US 20150064047A1

(19) United States
(12) Patent Application Publication (10) Pub. No.: US 2015/0064047 A1
Hyde et al. (43) Pub. Date: Mar. 5, 2015

(54) SYSTEMS AND METHODS FOR ADDITIVE MANUFACTURING OF THREE DIMENSIONAL STRUCTURES

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(21) Appl. No.: **14/012,889**

(22) Filed: **Aug. 28, 2013**

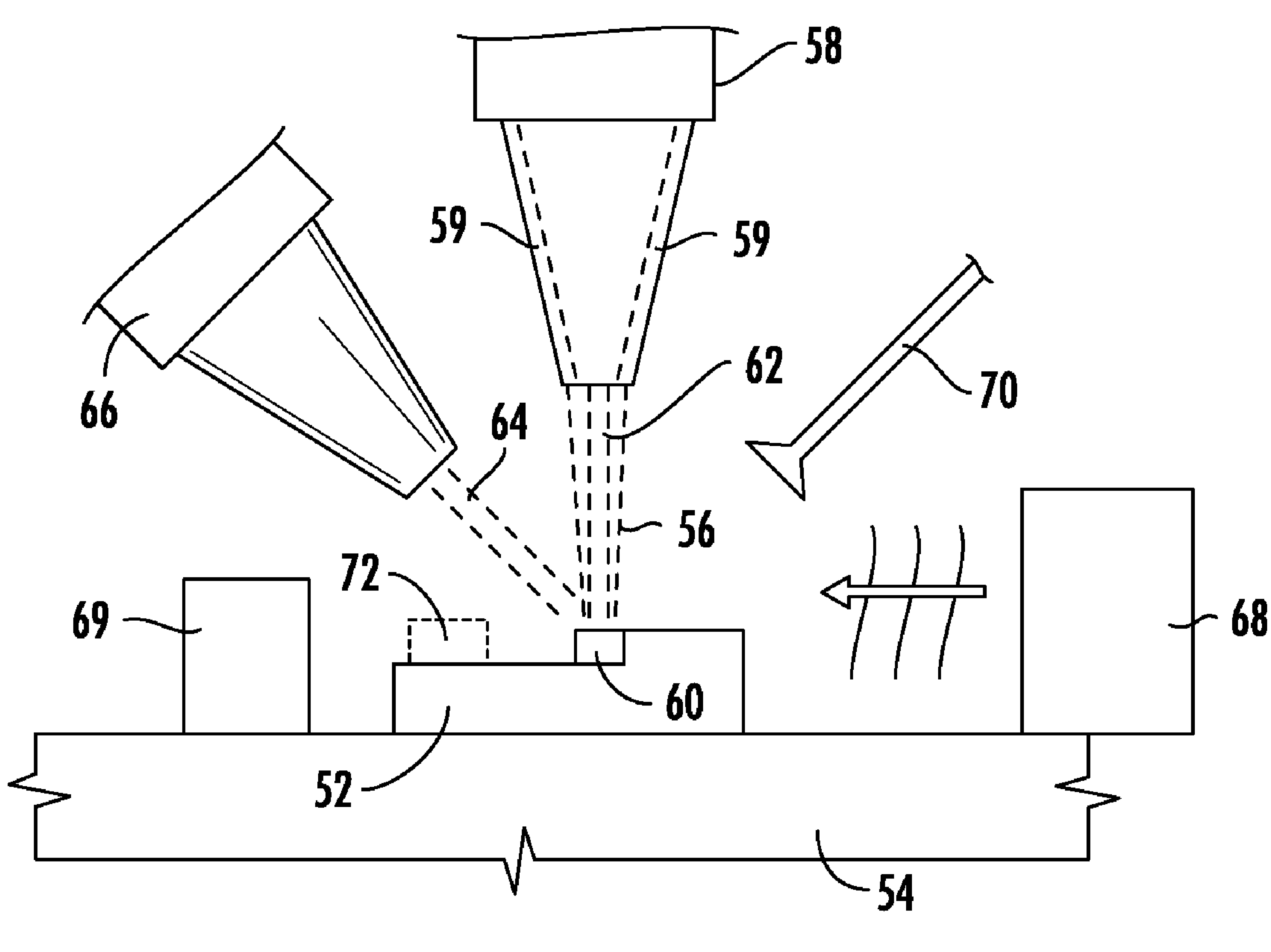
Publication Classification

(51) **Int. Cl.**
B22F 3/105 (2006.01)
B22F 3/115 (2006.01)
B22F 3/24 (2006.01)

(52) **U.S. Cl.**
CPC ***B22F 3/1055*** (2013.01); ***B22F 3/24*** (2013.01); ***B22F 3/115*** (2013.01); *B22F 2003/248* (2013.01); *B22F 2202/11* (2013.01); *B22F 2202/01* (2013.01)
USPC **419/26**; 419/55; 164/113

(57) **ABSTRACT**

A method of fabricating a three dimensional structure includes delivering a metal material to a printing site; and defining a microstructure of the metal material at the printing site by controlling the delivery of heating energy to the printing site and controlling the delivery of ultrasonic vibrations to the printing site.



