) data from the memory device(s) (126) and, using user (131)-defined software instructions stored in the memory device(s) (126), use the model (140) data during execution of a control algorithm and/or scheme (also stored as data and/or software program instructions in memory device(s) (126)) to perform the steps of method (200).

[0071] In one embodiment, the model (140) specifies the dimensions in the x,y,z space of the workspace (W). The 3D dimensions of the model (140) may be broken down in a layer-by-layer fashion, with each layer (e.g., planar slice having a finite mass in the final AMMP (158) form) of a plurality of finished layers (e.g., 142a, 142b) having a respective subset of x,y,z spatial dimensions. In one embodiment, the AMMP (158) is produced using process (100) and system (102) on a layer-by-layer basis, where the x and y dimensions may vary between finished layers (e.g., 142a, 142b). In one embodiment, during production of the AMMP (158) using process (100) and system (102), the z dimensions (e.g., layer thicknesses (146a, 146b)) may vary between finished layers (142a, 142b). In one embodiment, the AMMP (158) may include one or more finished layers (142a) having a first thickness (146a) and one or more finished layers (e.g., 142b) having a second thickness (146b). In one embodiment, the first thickness (146a) may be equal to the second thickness (146b). In another embodiment, the first (146a) and second (146b) thicknesses may be different. In one embodiment, the AMMP (158) may include a first plurality of finished layers (148) having the first thickness (146a) and a second plurality of finished layers (150) having the second thickness (146b).

[0072] Referring now to FIGS. 1-3, the method (200, 300) may include depositing (202), at a mass rate ($\dot{m}$) (i.e., dm/dt), metal-based particles (136) on the base material (144), thereby creating (302) a precursor layer (138) of the AMMP (158). In one embodiment, the method (200) may include directing (204) the energy beam (128) from an energy source (e.g., the energy beam generator (116)) toward the precursor layer (138), thereby forming (306) a finished layer (e.g., 142b).

[0073] Characteristics of the energy beam (128) that may be predetermined by the user (131) and/or controlled by the user (131) and/or processor(s) (124) may include a power (P) and a spot size (e.g., a spot diameter (d) (152)) on the surface of the precursor layer (138). In one embodiment, the spot size of the energy beam (128) is characterized by a dimension other than a spot diameter (d) (152). In one embodiment, the spot size of the energy beam (128) is defined by a polygon having three or more sides, and the spot size may be characterized by at least one length dimension and/or an area of the polygonal spot of the energy beam (128) on the surface of the precursor layer (138). In another embodiment, the spot size of the energy beam (128) is defined by an ellipse, and the spot size may be characterized by a major radius, a minor radius, and/or an area of the ellipsoidal spot of the energy beam (128) on the surface of the precursor layer (138).

[0074] Referring now to FIG. 3, in one embodiment (e.g., method (300)), the depositing (202) and/or directing (204) steps may include moving (304) the energy beam (128) at a velocity (v) (e.g., in the x, y, or z direction(s), and combinations thereof) relative to the base material (144). In one embodiment, the depositing (202) and/or directing (204) steps may include controlling (308) one or more of $\dot{m}$, P, d, and v to facilitate forming (306) the finished layer (142a, 142b) of the AMMP (158) having a user (131)-predetermined grain structure (GS). In one embodiment, the user (131)-predetermined GS is an equiaxed GS. In another embodiment, the user (131)-predetermined GS is a near-equiaxed GS. In yet another embodiment, the user (131)-predetermined GS is a non-equiaxed GS. In still another embodiment, the user (131)-predetermined GS is a columnar GS. In another embodiment, the user (131)-predetermined GS is a combination of two or more of the equiaxed, near-equiaxed, non-equiaxed, and columnar grain structures.

[0075] In one embodiment, the controlling (308) step may include regulating (311) the mass rate ($\dot{m}$) using the sensor(s) (122), power supply (127), heater/cooler (113), motor(s) (120), pump(s) (110), valve(s) (112), and/or the processor(s) (124). In one embodiment, a user (131)-predetermined $\dot{m}$ value and/or range of values for $\dot{m}$ may be stored in the memory device(s) (126), and regulating (311) the $\dot{m}$ during the controlling (308) step may include maintaining the actual (e.g., as measured and/or as sensed in operation of process (100) and system (102)) value of $\dot{m}$ within a predetermined tolerance of the user (131)-predetermined value of $\dot{m}$ and/or within the user (131)-predetermined range of values for $\dot{m}$.

[0076] In one embodiment, the controlling (308) step may include regulating (311) the power (P) using the sensor(s) (122), power supply (127), heater/cooler (113), pump(s) (110), valve(s) (112), energy beam generator (116), lens (118), and/or the processor(s) (124). In one embodiment, a user (131)-predetermined P value and/or range of values for P may be stored in the memory device(s) (126), and regulating (311) the P during the controlling (308) step may include maintaining the actual (e.g., as measured and/or as sensed in operation of process (100) and system (102)) value of P within a predetermined tolerance of the user (131)-predetermined value of P and/or within the user (131)-predetermined range of values for P.

[0077] In one embodiment, the controlling (308) step may include regulating (311) the spot diameter (d) (152) using the sensor(s) (122), power supply (127), energy beam generator (116), lens (118), heater/cooler (113), motor(s) (120), pump(s) (110), valve(s) (112), and/or the processor(s) (124). In one embodiment, a user (131)-predetermined d value and/or range of values for d may be stored in the memory device(s) (126), and regulating (311) the d during the controlling (308) step may include maintaining the actual (e.g., as measured and/or as sensed in operation of process (100) and system (102)) value of d within a predetermined tolerance of the user (131)-predetermined value of d and/or within the user (131)-predetermined range of values for d.

[0078] In one embodiment, the controlling (308) step may include regulating (311) the velocity (v) using the sensor(s) (122), motor(s) (120), heater/cooler (113), pump(s) (110), valve(s) (112), power supply (127), lens (118), and/or the processor(s) (124). In one embodiment, a user (131)-predetermined v value and/or range of values for v may be stored in the memory device(s) (126), and regulating (311) the v during the controlling (308) step may include maintaining the actual (e.g., as measured and/or as sensed in operation of process (100) and system (102)) value of v within a predetermined tolerance of the user (131)-predetermined value of v and/or within the user (131)-predetermined range of values for v.

[0079] In one embodiment, the controlling (308) step may include computing (310), using the processor(s) (124), a value of a quotient defined as:

$$\left(\frac{\dot{m}}{v d Q}\right), \text{ (Eqn. 1);}$$

where Q is an average effective heat flux of the energy beam (128) defined as:

$$\frac{\eta P}{\pi d^2/4}, \text{ (Eqn. 2);}$$

where π is the constant “pi,” and where η (“eta”) is an energy beam (128) energy absorption rate of the precursor layer (138). In one embodiment, η may be an instantaneous energy absorption rate of the precursor layer (138) determined (e.g., measured and/or sensed) at an instant in time. In another embodiment, η is an average energy absorption rate of the precursor layer (138) determined (e.g., computed) using a plurality of instantaneous η values determined over a user (131)-predetermined time interval. In yet another embodiment, η may be a user (131)-predetermined constant value for purposes of computing Q (Eqn. 2).

[0080] In one embodiment, the value of the quotient (Eqn. 1) may be computed (310) by the processor(s) (124) using actual (e.g., as measured and/or as-sensed) values stored in memory device(s) (126) for ṁ, P, v, and d. In another embodiment, the value of the quotient (Eqn. 1) may be computed (310) by the processor(s) (124) using the user (131)-predetermined values stored in memory device(s) (126) for ṁ, P, v, and d. In yet another embodiment, the value of the quotient (Eqn. 1) may be computed (310) by the processor(s) (124) using one or more of the user (131)-predetermined ranges of values stored in memory device(s) (126) for ṁ, P, v, and/or d, and the computing (310) step may include computing an error value associated with the quotient. In still another embodiment, the value of the quotient (Eqn. 1) may be computed (310) by the processor(s) (124) using a combination of one or more of the actual values stored in memory device(s) (126) for $\dot{m}$, P, v, and/or d and one or more of the user (131)-predetermined values for $\dot{m}$, P, v, and/or d stored in memory device(s) (126). In one embodiment, the value of the quotient (Eqn. 1) may be computed (310) by the processor(s) (124) at user (131)-predetermined time intervals during operation of process (100) using system (102).

[0081] In one embodiment, the controlling (308) step may include maintaining (312) the value of the quotient (Eqn. 1) within a user (131)-predetermined quotient range. In one embodiment, the maintaining (312) may include regulating (311) at least one of $\dot{m}$, P, d, and v. For example, an encoder-type sensor (122) coupled to shaft(s) of motor(s) (120) responsible for moving (304) the at least nozzle (133) and/or the aperture (134) in the x direction may transmit a data signal to the processor(s) (124), where these data may be stored in the memory device(s) (126). The processor(s) (124) may determine and store in memory device(s) (126) an angular velocity of the shaft(s) of motor(s) (120) based on computations directed by software instructions stored in memory device(s) (126) using the received encoder-type sensor (122) data. In one embodiment, the processor(s) (124) may use the determined angular velocity values stored in memory device(s) (126) to maintain v at a constant value to facilitate maintaining (312) the value of the quotient (Eqn. 1) within the user (131)-predetermined quotient range (e.g., by regulating (311) electric current flow from power supply (127) to motor(s) (120)). In another embodiment, the processor(s) (124) may use the determined angular velocity values stored in memory device(s) (126) to vary v in response to a detected change in $\dot{m}$, P, and/or d, and to facilitate maintaining (312) the value of the quotient (Eqn. 1) within the user (131)-predetermined quotient range (e.g., by regulating (311) electric current flow from power supply (127) to motor(s) (120)). In one embodiment, the moving (304) step includes moving (304) the aperture (134) and the at least one nozzle (133) at the same velocity (v).

[0082] In one embodiment, the user (131)-predetermined quotient range is dependent on the composition of the metal-based particles (136) used during the depositing (202) step. In one embodiment, the user (131)-predetermined quotient range is selected (305) based on the composition of the metal-based particles (136) to be used during the depositing (202) step.

[0083] In one embodiment, the user (131)-predetermined quotient range is dependent on the type of the energy beam (128) used during the directing (204) step (e.g., laser beam). In one embodiment, the user (131)-predetermined quotient range is selected (305) based on the type of the energy beam (128) to be used during the directing (204) step.

[0084] In one embodiment, the energy absorption rate (η), and thus also Q and the user (131)-predetermined quotient range, is dependent on the composition of the metal-based particles (136) used during the depositing (202) step. In one embodiment (e.g., where η is a constant), the user (131)-predetermined value or range of values for η, and thus also the user (131)-predetermined quotient range, is selected (305) based on the composition of the metal-based particles (136) to be used during the depositing (202) step.

[0085] In one embodiment, η, and thus also Q and the user (131)-predetermined quotient range, is dependent on the type of the energy beam (128) used during the directing (204) step. In one embodiment (e.g., where η is a constant), the user (131)-predetermined value or range of values for η, and thus also the user (131)-predetermined quotient range, is selected (305) based on the type of the energy beam (128) used during the directing (204) step.