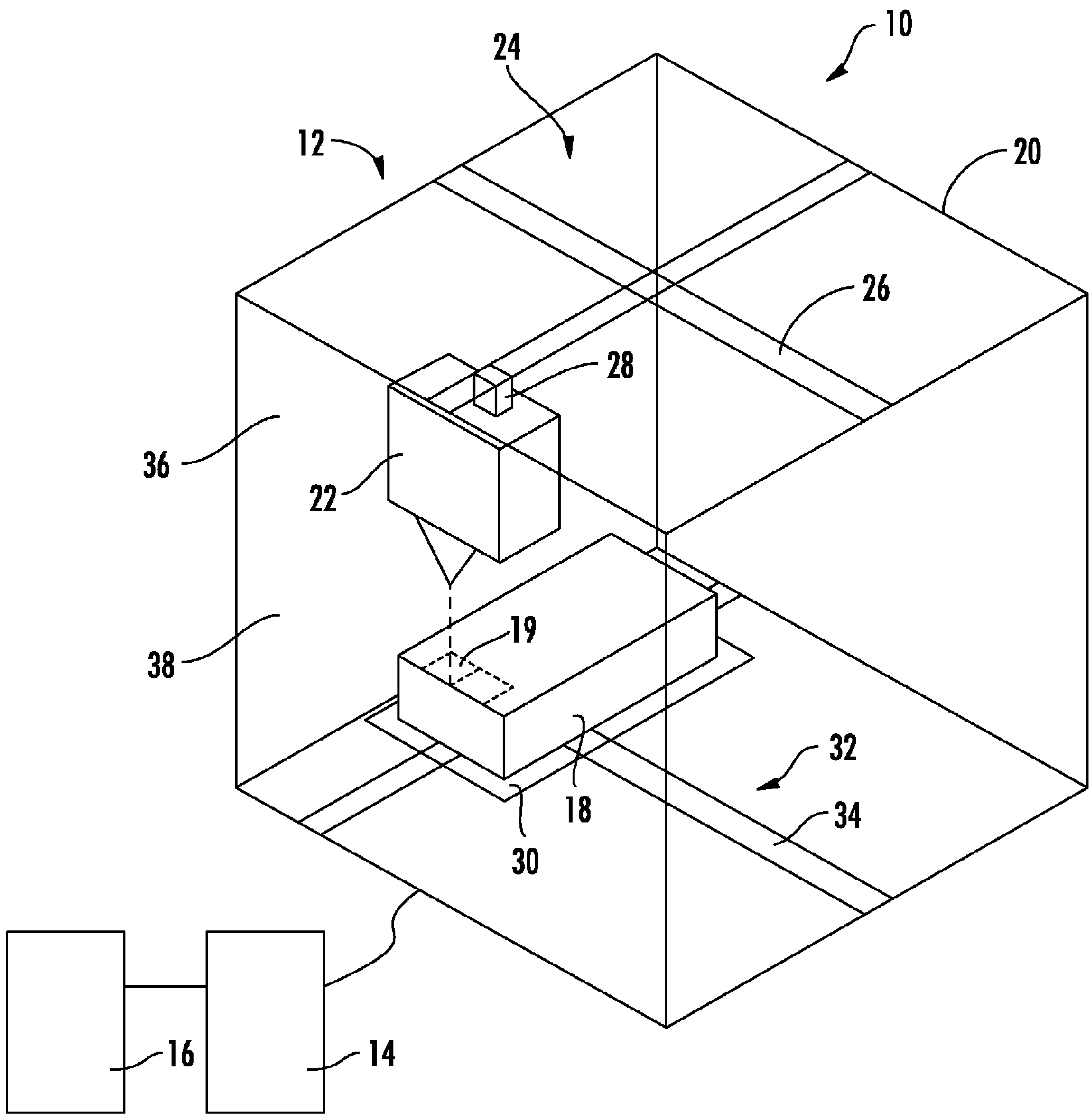
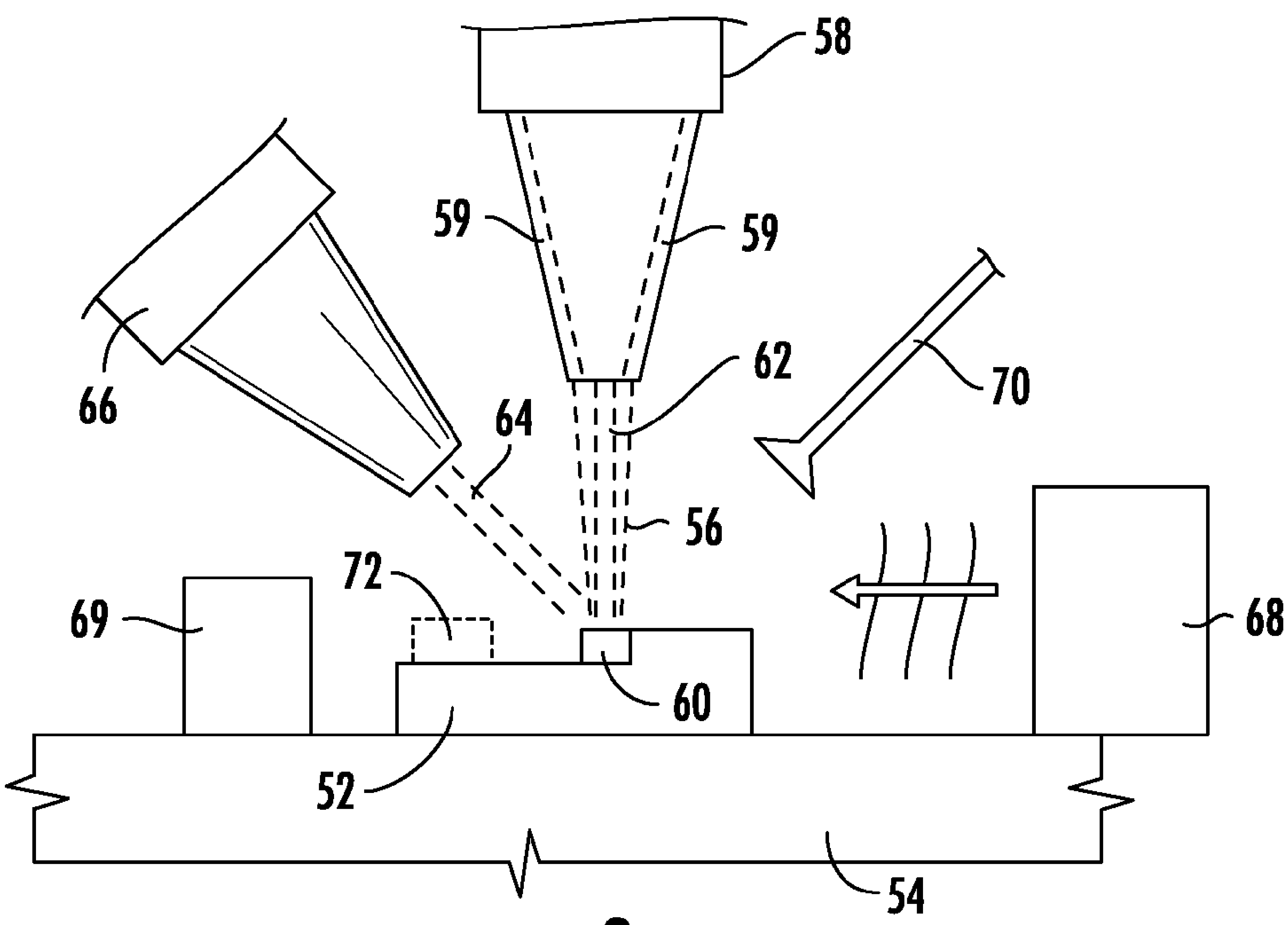


FIG. 1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52
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FIG. 2

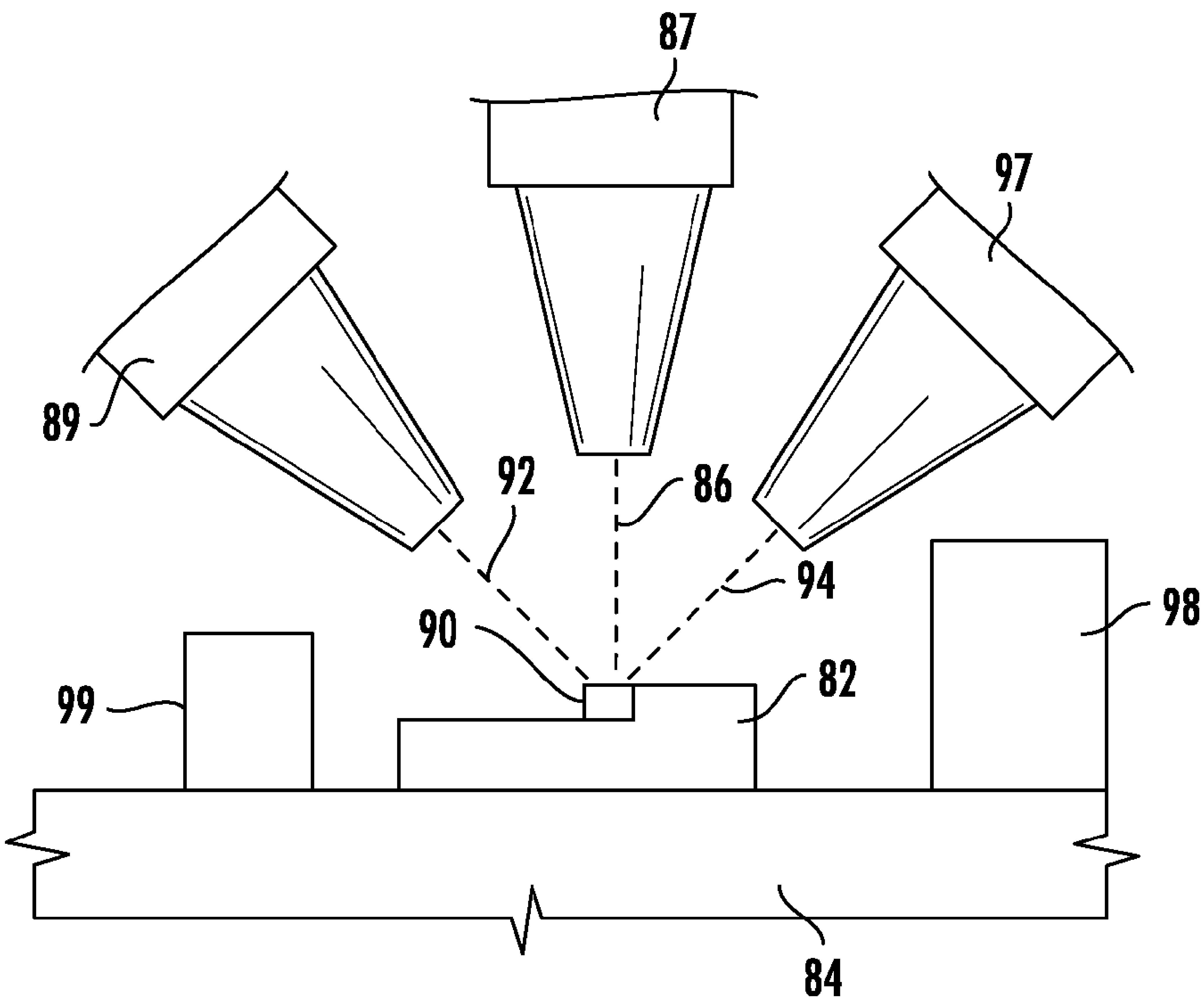
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FIG. 3