[0086] In one embodiment, the thickness (e.g., 146b) of the deposited (202) precursor layer (138) may depend on the mass rate ($\dot{m}$) (e.g., provided a constant or near constant velocity (v)). In one embodiment, the thickness (e.g., 146b) of the deposited (202) precursor layer (138) may depend on v (e.g., provided a constant or near constant $\dot{m}$). In one embodiment, the controlling (308) step may include controlling (308) $\dot{m}$ and/or v to facilitate maintaining the thickness (e.g., 146b) within a user (131)-predetermined thickness tolerance during the depositing (202) step. In one embodiment, the user (131)-predetermined value(s) or range(s) of values for $\dot{m}$ and/or v may be selected (305) based on the user (131)-predetermined thickness (e.g., 146b) and/or thickness tolerance to be used for the respective precursor layer (e.g., 138) during the depositing (202) step. In one embodiment, the controlling (308) step may include controlling (308) $\dot{m}$ and/or v to facilitate maintaining the thickness (e.g., 146b) within a user (131)-predetermined thickness tolerance during the directing (204) step. In one embodiment, the user (131)-predetermined value(s) or range(s) of values for $\dot{m}$ and/or v may be selected (305) based on the user (131)-predetermined thickness (e.g., 146b) and/or thickness tolerance to be used for the respective finished layer (e.g., 142b) during the directing (204) step.

[0087] In one embodiment, the depositing (202) step may include depositing (202) the metal-based particles (136) from the at least one nozzle (133) of system (102). In one embodiment, the at least one nozzle (133) may be spaced from the base material (144) by a first distance (e.g., first elevation) (154, also referred to herein as "E1"). In one embodiment, the controlling (308) step may include maintaining a value of E1 (154) within a user (131)-predetermined first distance tolerance to facilitate controlling (308) the mass rate ($\dot{m}$).

[0088] In one embodiment, the directing (204) step may include directing (204) the energy beam (128) from the aperture (134) of system (102). The aperture (134) may be spaced from the base material (144) by a second distance (e.g., second elevation) (156, also referred to herein as "E2"). In one embodiment, the controlling (308) step may include maintaining a value of E2 (156) within a user (131)-predetermined second distance tolerance to facilitate controlling (308) the spot diameter (d) (152). In one embodiment, the controlling (308) step may include maintaining the value of E2 (156) within the user (131)-predetermined second distance tolerance to facilitate controlling (308) the power (P). In one embodiment, the controlling (308) step may include maintaining the value of E2 (156) within the user (131)-predetermined second distance tolerance to facilitate controlling (308) the energy absorption rate (η).

[0089] In one embodiment, the controlling (308) step may include concurrently maintaining the values of E1 (154) and E2 (156) within the first and second user (131)-predetermined tolerances, respectively.

[0090] In one embodiment, the controlling (308) step may include maintaining a spacing distance between the lens (118) and the energy beam generator (116). In one embodiment, the controlling (308) step may include maintaining a spacing distance between the lens (118) and the base material (144). In one embodiment, the controlling (308) step may include maintaining a spacing distance between the lens (118) and the precursor layer (138). In one embodiment, the controlling (308) step may include maintaining a spacing distance between the energy beam generator (116) and the base material (144). In one embodiment, the controlling (308) step may include maintaining a spacing distance between the energy beam generator (116) and the precursor layer (138).

[0091] In one embodiment, the disclosed method (300) may include selecting (305), before the depositing (202) and directing (204) steps, the user (131)-predetermined GS. In one embodiment, the user (131)-predetermined GS is an equiaxed GS. In another embodiment, the user (131)-predetermined GS is a near-equiaxed GS. In yet another embodiment, the user (131)-predetermined GS is a non-equiaxed GS. In still another embodiment, the user (131)-predetermined GS is a columnar GS. In another embodiment, the user (131)-predetermined GS is a combination of two or more of the equiaxed, near-equiaxed, non-equiaxed, and columnar grain structures.

[0092] In one embodiment, the selecting (305) step includes selecting (305) a user (131)-predetermined composition of the metal-based particles (136) before the depositing (202) and directing (204) steps. In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) is selected from the group consisting of Ni-, Ti-, Al-, Co-, Cr-, Cu-, Mg, and/or steel-based metal-based particles (136). In some embodiments, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes one or more of Ni-, Fe-, Ti-, Al-, Co-, Cr-, Cu-, Mg-, and steel-based metal-based particles (136). In some embodiments, one of Ni, Fe, Ti, Al, Co, Cr, Cu, Mg, and steel may be the predominate element present in the metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes Ni-alloy-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes Inconel-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes Inconel 718-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes stainless steel-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes stainless steel 316 (SS316)-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes Ti-alloy-based metal-based particles (136). In one embodiment, the selected (305) user (131)-predetermined composition of the metal-based particles (136) includes Ti-6Al-4V-based metal based particles (136).

[0093] In some embodiments, the metal-based particles described above are utilized in the absence of a grain refiner (e.g., grain refining is completed via the method, rather than via a chemical addition). In some embodiments, the metal-based particles described above are utilized with an appropriate grain refiner (e.g., grain refining is completed via a combination of the method and grain refiner chemical addition to the alloy). For example, the metal-based particles may include one or more grain refiners therein and/or the metal-based particles may be mixed with grain refiner-containing particles to be utilized with the methods described herein.

[0094] In one embodiment, the selecting (305) step includes selecting (305) a user (131)-predetermined template model (140) of the AMMP (158) before the depositing (202) and directing (204) steps. In one embodiment, the selecting (305) step may include reading, by the processor(s) (124), data stored in the one or more memory device(s) (126). In one embodiment, the data read during the selecting (305) step may include user (131)-predetermined value(s) and/or range(s) of value(s) for at least one of $\dot{m}$, P, d, η, v, E1, and E2. In one embodiment, the data read during the selecting (305) step may include the user (131)-

predetermined quotient range. In one embodiment, the data read during the selecting (305) step may be organized or otherwise stored in memory device(s) (126) based on the one or more user (131)-predetermined grain structure(s) that may be selected (305) for use in process (100). In one embodiment, the data read during the selecting (305) step may be organized or otherwise stored in memory device(s) (126) based on the one or more user (131)-predetermined composition(s) of the metal-based particles (136) that may be selected (305) for use in process (100).

[0095] In one use case, for example, process (100) may be implemented two or more times using system (100) from substantially the same template model (140) data, but using two different metal-based particles (136) compositions to produce two AMMPs having substantially the same final shape form. In a first run of process (100) using a first composition of metal-based particles (e.g., contained in the first reservoir (104)), the selecting (305) step includes reading, by the processor(s) (124), a first data set from the memory device(s) (126). In a second run of process (100) using a second composition of metal-based particles (e.g., contained in the second reservoir (106)) that is different from the first composition, the selecting (305) step includes reading, by the processor(s) (124), a second data set from the memory device(s) (126), where the second data set is at least partially different from the first data set. For example, in this use case, the first data set may include a first user (131)-predetermined quotient range that is different as compared to a second user (131)-predetermined quotient range of the second data set. Similarly, in this use case example, the first data set may include first user (131)-predetermined value(s) and/or range(s) of values for at least one of $\dot{m}$, P, d, η, ν, E1, and E2 that is/are different as compared to second user (131)-predetermined value(s) and/or range(s) of values for at least one of $\dot{m}$, P, d, η, ν, E1, and E2. Thus, process (100) may be implemented using system (100) to produce AMMPs having substantially similar final shape forms, but with varying compositions.

[0096] Generally, the data read from memory device(s) (126) by the processor(s) (124) during the selecting (305) step is used by the system (100) to implement the steps of the disclosed methods (e.g., 200, 300), and in particular the controlling (308) step to facilitate forming (306) the finished layer (e.g., 142b) of the AMMP (158) having the user-predetermined GS. As such, in process (100), the template model (140), the user (131)-predetermined quotient range, and the user (131)-predetermined value(s) and/or range(s) of values for at least one of $\dot{m}$, P, d, η, ν, E1, and E2 may be parameter data that are stored in memory device(s) (126) and read by the processor(s) (124) prior to performing the depositing (202) and directing (204) steps. In operation of process (100), actual values are determined (e.g., by sensor(s) (122) and/or processor(s) (124)), stored contemporaneously in memory device(s) (126), and used to compute (310) a current value of the quotient (Eqn. 1). Based on the determined actual values of at least one of $\dot{m}$, P, d, η, v, E1, and E2, as well as the current value of the computed (310) quotient (Eqn. 1), value(s) of one or more of $\dot{m}$, P, d, η, v, E1, and E2 are regulated (311), during the controlling (308) step, to facilitate maintaining (312) the current value of the quotient (Eqn. 1) within the user (131)-predetermined quotient range. As such, the determined actual values of at least one of $\dot{m}$, P, d, η, v, E1, and E2 may be variable data which, during operation of process (100), are regulated (311) by the control scheme and/or algorithm implemented by processor(s) (124) executing the user (131)-defined software instructions stored in memory device(s) (126).

[0097] In one embodiment, the base material (144) may include a previously formed (306) finished layer (e.g., 160). In embodiments where the base material (144) includes a previously formed (306) finished layer (160), method (300) includes iterating (314), for a plurality of iterations, through the depositing (202) and directing (204) steps to facilitate forming (306) the plurality of finished layers (e.g., 142a, 142b) having the user (131)-predetermined GS.

[0098] In one embodiment of method (300), the composition of the metal-based particles (136) during at least one iteration of the depositing (202) step may be different as compared to the composition of the metal-based particles (136) used for at least one other iteration of the depositing (202) step. In the embodiment, the controlling (308) step may include selecting (305) and controlling (308) the one or more of the mass rate ($\dot{m}$), the power (P), the spot diameter (d), and the velocity (v) to facilitate forming the plurality of finished layers (142a, 142b) having the user (131)-predetermined GS. In one embodiment, each layer (142a, 142b) of the plurality of layers (148, 150) has a substantially similar user (131)-predetermined GS. In another embodiment, at least one finished layer (e.g., 142a) of the plurality of finished layers (e.g., 148 and/or 150) has a user (131)-predetermined GS that is different from at least one other finished layer (e.g., 142b) of the plurality of finished layers (e.g., 148 and/or 150).

[0099] In one embodiment, method (300) may include maintaining a temperature of the metal-based particles (136) within a predetermined range of temperatures prior to and/or during the depositing (202) step. In one embodiment, the controlling (308) step may include controlling (308) (e.g., regulating (311), by the heater/cooler (113), sensor(s) (122), and/or processor(s) (124)) the temperature of the metal-based particles (136) to facilitate maintaining the temperature of the metal-based particles (136) within the predetermined range of temperatures prior to and/or during the depositing (202) step.

[00100] In one embodiment, method (300) may include maintaining a temperature of the base material (144) within a predetermined range of temperatures prior to and/or during the depositing (202) step. In one embodiment, the controlling (308) step may include controlling (308) (e.g., regulating (311), by the heater/cooler (113), sensor(s) (122), pump(s) (110), valve(s) (112), motor(s) (120), and/or processor(s) (124)) the temperature of the metal-based particles (136) to facilitate maintaining the temperature of the base material (144) within the predetermined range of temperatures prior to and/or during the depositing (202) step.

[00101] In one embodiment, the energy absorption rate (η) may be dependent on the temperature of the metal-based particles (136) during the depositing (202) and/or directing (204) steps. In one embodiment, η may be dependent on the temperature of the base material (144) during the depositing (202) and/or directing (204) steps.

[00102] In one embodiment, the depositing (202) step may include suspending (315) the metal-based particles (136) in a carrier gas stream (e.g., contained in and/or provided from the carrier gas supply (108)). In one embodiment, the controlling (308) step may include controlling (308) (e.g., regulating (311), by the pump(s) (110), valve(s) (112), sensor(s) (122), motor(s) (120), and/or the processor(s) (124)) a flow rate of the carrier gas stream (e.g., from the carrier gas supply (108) to the nozzle (133)) to facilitate controlling (308) (e.g., regulating (311)) the mass rate ($\dot{m}$) during the depositing (202) step. In one embodiment, the controlling (308) step may include controlling (308) (e.g., regulating (311), by the heater/cooler (113), sensor(s) (122), and/or processor(s) (124)) a temperature of the carrier gas stream to facilitate maintaining the temperature of the metal-based particles within a predetermined range of temperatures during the depositing (202) step. In one embodiment, the controlling (308) step may include controlling (308) (e.g., regulating (311)) the temperature of the carrier gas stream to facilitate maintaining a temperature of the base material (144) within a predetermined range of temperatures during the depositing (202) step.