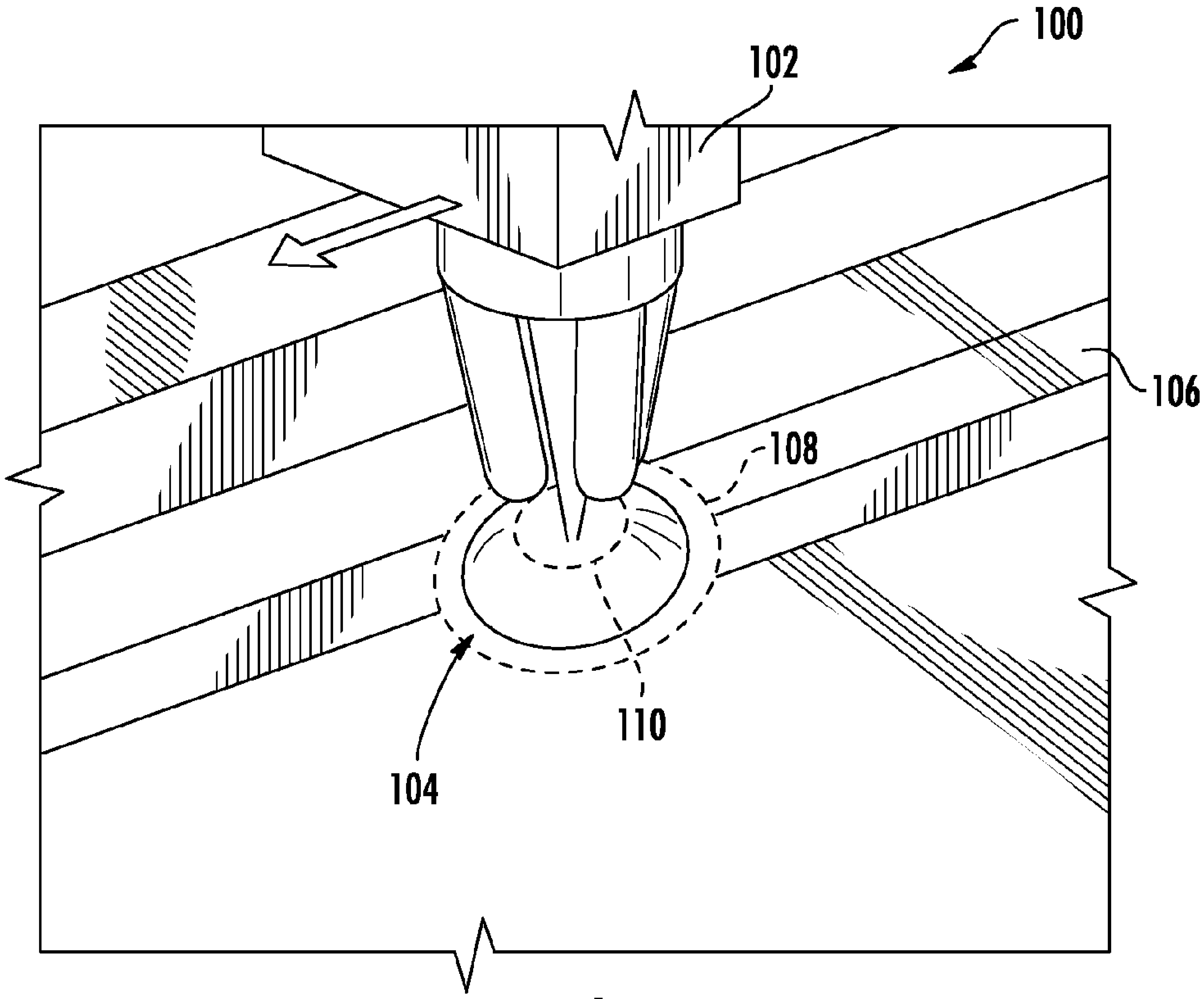


FIG. 4

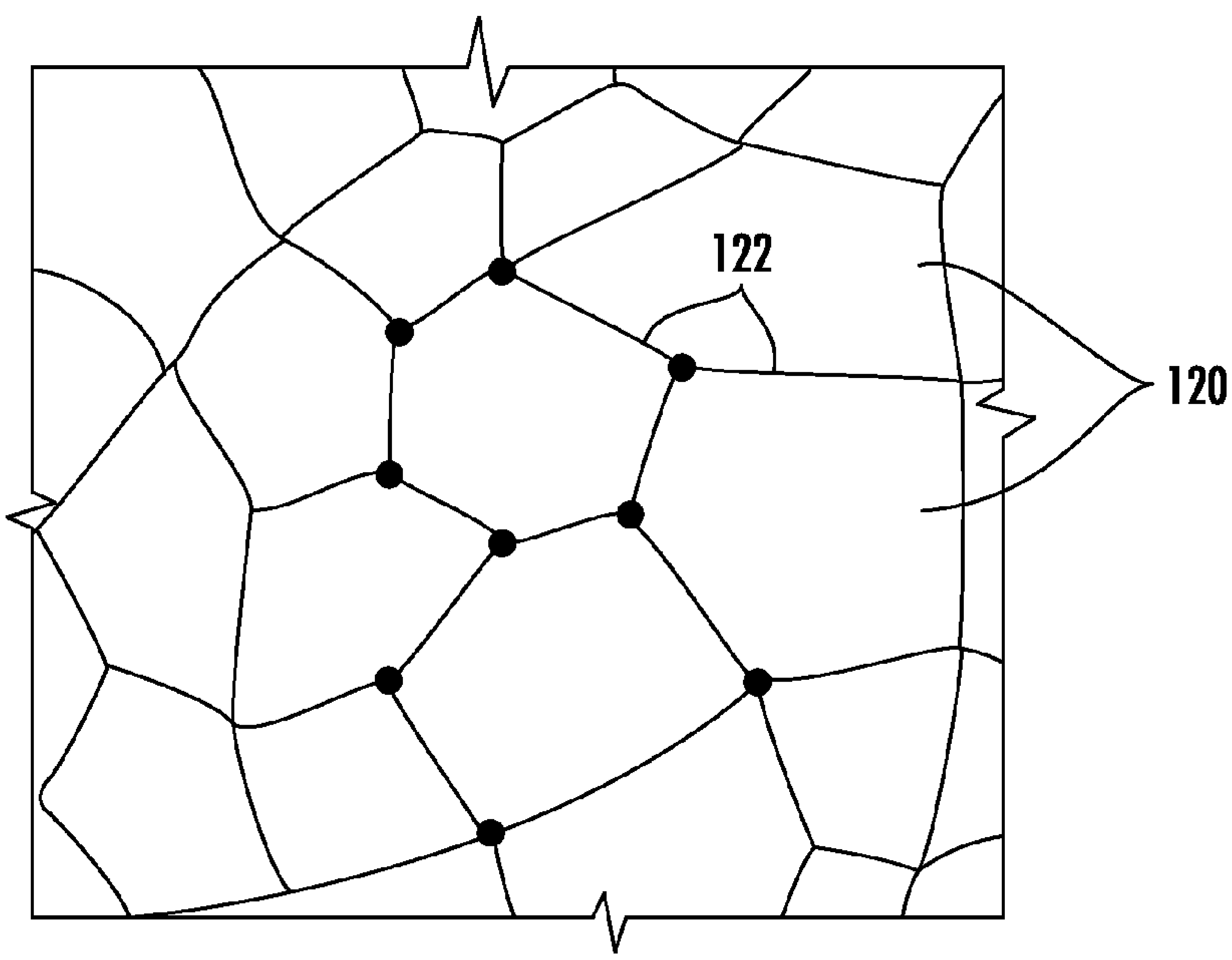
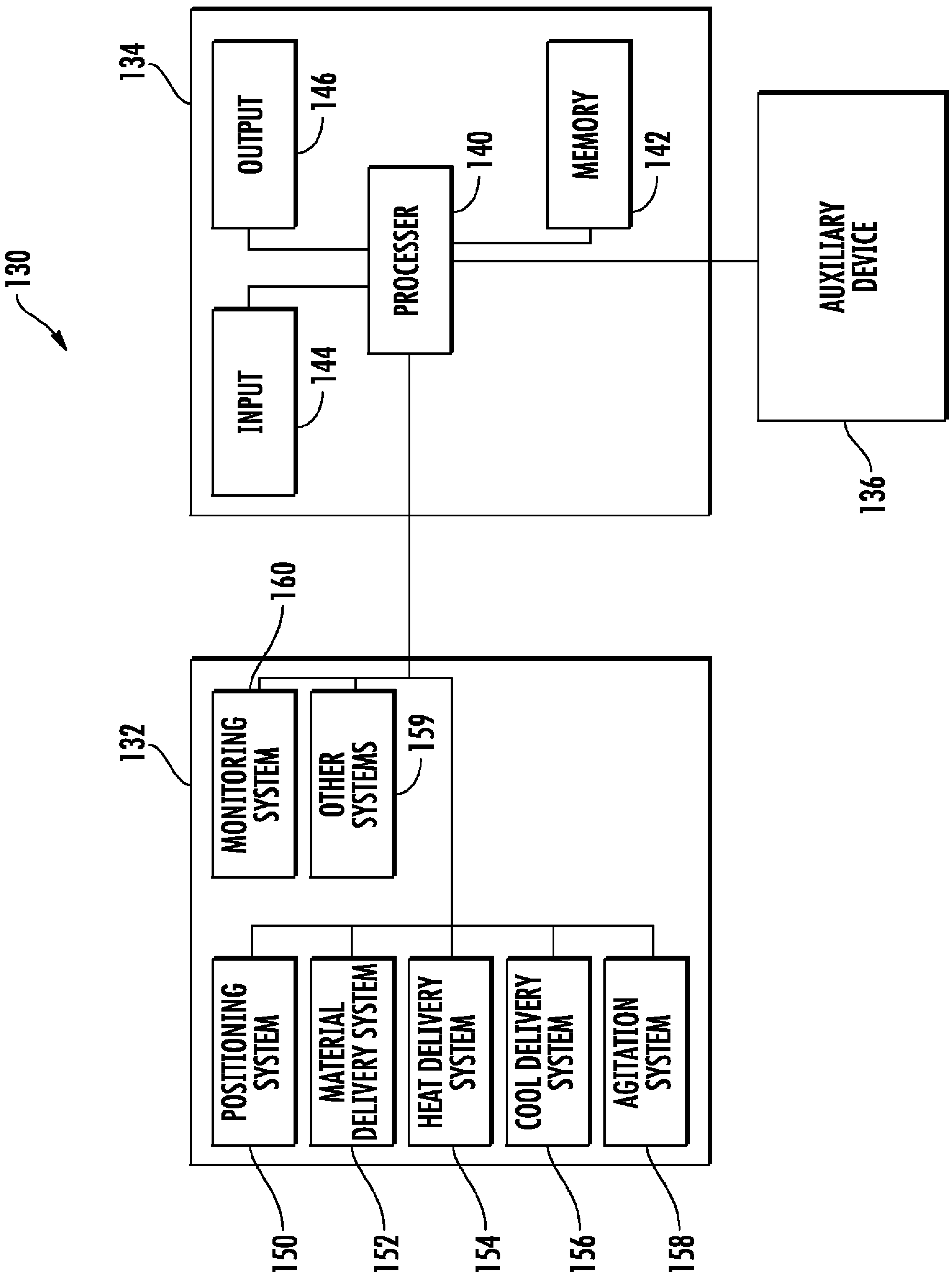