[00103] In one embodiment, the depositing (202) and directing (204) steps are performed substantially simultaneously by system (102) during operation of process (100).

<u>Example 1</u>

[00104] FIG. 4 depicts a micro-section (400) of an Inconel 718 (IN718) AMMP produced using a known powder-fed additive system in accordance with a known method. The micro-section (400) was taken in the x,z plane. The build direction is indicated by an

arrow (401) (i.e., the positive z direction). Micro-section (400) includes at least three finished layers (402, 404, 406) of the AMMP consecutively laid down in the build direction (401) using the conventional system and method. The grain structures of FIG. 4 were characterized by determining the aspect ratios of grains shown in the micro-section.

[00105] The grain structure (GS) of the Inconel 718 (IN718) AMMP produced using the known system and method consists mostly of columnar grains (408). A directional arrangement of the columnar grains (408) is mainly along the build direction (401). Some columnar grains (e.g., 409) are arranged more horizontally in the x,z plane of micro-section (400), while other columnar grains (e.g., 410) are arranged diagonally in the x,z plane of micro-section (400). To a lesser extent as compared to the columnar grains (408, 409, 410), the GS of the IN718 AMMP includes non-equiaxed grains (411), near-equiaxed grains (412), and equiaxed grains (414).

[00106] As shown in micro-section (400), the number of columnar grains (408, 409, 410) is greater than the number of non-equiaxed grains (411), near-equiaxed grains (412), and equiaxed grains (414). The total cross-sectional areas of the columnar grains (408, 409, 410) is greater than the total cross-sectional areas of the non-equiaxed grains (411), near-equiaxed grains (412), and equiaxed grains (414). The cross-sectional areas of each type of grain (408, 409, 410, 411, 412, 414) shown in micro-section (400) varies, but, on average, the cross-sectional area of the equiaxed grains (414) is the lowest as compared to the average cross-sectional areas of the columnar grains (408, 409, 410), the non-equiaxed grains (411), and the near-equiaxed grains (412).

[00107] Without being bound by any particular mechanism or theory, it is believed that the predominance of non-equiaxed (411) and columnar (408, 409, 410) grains at varying orientations in the x,z plane of micro-section (400), as well as the relatively low population of equiaxed (414) and near-equiaxed grains (412), may be due to a lack of control of solidification in the known systems and methods as compared to the systems and methods disclosed herein. During solidification, grains (e.g., crystals) may grow directionally in contact with solid surfaces and may develop various morphologies. Grains may also grow independently in a super-cooled liquid, which results in equiaxed crystal growth. High temperatures may promote crystal growth of the grains. Therefore, coarsening of grain crystals may occur when the solidifying materials are kept at high temperatures.

[00108] In known powder-fed additive systems and methods of producing AMMPs, the solidification of grain crystals is not well controlled in a purposeful manner, which may cause grain crystals to grow at high temperature during layer-by-layer deposition and liquid

to solid state transitions. As compared to the systems and method disclosed herein, a lack of purposeful, computer processor-implemented control in known systems and methods may undesirably promote the formation of grain structures where grain crystals have larger aspect ratios as compared to the equiaxed grains (414). Such large aspect ratio grains include the columnar grains (408) generally oriented in the build direction (401) (e.g., opposite the heat flow direction).

[00109] During solidification of the layers in the IN718 AMMP shown in micro-section (400), equiaxed grains (414) may grow under cooling liquid metal material. A ratio of columnar (408, 409, 410) to equiaxed (414) grain growth may be determined by the amount of undercooling (e.g., ΔT), the number of nucleation sites (N), the temperature gradients of the solidifying grains (∇T), and the growing velocity of the solidifying grains (ds/dt). These four parameters depend on the composition of the materials laid down in a layer-by-layer fashion, as well on process conditions and parameters.

[00110] Absent effective control of these four parameters (e.g., ΔT, N, ∇T, and ds/dt) in known powder-fed additive systems and methods, the ratio of columnar (408, 409, 410) to equiaxed (414) grain growth and their relative numbers in the final AMMP product may not be effectively controlled so as to achieve a desired, predetermined GS. In some embodiments, grains having larger aspect ratios than the equiaxed grains (414) are not desirable (e.g. due to unfavorable mechanical performance in particular end-use applications and/or difficulties that they may introduce into existing non-destructive inspect techniques such as ultrasonic-based methods).

<u>Example 2</u>

[00111] FIG. 5 is a plot (500) of quotient (Eqn. 1) values (y-axis) versus mass rate ($\dot{m}$) (x-axis) in accordance with the disclosed method (200, 300) of FIGS. 2 and 3. As described above with reference to FIGS. 2 and 3, the quotient (Eqn. 1) may be maintained (312) in the user (131)-predetermined quotient range to facilitate achieving the user (131)-predetermined GS. To this end, plot (500) may be used as a process parameter map and may aid user (131) in visualizing data structures stored in memory device(s) (126) and manipulated by processor(s) (124), as described above with reference to FIGS. 2 and 3. Plot (500) includes three regions defined by diagonal (502, e.g., $y = (0.023\overline{3})x + 0.1$) and horizontal (504, e.g., y = 0.1) dashed lines. A first region (506) between the diagonal (502) and horizontal (504) dashed lines defines a user (131)-predetermined quotient range to facilitate achieving an equiaxed or near-equiaxed GS in the AMMP (158). A second region (508) under the

horizontal (504) dashed line and to the right of the y-axis defines a user (131)-predetermined quotient range to facilitate achieving a columnar or non-equiaxed GS in the AMMP (158). A third region (510) above the diagonal (502) dashed line and to the right of the y-axis defines a user (131)-predetermined quotient range to be avoided in process (100) due to improper melting and solidification, which may be caused by improper balance of the energy beam (128) power (P), the metal-based particles (136) mass rate ($\dot{m}$), and the velocity (v). It was determined that the process conditions for producing the IN718 AMMP using the known system and method corresponded to a quotient (Eqn. 1) value of 0.053, denoted in FIG. 5 as an open circle in the second region (508) of plot (500).

[00112] FIGS. 6A, 6B, 6C, and 6D are micro-sections (600, 602, 604, 606) of IN718 AMMPs produced by process (100) using powder-fed additive system (102) according to the disclosed methods (200, 300). The micro-sections (600, 602, 604, 606) were taken in the x,z plane. The build direction is indicated by an arrow (601) (i.e., the positive z direction). The grain structures of FIGS. 6A-6D were characterized by determining the aspect ratios of grains shown in the micro-sections.

[00113] FIG. 6A depicts a micro-section (600) of an IN718 AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.466. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.466 is within the first region (506). The GS of this IN718 AMMP produced by process (100) consists mostly of equiaxed (608) and near-equiaxed (610) grains, especially in upper layers (609) (e.g., higher positive z values in the build direction (601)). In the upper layers (609), equiaxed grains (608) predominate in number over near-equiaxed grains (610). In lower layers (611) (e.g., lower positive z values in the build direction (601)), some non-equiaxed grains (613) are also present. Columnar grains are notably absent from micro-section (600).

[00114] FIG. 6B depicts a micro-section (602) of an IN718 AMMP produced using the disclosed system (102) and methods (200, 300) where two user (131)-predetermined target values for the quotient (Eqn. 1) in process (100) were used. A first target quotient (Eqn. 1) value of 0.466 was used for lower layers (611), and then a second target quotient (Eqn. 1) value of 0 ("zero") was used for upper layers (609). As shown in FIG. 5, the target quotient (Eqn. 1) value of 0 falls on the lower left border of the second region (508) (e.g., at the origin of plot (500)). After the lower layers (611) were completed using process (100), the second target quotient value of 0 was implemented by setting the mass rate ($\dot{m}$) to 0. For both the lower (611) and upper (609) layers, the values of v, d, and Q in Eqn. 1 were held constant.

The GS of this IN718 AMMP produced by process (100) consists mostly of columnar (614) grains in its upper layers (609). In the upper layers (609), columnar grains (614) far outnumber non-equiaxed (613), near-equiaxed (610), and equiaxed (608) grains. In lower layers (611), near-equiaxed (610) and equiaxed (608) grains far outnumber columnar grains (614), thus demonstrating a pronounced effect on GS of an extreme case of setting $\dot{m} = 0$ in process (100).

[00115] FIG. 6C depicts a micro-section (604) of an IN718 AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.121. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.121 falls in the first region (506).

[00116] FIG. 6D depicts a micro-section (606) of an IN718 AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.118. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.118 falls in the first region (506). The GS of this IN718 AMMP produced by process (100) consists mostly of non-equiaxed (613) grains that are generally larger than any of the grains shown in FIGS. 6A-6C.

[00117] In summary, without being bound by a particular mechanism or theory, the Example 2 results shown and discussed above with reference to FIGS. 6A-6D are believed to demonstrate that targeting quotient (Eqn. 1) values within the first region (506) of plot (500) provides a higher probability of achieving an equiaxed (608) and/or a near-equiaxed (610) GS for IN718 AMMPs produced by process (100). Furthermore, without being bound by any particular mechanism or theory, the Example 2 results were observed to show that the disclosed methods (e.g., 200, 300) implemented using, for example, process (100) provides users (131) the ability to control and tailor GS and grain morphology by tuning the process parameters which dictate the quotient value (Eqn. 1). In some embodiments, this control may include alternately turning on and off one or more of the parameters, as shown and described above with reference to FIG. 6B.

<u>Example 3</u>

[00118] FIGS. 7A and 7B are micro-sections (700, 702) of stainless steel (SS316) AMMPs produced by process (100) using powder-fed additive system (102) according to the disclosed methods (200, 300). The micro-sections (700, 702) were taken in the x,z plane. The build direction is indicated by an arrow (701) (i.e., the positive z direction). The grain structures of FIGS. 7A and 7B were characterized by determining the aspect ratios of grains shown in the micro-sections.

[00119] FIG. 7A depicts a micro-section (700) of an SS316 AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.060. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.060 is within the second region (508). The GS of this SS316 AMMP produced by process (100) consists of a mixture of near-equiaxed (706) and equiaxed (704) grains.

[00120] FIG. 7B depicts a micro-section (702) of an SS316 AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.018. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.018 is within the second region (508). The GS of this SS316 AMMP produced by process (100) consists mostly of non-equiaxed grains (708) in both its upper (709) and lower (711) layers. In both the upper (709) and lower (711) layers, some columnar (710) and near-equiaxed (706) grains are also present. Throughout micro-section (702), the non-equiaxed grains (708) far outnumber near-equiaxed grains (706) and columnar (710) grains, and equiaxed grains (704) are not present.

[00121] In summary, the Example 3 results shown and discussed above with reference to FIGS. 7A and 7B demonstrate that, for SS316 AMMPs produced by process (100), as the target quotient (Eqn. 1) value is increased, and thus approaches the first region (506) of plot (500), the GS transitions from having relatively more non-equiaxed (708) and columnar (710) grains, to having a comparatively greater number of equiaxed (704) and near-equiaxed (706) grains. Furthermore, the Example 3 results show that the disclosed methods (e.g., 200, 300) implemented using, for example, process (100) provides users (131) the ability to control and tailor GS and grain morphology in SS316 AMMPs by tuning the process parameters which dictate the quotient value (Eqn. 1).

Example 4

[00122] FIGS. 8A, 8B, and 8C are micro-sections (800, 802, 804) of Ti-6Al-4V AMMPs produced by process (100) using powder-fed additive system (102) according to the disclosed methods (200, 300). The micro-sections (800, 802, 804) were taken in the x,z plane. The build direction is indicated by an arrow (801) (i.e., the positive z direction). The grain structures of FIGS. 8A-8C were characterized by determining the aspect ratios of grains shown in the micro-sections.

[00123] FIG. 8A depicts a micro-section (800) of a Ti-6Al-4V AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.081. As shown in FIG. 5, the target

quotient (Eqn. 1) value of 0.081 is within the second region (508). The GS of this Ti-6Al-4V AMMP produced by process (100) consists mostly of near-equiaxed (808) and non-equiaxed (810) grains. In both the upper (809) and lower (811) layers, some equiaxed grains (806) grains are also present. Throughout micro-section (800), the near-equiaxed (808) and non-equiaxed (810) grains predominate in number over equiaxed grains (806).

[00124] FIG. 8B depicts a micro-section (802) of a Ti-6Al-4V AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.047. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.047 is within the second region (508). The GS of this Ti-6Al-4V AMMP produced by process (100) consists mainly of columnar grains (812), with a more preferred crystallographic orientation of grains (i.e., a stronger texture) than that shown in FIG. 8A.

[00125] FIG. 8C depicts a micro-section (804) of a Ti-6Al-4V AMMP produced using the disclosed system (102) and methods (200, 300) where a user (131)-predetermined target value for the quotient (Eqn. 1) in process (100) was 0.01. As shown in FIG. 5, the target quotient (Eqn. 1) value of 0.01 is within the second region (508). The GS of this Ti-6Al-4V AMMP produced by process (100) consists mainly of columnar grains (812) (e.g., epitaxial prior-beta grains).

[00126] In summary and without being bound by any mechanism or theory, the Example 4 results shown and discussed above with reference to FIGS. 8A-8C demonstrate that, for Ti-6Al-4V AMMPs produced by process (100), as the target quotient (Eqn. 1) value is increased, and thus approaches the first region (506) of plot (500), the GS transitions from having relatively more and larger non-equiaxed (810) and columnar (812) grains (e.g., epitaxial prior-beta grains), to having a comparatively greater number of near-equiaxed grains (808) and a more random texture. Furthermore, the Example 3 results show that the disclosed methods (e.g., 200, 300) implemented using, for example, process (100) provides users (131) the ability to control and tailor GS and grain morphology in Ti-6Al-4V AMMPs by tuning the process parameters which dictate the quotient value (Eqn. 1).

[00127] Examples 2-4, described above, demonstrate that, by targeting specific quotient (Eqn. 1) values in process (100) using system (102) and the disclosed methods (200, 300), users (131) may purposefully tailor and control (308) process parameters in order to manufacture AMMPs having user (131)-predetermined grain structures and thus, having desired mechanical and other physical properties according to product requirements and design specifications. As demonstrated by the results presented above under Examples 2-4,

the user (131)-predetermined quotient range generally defined by the first region (506) of plot (500) may be further refined by users (131) on a case-by-case basis depending on the composition of metal-based particles (136) to be employed in process (100).

[00128] For instance, in Example 2, a target quotient (Eqn. 1) value of 0.466 (FIG. 6A) used in process (100) achieved the equiaxed (608) and near-equiaxed (610) grains. In addition, when the target quotient (Eqn. 1) value is set to 0, the GS transitioned to columnar grains (614), as shown and described above with reference to FIG. 6B.

[00129] Similarly, in Example 3, a substantial increase in the ratio of equiaxed (704) and/or near-equiaxed (706) grains to columnar (710) and/or non-equiaxed (708) grains was achieved by increasing the target quotient (Eqn. 1) value from 0.018 (FIG. 7B) to 0.060 (FIG. 7A), despite each of those two target quotient (Eqn. 1) values being within the second region (508). Each of Examples 2-4 demonstrate that, for at least IN718, SS316, and Ti-6Al-4V AMMPs (158), an increase in the ratio of equiaxed and/or near-equiaxed grains to columnar and/or non-equiaxed grains is achievable by moving the targeted quotient (Eqn. 1) values from the second region (508) closer to and/or into the first region (506) of plot (500).

[00130] Experiments such as those shown and described with reference to Examples 2-4 thus demonstrate that within a generally defined user (131)-predetermined quotient range (e.g., first region (506)), there may be some intra-region variability in the GS achieved for AMMPs (158) having equivalent metal-based particles (136) compositions. Furthermore, Examples 2-4 show that AMMPs (158) produced using differing compositions of metal-based particles (136) may each have their own respective subregion(s) defined in plot (500), including within one or both of the first (506) and second (508) regions. As such, the user (131)-predetermined quotient (Eqn. 1) range may be further refined so as to maintain (312) the value of the quotient (Eqn. 1) within a narrower, refined user (131)-predetermined quotient range and facilitate achieving a more narrowly defined user (131)-predetermined GS in the finished layers (e.g., 142a, 142b) of the AMMP (158) produced in process (100) using system (102) and the disclosed methods (200, 300).

[00131] In general, proportionally increasing fine equiaxed grain structures in AMMPs (158) using the above-described systems (e.g., 102) and methods (e.g., 200, 300) may provide several technical advantages. As compared to known AMMPs produced using known systems and methods (e.g., as shown in FIG. 4), these advantages include: (a) better distribution of secondary phases and microporosity; (b) better mechanical properties including higher yield and tensile strengths, better elongation, better toughness; and (c) higher consistency in quality and reduced operating costs associated with producing AMMPs.

[00132] For metal-based particles (136) yielding intermetallic phases in final product forms when used for producing AMMPs, a large amount of the intermetallic constituents may be segregated at melt pool boundaries. Without being bound by a particular mechanism or theory, the intermetallic phases may be brittle and/or promote crack formation in the region around the melt pool boundaries. Equiaxed grain structures can improve the distribution of the secondary phases, and thus, the equiaxed grain structures may significantly reduce the tendency of part cracking for this type of AMMP during part build due to better material homogeneity.

[00133] Ultrasonic inspection relies on the scattering of waves from discontinuities, such as fractures or voids. But many materials maintain a microstructure (e.g., GS) that causes scattering of the propagating waves, which may undermine ultrasonic inspection techniques as it becomes exceedingly difficult to discern the features of interest (voids, defects) from the scattering inherent to microstructural features, thereby limiting the range of materials which can be reliably inspected in this manner.

[00134] The columnar grain structures can lead to high ultrasonic attenuation, significant signal noises and cause erroneous indications regarding defects. The problems of ultrasonically inspecting structures with large columnar grains are well known. The large columnar grains cause material anisotropy and lead to preferred propagation directions for ultrasonic waves and to unexpected defect reflection behavior to the sound waves. The presence of large columnar grains of varying orientations (e.g., as shown in FIG. 4) cause high attenuation from scattering at grain boundaries. This issue is further complicated by inhomogeneity, thus leading to curved or otherwise suboptimal propagation paths for ultrasonic waves, which makes ultrasonic inspection very difficult or impossible. With fine equiaxed grains, by contrast, the aforementioned ultrasonic inspection problems can be significantly alleviated and signal noise levels can be significantly reduced, which makes ultrasonic inspection possible.

[00135] Aspects of the invention will now be described with reference to the following numbered clauses:

1. A method comprising the steps of (a) depositing, at a mass rate ($\dot{m}$), metal-based particles on a base material, thereby creating a precursor layer of an AMMP; (b) directing an energy beam from an energy source toward the precursor layer, thereby forming a finished layer, wherein characteristics of the energy beam include a power (P) and a spot diameter (d), wherein the directing step (b) includes: (i) moving the

energy beam at a velocity (v) relative to the base material; and (ii) controlling one or more of ṁ, P, d, and v to facilitate forming the finished layer of the AMMP having a predetermined grain structure (GS); and wherein the controlling step includes maintaining a value of a quotient $\left(\frac{\dot{m}}{v d Q}\right)$ within a predetermined quotient range, wherein Q is an average effective heat flux of the energy beam defined as $\frac{\eta P}{\pi d^2/4}$, and wherein η is an energy absorption rate of the precursor layer.

2. The method of clause 1, wherein the method comprises selecting, before the depositing step (a), the predetermined GS.
3. The method of any preceding clause, wherein the predetermined GS is an equiaxed GS.
4. The method of any preceding clause, wherein the predetermined GS is a near-equiaxed GS.
5. The method of any preceding clause, wherein the predetermined GS is a non-equiaxed GS.
6. The method of any preceding clause, wherein the predetermined GS is a columnar GS.
7. The method of any preceding clause, wherein the predetermined GS is a combination of two or more of the equiaxed GS, the near-equiaxed GS, the non-equiaxed GS, and the columnar GS.
8. The method of any preceding clause, wherein a type of the energy beam used during the directing step (b) is a laser beam.
9. The method of any preceding clause, wherein the predetermined quotient range is dependent on the type of the energy beam used during the directing step (b).
10. The method of any preceding clause, wherein the energy absorption rate (η) is dependent on the type of the energy beam used during the directing step (b).
11. The method of any preceding clause, wherein the predetermined quotient range is dependent on a composition of the metal-based particles.
12. The method of any preceding clause, wherein the energy absorption rate (η) is dependent on the composition of the metal-based particles.
13. The method of any preceding clause, wherein the deposited precursor layer has a thickness, wherein the thickness is dependent on the mass rate (ṁ), and wherein the controlling step (b)(ii) includes controlling the mass rate (ṁ) to facilitate maintaining

the thickness within a predetermined thickness tolerance during the depositing step (a).

14. The method of any preceding clause, wherein the depositing step (a) includes depositing the metal-based particles from at least one nozzle of an additive system, wherein the at least one nozzle is spaced from the base material by a first distance (E1), and wherein the controlling step (b)(ii) comprises maintaining the value of the first distance (E1) within a first predetermined distance tolerance to facilitate controlling the mass rate ($\dot{m}$).
15. The method of any preceding clause, wherein the directing step (b) includes directing the energy beam from an aperture of an additive system, wherein the aperture is spaced from the base material by a second distance (E2), and wherein the controlling step (b)(ii) includes maintaining the value of the second distance (E2) within a second predetermined distance tolerance to facilitate controlling the spot diameter (d).
16. The method of any preceding clause, wherein the depositing step (a) comprises depositing the metal-based particles from at least one nozzle of an additive system, wherein the at least one nozzle is spaced from the base material, wherein the directing step (b) includes directing the energy beam from an aperture of the additive system, wherein the aperture is spaced from the base material, and wherein the moving step (b)(i) includes moving the aperture and the at least one nozzle at the same velocity (v).
17. The method of any preceding clause, wherein the additive system is a powder-fed additive system.
18. The method of any preceding clause, wherein the base material includes a previously formed finished layer, and wherein the method includes iterating, for a plurality of iterations, through the depositing (a) and directing (b) steps to facilitate forming a plurality of finished layers having the predetermined GS.
19. The method of any preceding clause, wherein, for at least one iteration of the depositing step (a), the composition of the metal-based particles is different as compared to the composition of the metal-based particles used for at least one other iteration of the depositing step (a), and wherein the controlling step (b)(ii) includes controlling the one or more of the mass rate ($\dot{m}$), the power (P), the spot diameter (d), and the velocity (v) to facilitate forming the plurality of finished layers having the predetermined GS.
20. The method of any preceding clause, wherein the method includes selecting, before the depositing step (a), the composition of the metal-based particles.