FIG. 5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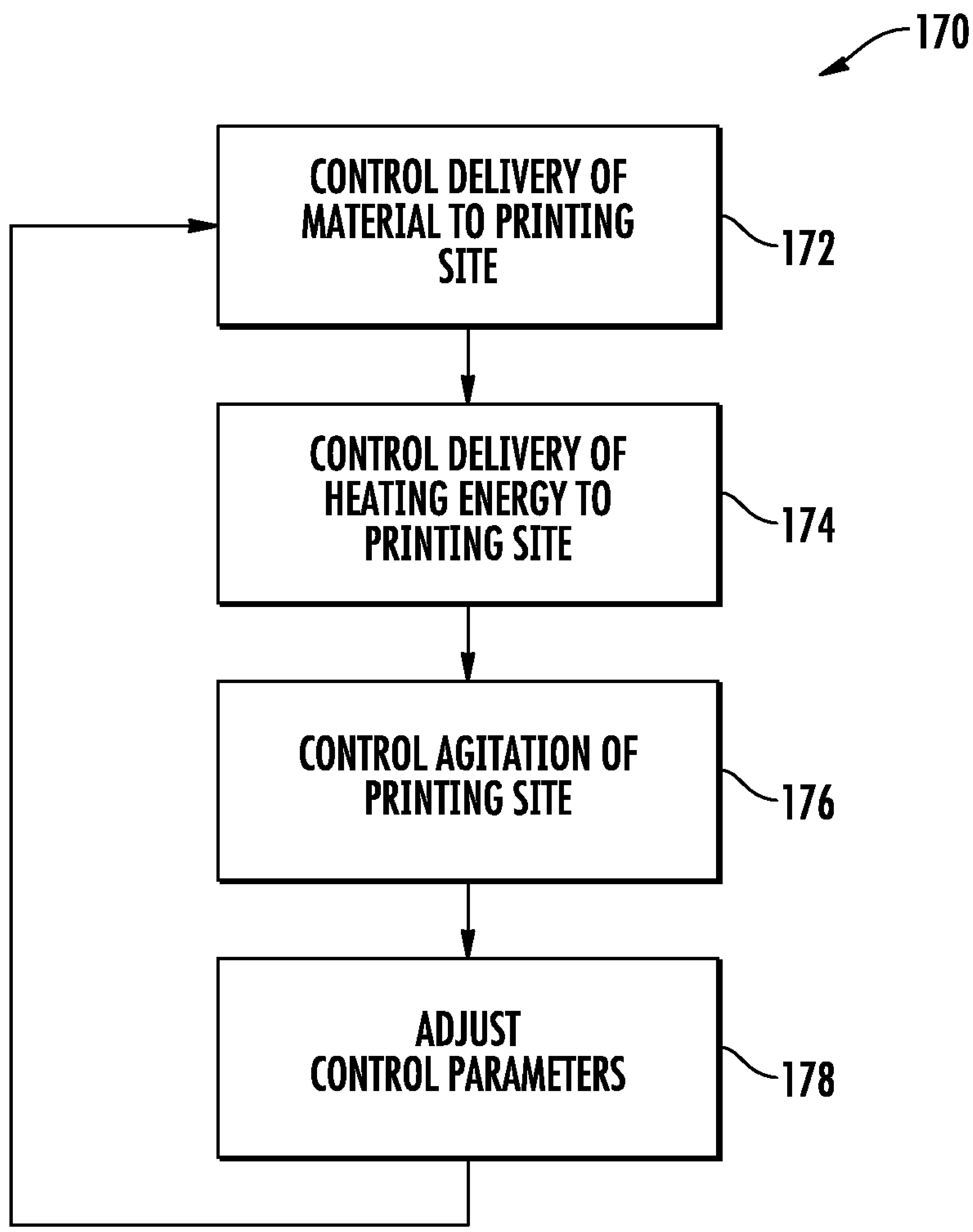
134
OUTPUT
146
MEMORY
142
PROCESSER
140
INPUT
144
AUXILIARY DEVICE
136
132
MONITORING SYSTEM
160
OTHER SYSTEMS
159
POSITIONING SYSTEM
150
MATERIAL DELIVERY SYSTEM
152
HEAT DELIVERY SYSTEM
154
COOL DELIVERY SYSTEM
156
AGITATION SYSTEM
158