21. The method of any preceding clause, wherein the method includes maintaining a temperature of the metal-based particles within a predetermined range of temperatures during the depositing step (a).
22. The method of any preceding clause, wherein the method includes maintaining a temperature of the base material within a predetermined range of temperatures during the depositing step (a).
23. The method of any preceding clause, wherein the energy absorption rate (η) is dependent on a temperature of the metal-based particles during the depositing step (a).
24. The method of any preceding clause, wherein the depositing step (a) includes suspending the metal-based particles in a carrier gas stream.
25. The method of any preceding clause, wherein the controlling step (b)(ii) includes controlling a flow rate of the carrier gas stream to facilitate controlling the mass rate ($\dot{m}$).
26. The method of any preceding clause, wherein the controlling step (b)(ii) includes controlling a temperature of the carrier gas stream to facilitate maintaining the temperature of the metal-based particles within the predetermined range of temperatures during the depositing step (a).
27. The method of any preceding clause, wherein the controlling step (b)(ii) includes controlling the temperature of the carrier gas stream to facilitate maintaining the temperature of the metal-based particles within the predetermined range of temperatures during the depositing step (a).
28. The method of any preceding clause, wherein the controlling step (b)(ii) includes controlling the temperature of the carrier gas stream to facilitate maintaining the temperature of the base material within the predetermined range of temperatures during the depositing step (a).
29. The method of any preceding clause, wherein the depositing (a) and directing (b) steps are performed substantially simultaneously.

[00136] While a number of embodiments of the present disclosure have been described, it is understood that these embodiments are illustrative only, and not restrictive, and that many modifications may become apparent to those of ordinary skill in the art. Further still, the various steps may be carried out in any desired order (and any desired steps may be added and/or any desired steps may be eliminated).

CLAIMS

What is claimed is:

1. A method comprising:

(a) depositing, at a mass rate ($\dot{m}$), metal-based particles on a base material, thereby creating a precursor layer of an additively-manufactured metal-based product (AMMP);

(b) directing an energy beam from an energy source toward the precursor layer, thereby forming a finished layer, wherein characteristics of the energy beam include a power (P) and a spot diameter (d), and wherein the directing step (b) comprises:

(i) moving the energy beam at a velocity (v) relative to the base material; and

(ii) controlling one or more of $\dot{m}$, P, d, and v to facilitate forming the finished layer of the AMMP having an equiaxed grain structure, wherein the controlling step comprises:

maintaining a value of a quotient $\left(\frac{\dot{m}}{v d Q}\right)$ within a predetermined quotient range, wherein Q is an average effective heat flux of the energy beam defined as $\frac{\eta P}{\pi d^2/4}$, and wherein η is an energy absorption rate of the precursor layer.

2. The method of claim 1, wherein a type of the energy beam used during the directing step (b) is a laser beam.

3. The method of claim 2, wherein the predetermined quotient range is dependent on the type of the energy beam used during the directing step (b).

4. The method of claim 2, wherein the energy absorption rate (η) is dependent on the type of the energy beam used during the directing step (b).

5. The method of claim 1, wherein the predetermined quotient range is dependent on a composition of the metal-based particles.

6. The method of claim 1, wherein the energy absorption rate (η) is dependent on a composition of the metal-based particles.

7. The method of claim 1, wherein:

the deposited precursor layer has a thickness;

the thickness is dependent on the mass rate ($\dot{m}$);

and

the controlling step (b)(ii) comprises controlling the mass rate ($\dot{m}$) to facilitate maintaining the thickness within a predetermined thickness tolerance during the depositing step (a).

8. The method of claim 1, wherein:

the depositing step (a) comprises depositing the metal-based particles from at least one nozzle of an additive system, the at least one nozzle spaced from the base material by a first distance (E1);

the controlling step (b)(ii) comprises maintaining the value of the first distance (E1) within a first predetermined distance tolerance; and

maintaining the value of the first distance (E1) within the first predetermined distance tolerance facilitates controlling the mass rate ($\dot{m}$).

9. The method of claim 1, wherein:

the directing step (b) comprises directing the energy beam from an aperture of an additive system, the aperture spaced from the base material by a second distance (E2);

the controlling step (b)(ii) comprises maintaining the value of the second distance (E2) within a second predetermined distance tolerance; and

maintaining the value of the second distance (E2) within the second predetermined distance tolerance facilitates controlling the spot diameter (d).

10. The method of claim 1, wherein:

the depositing step (a) comprises depositing the metal-based particles from at least one nozzle of an additive system, the at least one nozzle spaced from the base material;

the directing step (b) comprises directing the energy beam from an aperture of the additive system, the aperture spaced from the base material; and

the moving step (b)(i) comprises moving the aperture and the at least one nozzle at the same velocity (v).

11. The method of claim 1, wherein:

the base material includes a previously formed finished layer; and

the method comprises iterating, for a plurality of iterations, through the depositing (a) and directing (b) steps to facilitate forming a plurality of finished layers having the equiaxed grain structure.

12. The method of claim 11, wherein:

for at least one iteration of the depositing step (a), a composition of the metal-based particles is different as compared to the composition used for at least one other iteration of the depositing step (a); and

the controlling step (b)(ii) comprises controlling the one or more of the mass rate ($\dot{m}$), the power (P), the spot diameter (d), and the velocity (v) to facilitate forming the plurality of finished layers having the equiaxed grain structure.

13. The method of claim 1 comprising maintaining a temperature of the metal-based particles within a predetermined range of temperatures during the depositing step (a).

14. The method of claim 1 comprising maintaining a temperature of the base material within a predetermined range of temperatures during the depositing step (a).

15. The method of claim 1, wherein the energy absorption rate (η) is dependent on a temperature of the metal-based particles during the depositing step (a).

16. The method of claim 1, wherein:

the depositing step (a) comprises suspending the metal-based particles in a carrier gas stream; and

the controlling step (b)(ii) comprises controlling a flow rate of the carrier gas stream to facilitate controlling the mass rate ($\dot{m}$).

17. The method of claim 1, wherein:

the depositing step (a) comprises suspending the metal-based particles in a carrier gas stream; and

the controlling step (b)(ii) comprises controlling a temperature of the carrier gas stream to facilitate maintaining a temperature of the metal-based particles during the depositing step (a).

18. The method of claim 1, wherein:

the depositing step (a) comprises suspending the metal-based particles in a carrier gas stream; and

the controlling step (b)(ii) comprises controlling a temperature of the carrier gas stream to facilitate maintaining a temperature of the base material during the depositing step (a).

19. The method of claim 1, wherein the depositing (a) and directing (b) steps are performed substantially simultaneously.

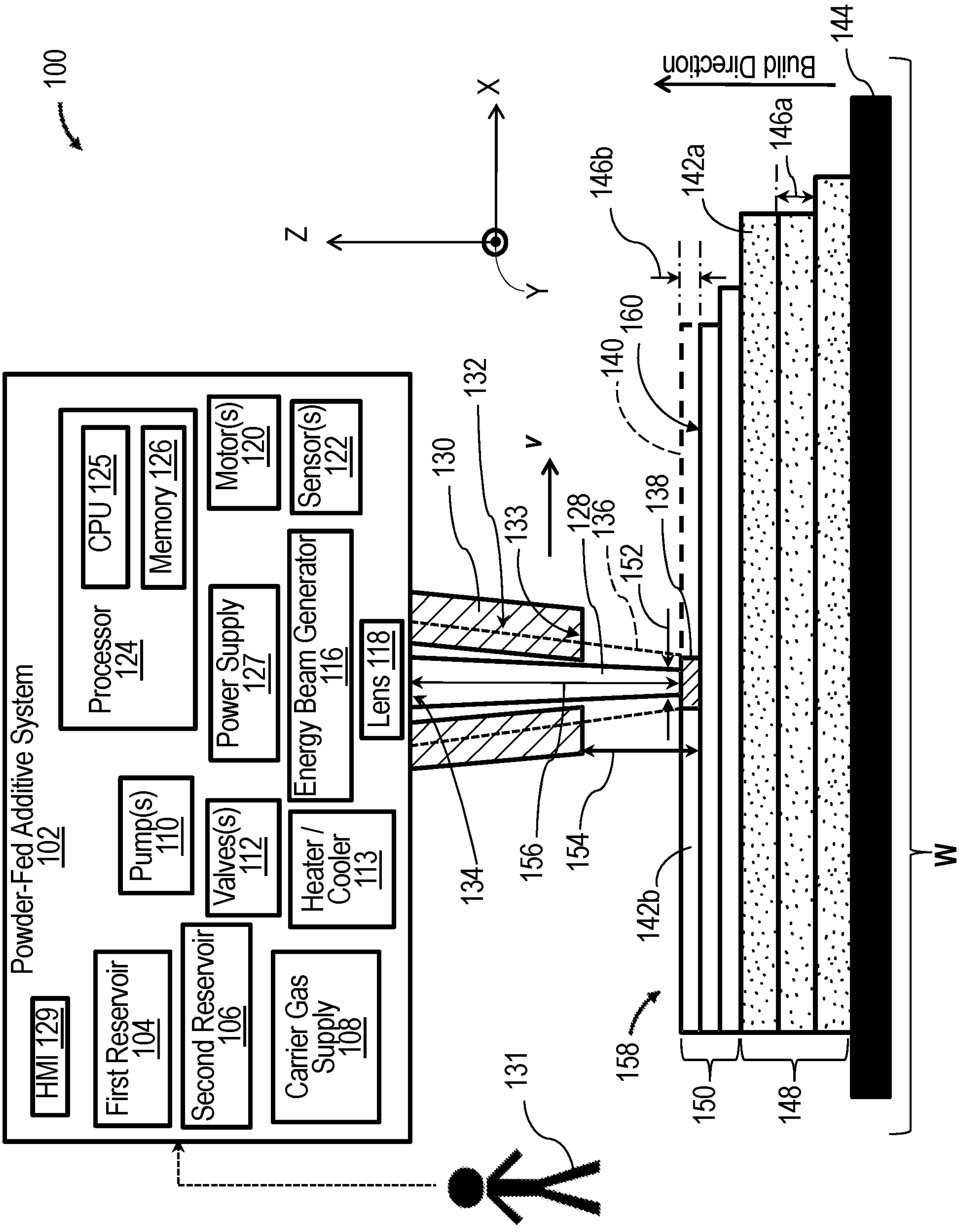

100
Powder-Fed Additive System
102
HMI 129
First Reservoir
104
Second Reservoir
106
Carrier Gas
Supply
108
Pump(s)
110
Valves(s)
112
Heater /
Cooler
113
Processor
124
CPU 125
Memory 126
Power Supply
127
Energy Beam Generator
116
Lens 118
Motor(s)
120
Sensor(s)
122
131
X
Y
Z
v
130
132
133
128
136
138
152
134
156
154
140
160
146b
142a
146a
144
Build Direction
142b
158
150
148
W