FIG. 6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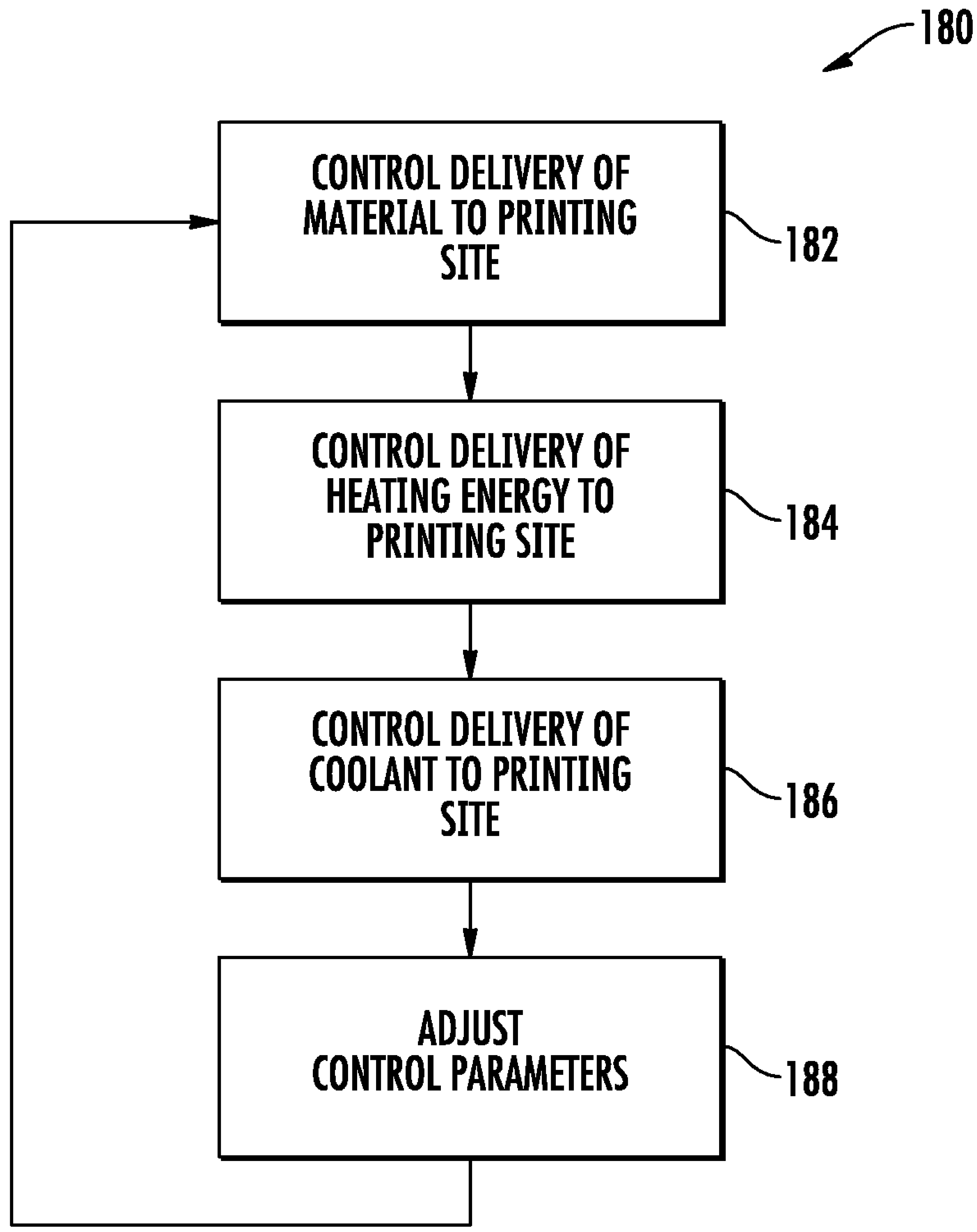
CONTROL DELIVERY OF MATERIAL TO PRINTING SITE
172
CONTROL DELIVERY OF HEATING ENERGY TO PRINTING SITE
174
CONTROL AGITATION OF PRINTING SITE
176
ADJUST CONTROL PARAMETERS
178

FIG. 7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CONTROL DELIVERY OF MATERIAL TO PRINTING SITE
182
CONTROL DELIVERY OF HEATING ENERGY TO PRINTING SITE
184
CONTROL DELIVERY OF COOLANT TO PRINTING SITE
186
ADJUST CONTROL PARAMETERS
188