FIG.1

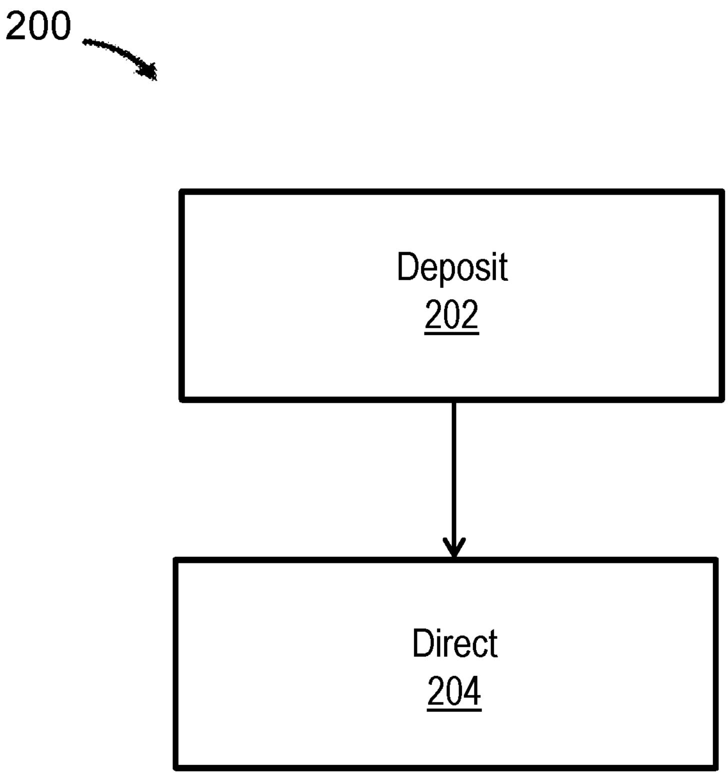


FIG.2

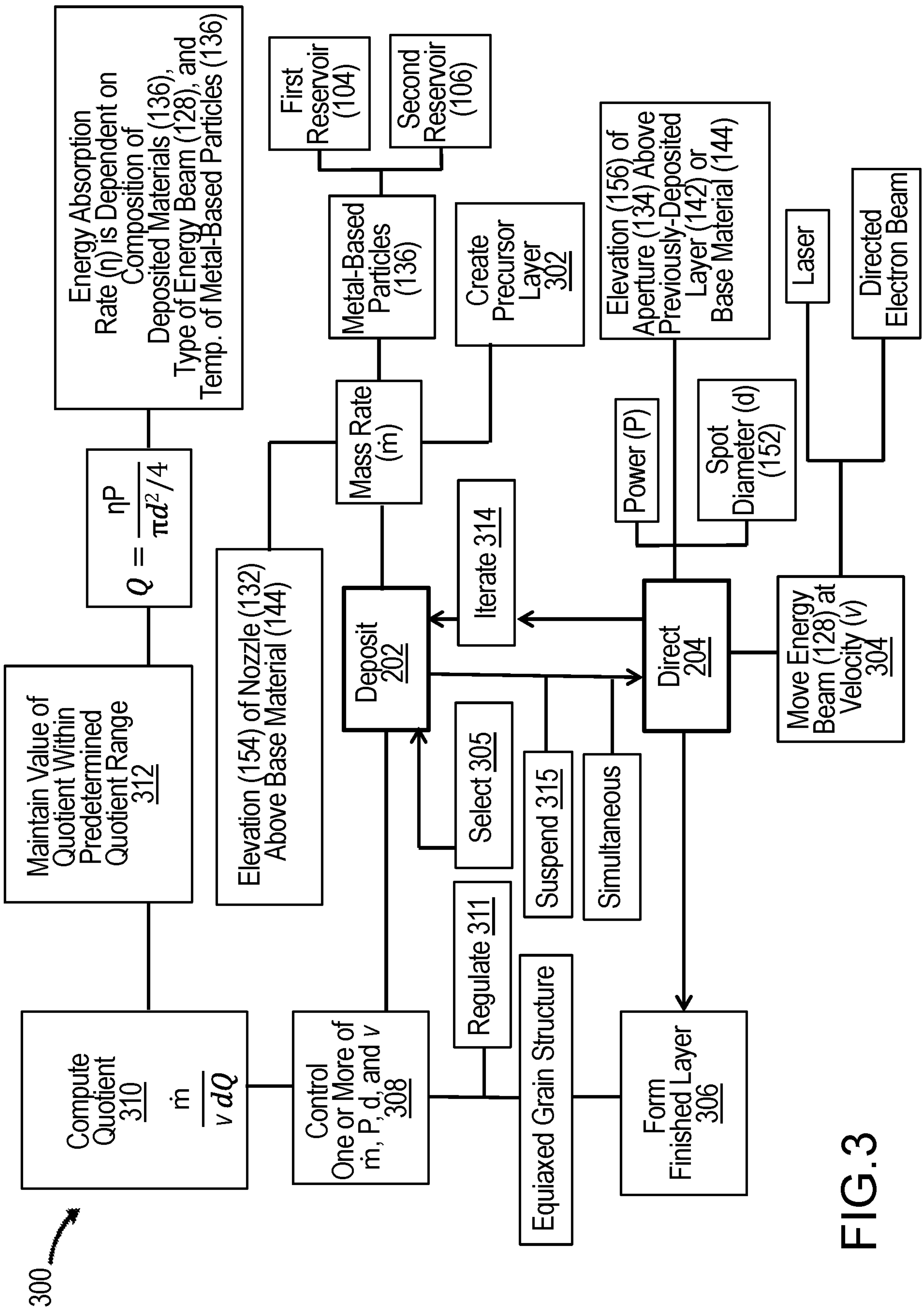
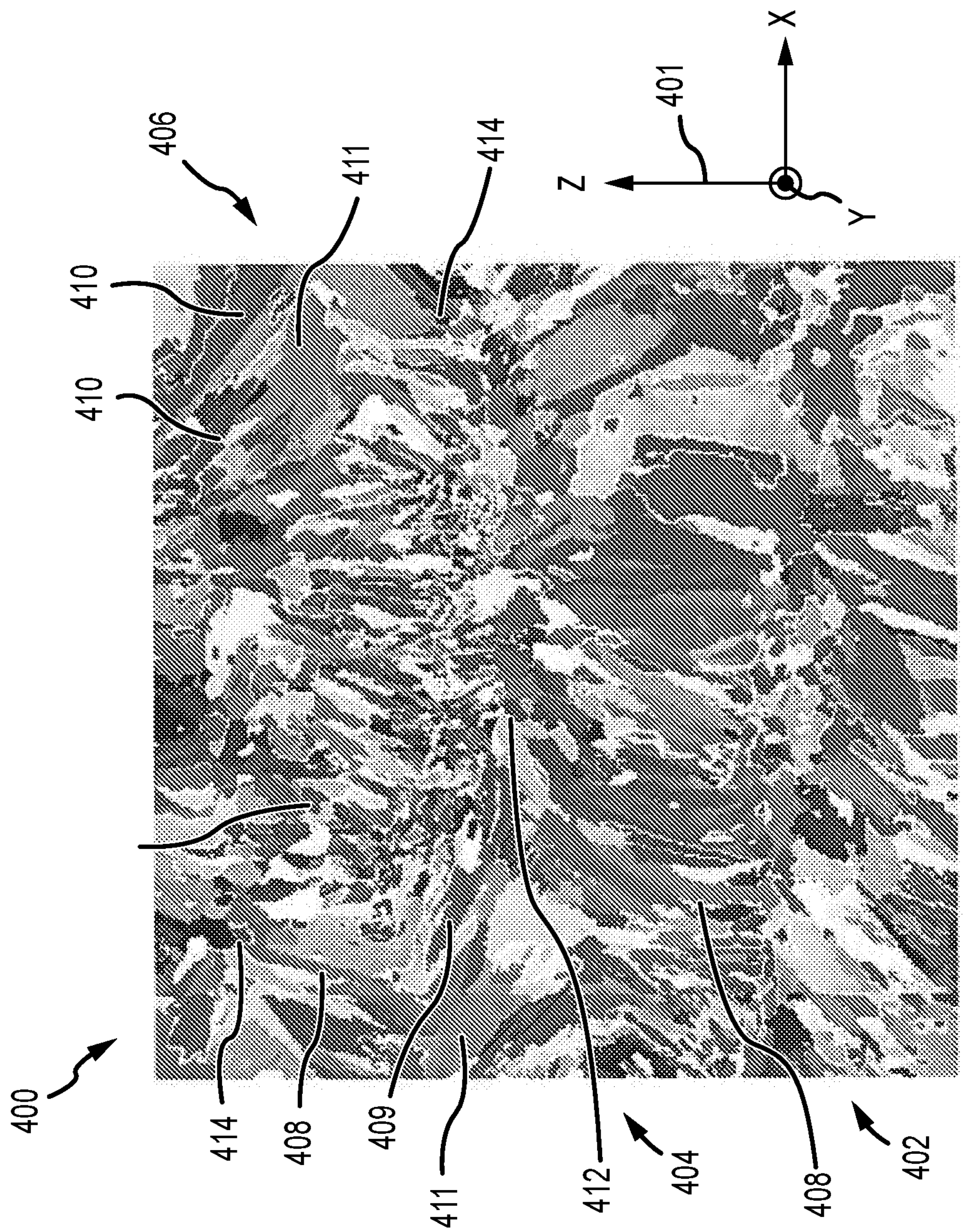

300
Energy Absorption Rate (η) is Dependent on Composition of Deposited Materials (136), Type of Energy Beam (128), and Temp. of Metal-Based Particles (136)
$Q = \frac{\eta P}{\pi d^2/4}$
Maintain Value of Quotient Within Predetermined Quotient Range 312
Compute Quotient 310
$\frac{\dot{m}}{v\,dQ}$
First Reservoir (104)
Second Reservoir (106)
Metal-Based Particles (136)
Mass Rate (ṁ)
Elevation (154) of Nozzle (132) Above Base Material (144)
Create Precursor Layer 302
Deposit 202
Iterate 314
Select 305
Control One or More of ṁ, P, d, and v 308
Regulate 311
Suspend 315
Simultaneous
Equiaxed Grain Structure
Elevation (156) of Aperture (134) Above Previously-Deposited Layer (142) or Base Material (144)
Power (P)
Spot Diameter (d) (152)
Direct 204
Form Finished Layer 306
Laser
Directed Electron Beam
Move Energy Beam (128) at Velocity (v) 304

FIG.3



A typical grain morphology of IN718 parts made through laser-powder-fed processes.