FIG. 8

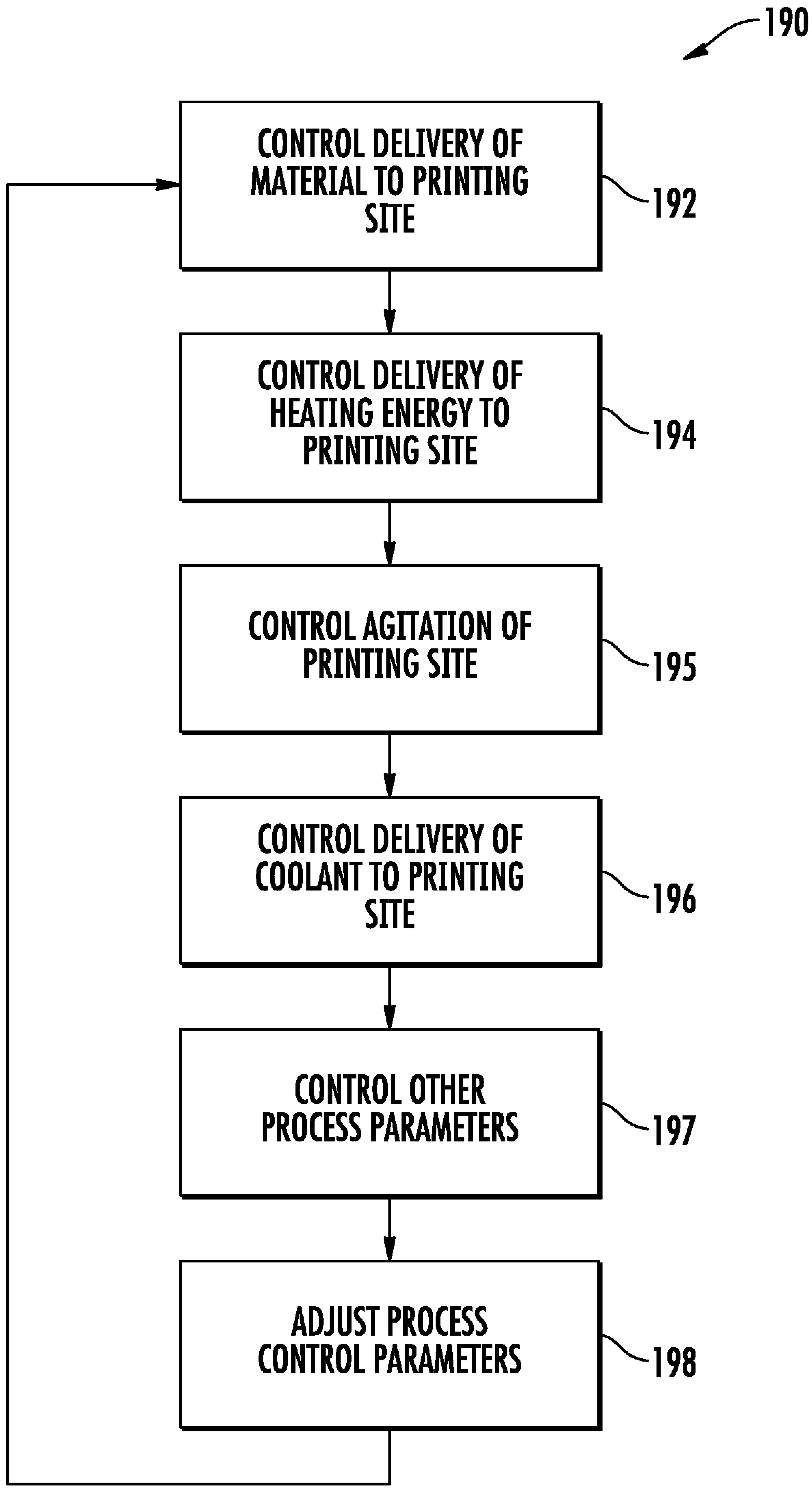
190
CONTROL DELIVERY OF MATERIAL TO PRINTING SITE
192
CONTROL DELIVERY OF HEATING ENERGY TO PRINTING SITE
194
CONTROL AGITATION OF PRINTING SITE
195
CONTROL DELIVERY OF COOLANT TO PRINTING SITE
196
CONTROL OTHER PROCESS PARAMETERS
197
ADJUST PROCESS CONTROL PARAMETERS
198

FIG. 9

SYSTEMS AND METHODS FOR ADDITIVE MANUFACTURING OF THREE DIMENSIONAL STRUCTURES

BACKGROUND

[0001] The present disclosure relates generally to the field of additive manufacturing (also referred to as three dimensional (3D) printing). Additive manufacturing has become more prevalent in recent years as an option not only to rapidly produce prototypes, but also to manufacture final products. While more commonly used to produce polymer objects, current advances have allowed additive manufacturing to also be used to produce metal objects.

SUMMARY

[0002] One embodiment relates to a method of fabricating a three dimensional structure, comprising delivering a metal material to a printing site; and defining a microstructure of the metal material at the printing site by controlling the delivery of heating energy to the printing site; and controlling the delivery of ultrasonic vibrations to the printing site.

[0003] Another embodiment relates to a method of fabricating a three dimensional structure, comprising delivering a metal material to a printing site; delivering heating energy to the printing site; delivering a vaporizable coolant to the printing site; and defining a microstructure for the metal structure based on providing the heating energy to the metal material at the printing site and vaporizing the vaporizable coolant.

[0004] Another embodiment relates to a method of fabricating a three dimensional structure, comprising delivering a first metal material to a first printing site; delivering a first amount of heating energy to the first printing site; delivering a first vaporizable coolant to the first printing site; agitating the first printing site; and forming a first portion of a printed metal structure by providing the first amount of heating energy to the first metal material at the first printing site and vaporizing the first vaporizable coolant while agitating the first printing site.

[0005] Another embodiment relates to a system for fabricating a three dimensional structure, comprising a support for supporting the structure; a material delivery device configured to provide a metal material to a printing site; a heating energy delivery device configured to heat the material at the printing site; and a vibration delivery device configured to provide ultrasonic vibrations to the printing site.

[0006] Another embodiment relates to a system for fabricating a three dimensional structure, comprising a material delivery device configured to deliver a metal material to a printing site; a heating energy delivery device configured to deliver heating energy to the printing site; a coolant delivery device configured to deliver a vaporizable coolant to the printing site; and an ultrasonic vibration delivery device configured to deliver ultrasonic vibrations to the printing site.

[0007] Another embodiment relates to a method of forming a three dimensional structure comprising delivering material, heating energy, and vibrations to a first printing site to define a first grain structure at the first printing site; and delivering material, heating energy, and vibrations to a second printing site to define a second grain structure at a second printing site; wherein at least one of the delivered material, heating energy, and vibrations differs between the first and second printing sites to modify the second grain structure relative to the first grain structure.

[0008] The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features descried above, further aspects, embodiments, and features will become apparent by reference to the drawings and the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a schematic perspective view of a system for fabricating a three dimensional structure according to one embodiment.

[0010] FIG. **2** is a schematic side view of a printing device of the system of FIG. **1** according to one embodiment.

[0011] FIG. **3** is a schematic side view of a printing device of the system of FIG. **1** according to another embodiment.

[0012] FIG. **4** is a schematic side view of a printing device of the system of FIG. **1** according to another embodiment.

[0013] FIG. **5** is a schematic view of a microstructure of a three dimensional structure according to one embodiment.

[0014] FIG. **6** is a block diagram of a control system for a device for fabricating a three dimensional structure according to one embodiment.

[0015] FIG. **7** is a flowchart of a method of fabricating a three dimensional structure according to one embodiment.

[0016] FIG. **8** is a flowchart of a method of fabricating a three dimensional structure according to another embodiment.