FIG.4

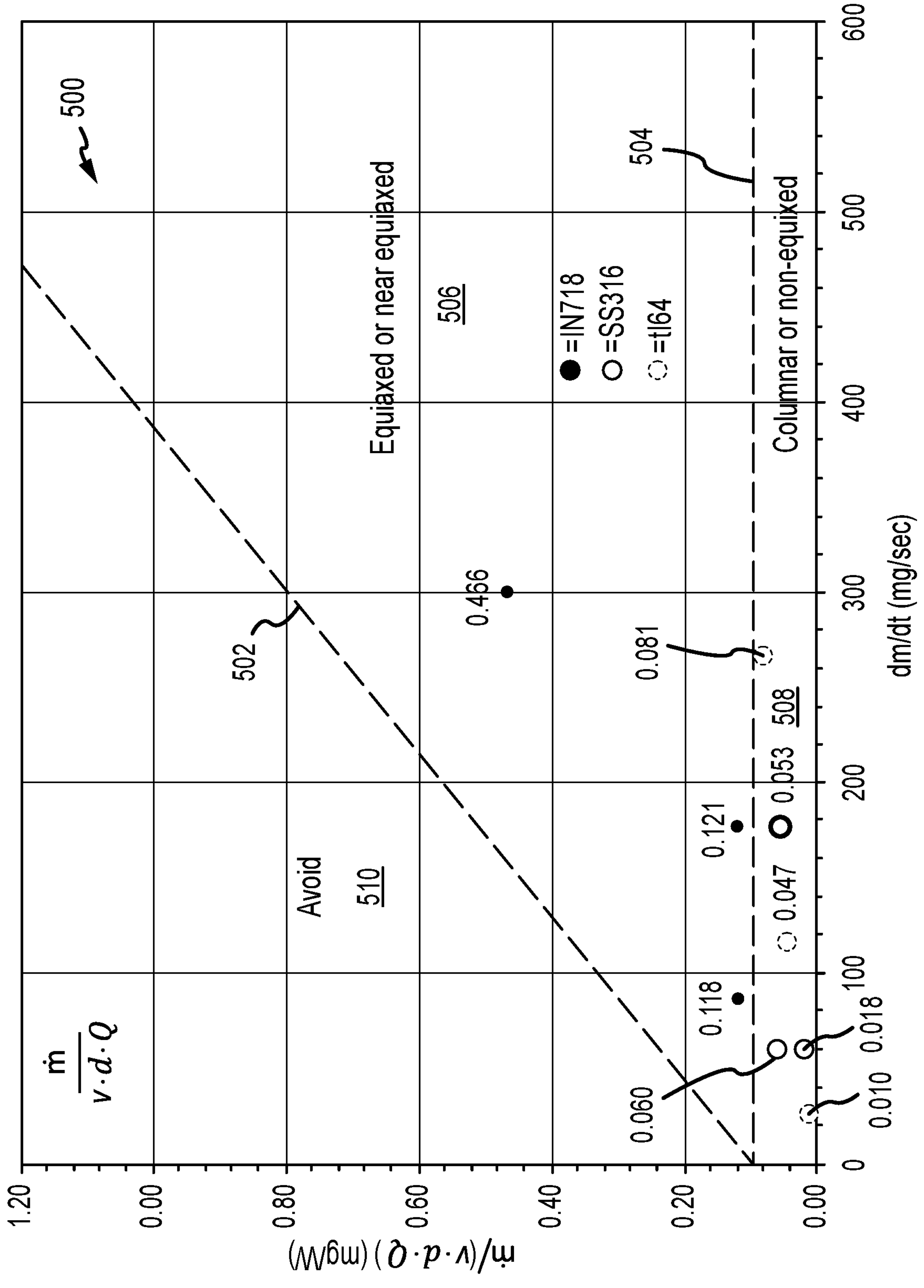
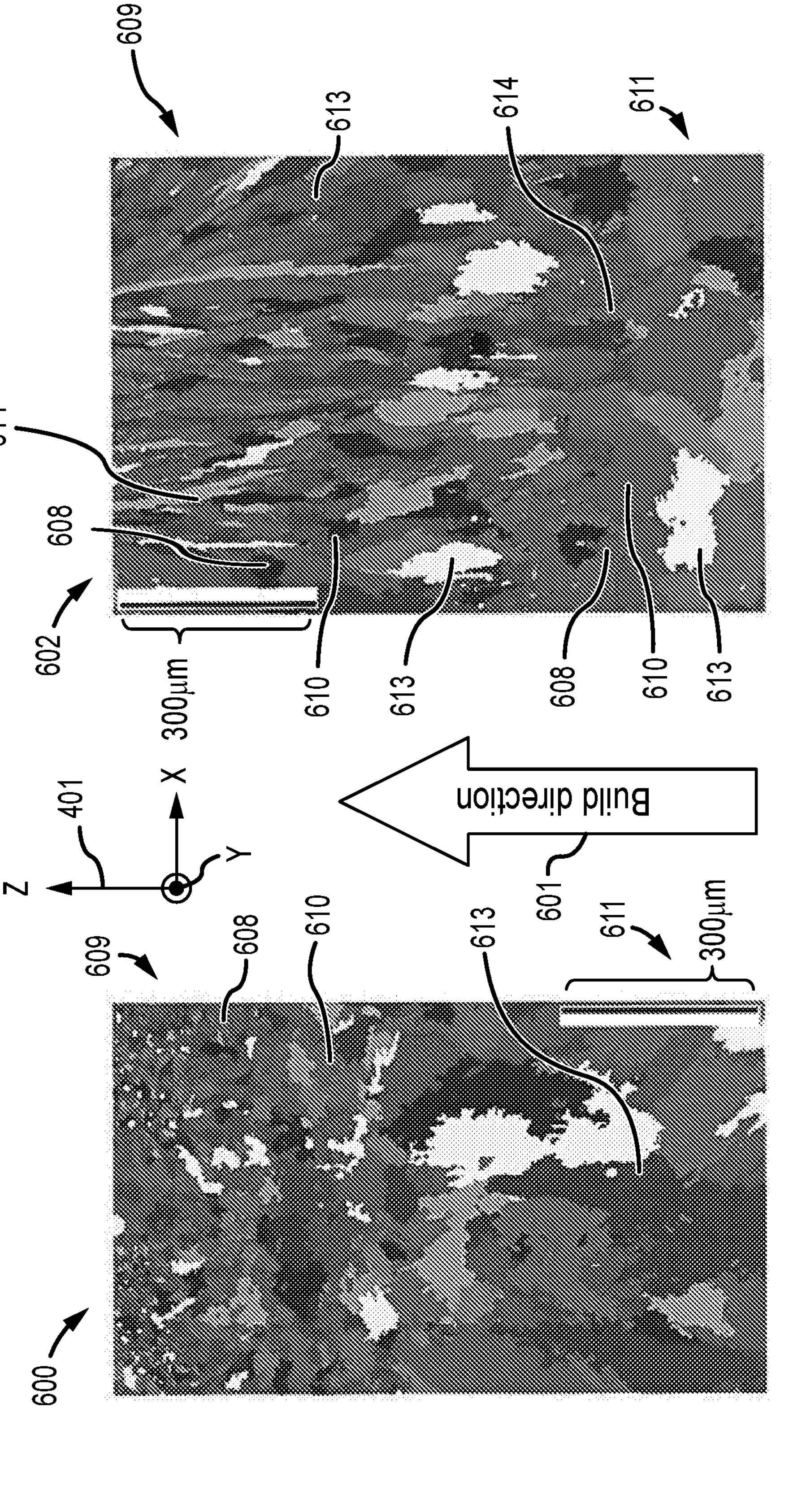

500
ṁ / v·d·Q
Equiaxed or near equiaxed
506
Avoid
510
● =IN718
○ =SS316
◌ =tI64
502
504
0.466
0.081
0.121
0.053
508
0.047
0.118
0.060
0.018
0.010
Columnar or non-equixed
1.20
0.00
0.80
0.60
0.40
0.20
0.00
ṁ/(v·d·Q) (mg/W)
0
100
200
300
400
500
600
dm/dt (mg/sec)

FIG.5

6/10

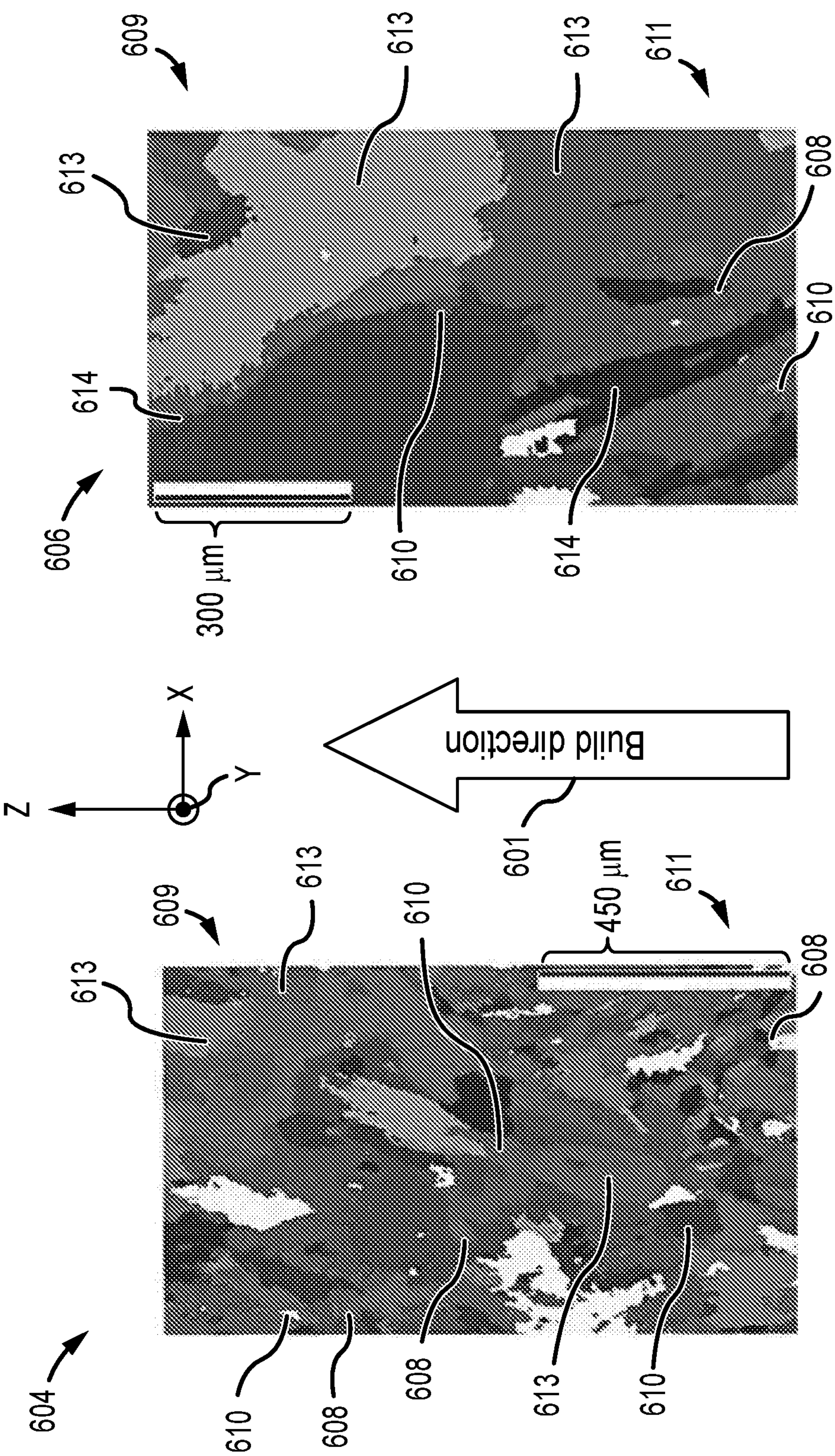


IN718 grains structures under the condition of (dm/dt)/(V •d •Q)= 0.466

FIG.6A

IN718 grains structures under the condition of (dm/dt)/(V •d •Q)= 0.466 and 0

FIG.6B

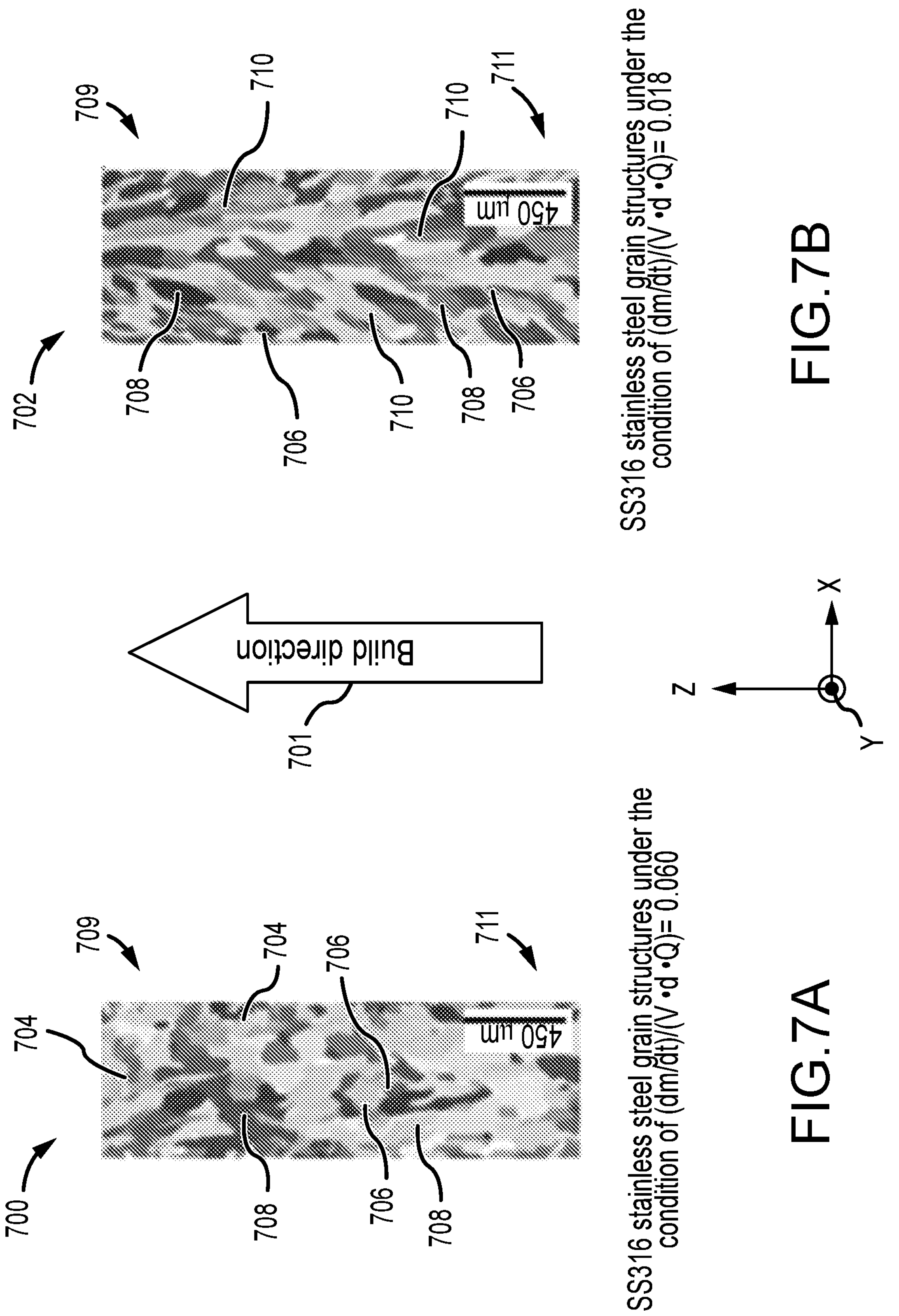


IN718 grains structures under the condition of (dm/dt)/(V •d •Q)= 0.121

FIG.6C

IN718 grains structures under the condition of (dm/dt)/(V •d •Q)= 0.118

FIG.6D

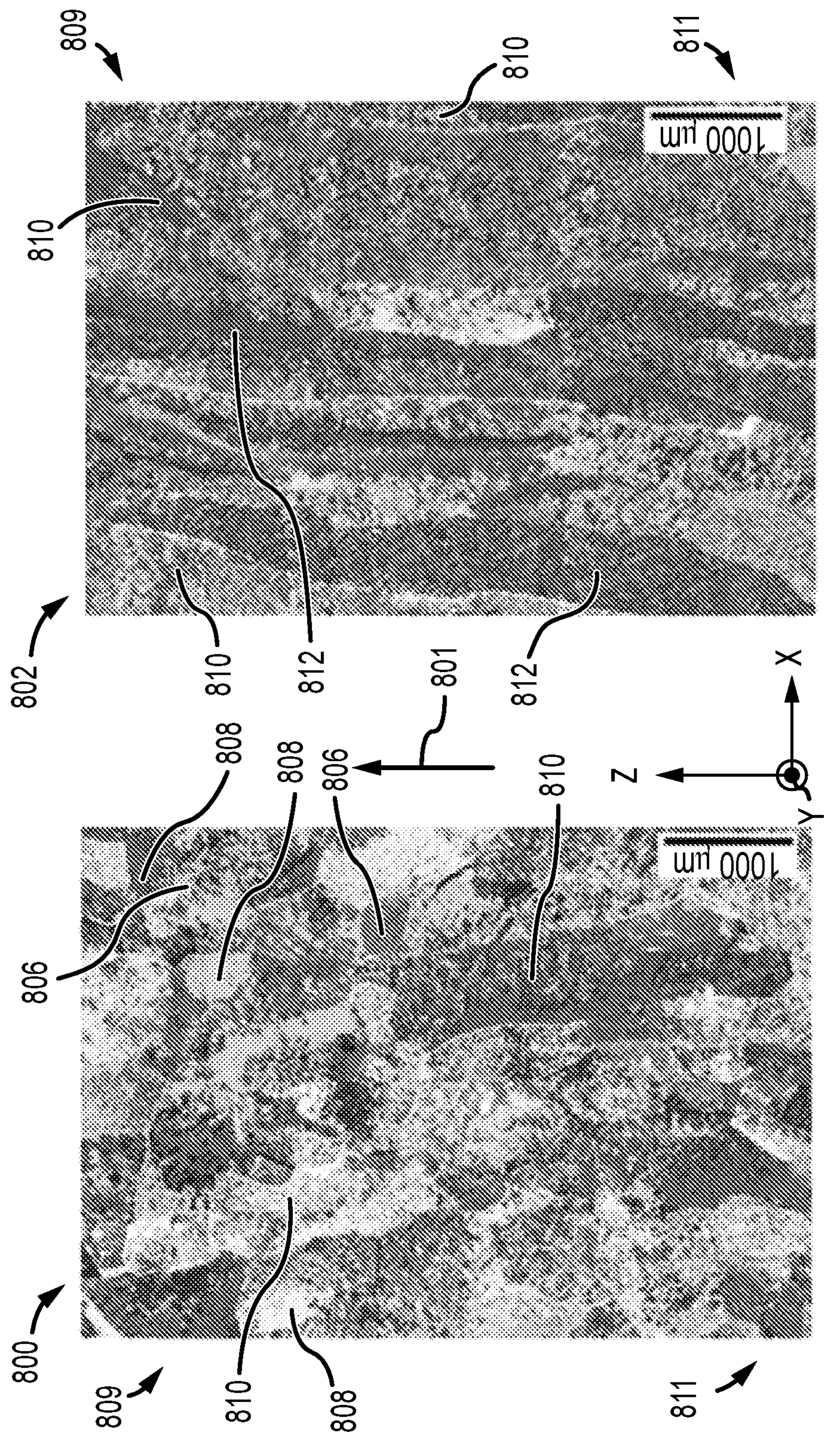


SS316 stainless steel grain structures under the condition of (dm/dt)/(V •d •Q)= 0.018

FIG.7B

SS316 stainless steel grain structures under the condition of (dm/dt)/(V •d •Q)= 0.060

FIG.7A

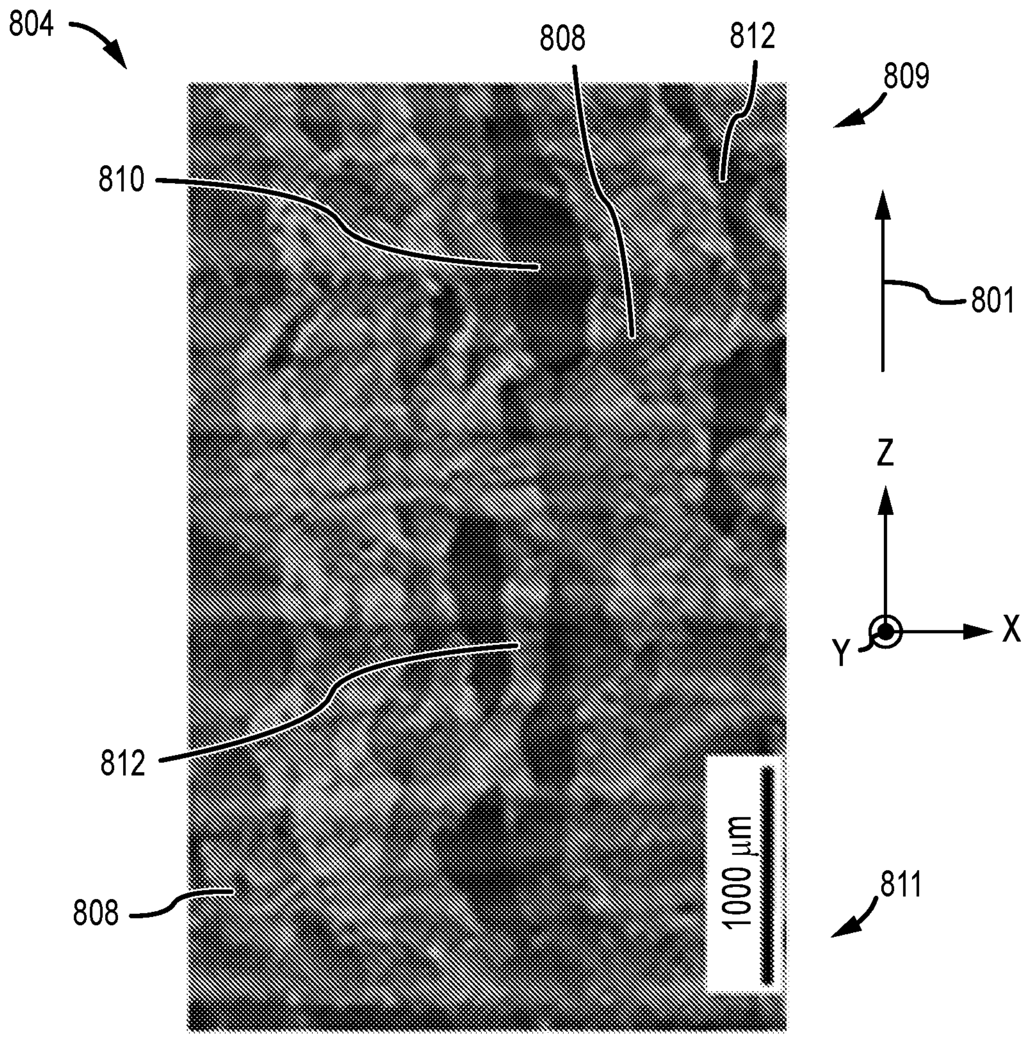


Ti64 grain structures under the condition of (dm/dt)/(V •d •Q)= 0.081

FIG.8A

Ti64 grain structures under the condition of (dm/dt)/(V •d •Q)= 0.047

FIG.8B



Ti64 grain structures under the condition of (dm/dt)/(V •d •Q)= 0.01

FIG.8C

INTERNATIONAL SEARCH REPORT	International application No. **PCT/US2018/067742**

A. CLASSIFICATION OF SUBJECT MATTER

B22F 3/105(2006.01)i, B33Y 10/00(2015.01)i, B33Y 70/00(2015.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B22F 3/105; B23K 26/342; B29C 67/00; B33Y 50/00; C22C 19/07; G06F 17/50; B33Y 10/00; B33Y 70/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: grain structure, equiaxed, spot diameter, power, velocity, mass rate, parameter

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KR 10-2017-0068014 A (KOREA INSTITUTE OF INDUSTRIAL TECHNOLOGY) 19 June 2017 See claims 1-8.	1-19
A	YAN et al. Grain structure control of additively manufactured metallic materials. Materials. 2 November 2017 See pages 1-11.	1-19
A	US 2016-0151860 A1 (ALSTOM TECHNOLOGY LTD.) 02 June 2016 See paragraphs [0053]-[0054], [0091]-[0109] and claim 1, 7.	1-19
A	US 2017-0212979 A1 (CHENG, JINQUAN) 27 July 2017 See paragraphs [0009]-[0011].	1-19
A	GORSSE et al. Additive manufacturing of metals: a brief review of the characteristic microstructures and properties of steel, Ti-6Al-4V and high-entropy alloy. Science and technology of advanced materials, Vol. 18, No. 1. 25 August 2017, pp. 584-610. See pages 584-610	1-19

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 April 2019 (18.04.2019)	**19 April 2019 (19.04.2019)**

Name and mailing address of the ISA/KR	Authorized officer
International Application Division Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea	LEE, Se Gyoung
Facsimile No. +82-42-481-8578	Telephone No. +82-42-481-8740

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2018/067742

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		KR 10-1780465 B1	10/10/2017
		KR 10-1863075 B1	29/06/2018
		KR 10-2017-0068065 A	19/06/2017
		WO 2017-099478 A1	15/06/2017
US 2016-0151860 A1	02/06/2016	CA 2906426 A1	28/05/2016
		CN 105642890 A	08/06/2016
		EP 3025809 A1	01/06/2016
		EP 3025809 B1	08/11/2017
		JP 2016-102257 A	02/06/2016
		KR 10-2016-0064957 A	08/06/2016
		RU 2015141421 A	04/04/2017
US 2017-0212979 A1	27/07/2017	None	