[0017] FIG. **9** is a flowchart of a method of fabricating a three dimensional structure according to another embodiment.

DETAILED DESCRIPTION

[0018] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

[0019] Additive manufacturing is a process in which an object is built up layer by layer, with the desired geometry typically being read from a computer file and recreated by extrapolating the geometry into a series of thin layers. The layers may be cut and joined together with a lamination process, formed by selectively curing portions of a substance (e.g., stereolithography, etc.), or formed by transforming a powdered material to a solid mass by melting or otherwise fusing the powdered material together (e.g., selective laser sintering, fused deposition, laser deposition, etc.). Current additive manufacturing processes often do not produce objects with material properties that are suitable for use as a final product. Instead, the objects are often more suitable for display or prototype and proof-of-concept purposes.

[0020] Referring to the figures generally, systems and methods for fabricating a metal object with an additive manufacturing process are shown. In some embodiments, additive manufacturing is used to form an object by depositing material at various printing sites, or areas, in succession to eventually form a completed object. The additive manufacturing process can be configured such that the delivery of heating energy, material, cooling, and other processing is controlled locally at each individual printing site (or, alternatively, at sub-areas within an individual printing site). The microstructure of the fabricated object may therefore be controlled at each printing site and/or varied between printing sites to achieve a desired grain size, phase concentration, impurity concentration, pinning point distribution, or other characteristic. In this way, the fabricated object can be engineered to have superior material properties relative to objects provided with more conventional processes.

[0021] Referring now to FIG. **1**, printing system **10** (e.g., an additive manufacturing system, etc.) configured to fabricate a metal structure is shown according to one embodiment. Printing system **10** includes printing device **12** (e.g., an additive or 3D printing device, etc.) operated by control system **14**. Printing system **10** can form object **18** using digital data, such as a 3D computer-aided design (CAD) model. Control system **14** may receive additional instructions or data from auxiliary system **16**. Auxiliary system **16** may be, for example, an external drive or storage device containing a CAD model and/or other control data. The CAD model may be generated with any suitable CAD program, and may be stored in any suitable digital file format. According to various alternative embodiments, one or both of control system **14** and auxiliary system **16** can be integrated into device **12**.

[0022] According to one embodiment, printing device **12** includes frame **20** and delivery device **22** movable relative to frame **20** via positioning system **24**. Printing device **12** may include a multitude of delivery devices configured to deliver a material (e.g., a powdered metal, a metal wire, a liquid metal, etc.) to form object **18**, as well as heating energy, cooling, agitation, or other means of manipulating the material, as described in more detail below. Printing device **12** forms object **18** by delivering and manipulating the material at successive printing sites **19** (e.g. printing zones or areas, work zones, delivery zones, fabrication zones, etc.). Object **18** is formed in interior **38** of printing device **12**. Interior **38** is defined by sidewalls **36**. According to one embodiment, interior **38** can be a sealed interior, which can have characteristics different from the characteristics of the surrounding environment. For example, the temperature, pressure, or other characteristics (e.g., composition of atmospheric gases, etc.) of interior **38** can be controlled to facilitate improved fabrication of object **18**. According to one embodiment, interior **38** can be maintained at a partial vacuum or in an atmosphere of an inert gas (e.g., argon, helium, etc.).

[0023] According to one embodiment, positioning system **24** is configured to position delivery device **22** using, for example, coordinates provided to printing device **12** from control system **14**. Positioning system **24** can use a Cartesian coordinate system, with delivery device **22** movable via carriage system **26**. Carriage system **26** includes a rail oriented in the X direction and a rail in the Y direction (providing X-Y horizontal movement), and a vertical adjustment member **28** (providing Z direction vertical movement).

[0024] Object **18** is supported by object support platform **30**, which is in turn supported by frame **20**. Platform **30** can be coupled to frame **20** via positioning system **32**. Positioning system **32** can be configured to position support platform **30** using coordinates provided to printing device **12** from control system **14**. According to one embodiment, support platform **30** is movable relative to frame **20** on a horizontal X-Y plane through carriage system **34**. According to a further embodiment, support platform **30** is further movable in a vertical direction using a vertical adjustment member (e.g., a vertical adjustment member similar to vertical adjustment member **28**, etc.). According to another embodiment, support platform **30** may not be movable and may instead be rigidly coupled to frame **20**.

[0025] According to another embodiment, rather than using an X-Y-Z Cartesian coordinate system, positioning systems **24** and **32** may use an alternative coordinate system, such as a cylindrical coordinate system, to position delivery device **22** and/or support platform **30**. According to other embodiments, positioning systems **24** and **32** may be configured to tilt or rotate support platform **30** or delivery device **22** about any of the X, Y, Z, or another positioning axis.

[0026] Positioning systems **24**, **32** are configured to properly position object **18** relative to delivery device **22** during the 3D printing of object **18**. Object **18** is formed through an additive process, with material being selectively added to object **18** by delivery device **22** at printing site **19**. The added material is joined together or fused with material in neighboring printing sites (e.g., material below the printing site **19** on another plane, material surrounding the printing site **19** on the same plane, etc.) to form a solid object.

[0027] Referring now to FIG. **2**, a portion of printing device **50** is shown according to one embodiment as a laser deposition device. Printing device **50** can be incorporated into a 3D printing system such as system **10** or a similar system. Printing device **50** forms object **52** supported by platform **54**. Object **52** is formed from material **56** delivered from first delivery device **58** to printing site **60**. Material **56** is melted by heating energy **62** delivered to printing site **60** from first delivery device **58** (e.g., via a laser, etc.). According to one embodiment, material **56** can be melted by heating energy **62** (e.g., heat or energy provided as radiant energy, etc.) and manipulated during and/or after the application of heating energy **62** with coolant **64** delivered to the printing site **60** from second delivery device **66**, and/or energy such as ultrasonic vibrations generated by a transducer shown as agitation device **68**. The manipulation of material **56** during formation at printing site **60** enables the controlled formation of a desired microstructure of material **56**.

[0028] According to one embodiment, material **56** is or includes a powdered metal material (e.g., tool steel, stainless steel (e.g., 420, 316, 304, etc.), nickel alloys, cobalt alloys, titanium alloys, etc.). The powdered metal is supplied to first delivery device **58** from a supply (e.g., hopper, feeder, bin, etc.). The powdered metal is ejected from first delivery device **58** from one or more nozzles **59**. Multiple nozzles **59** can be angled relative to one another to focus the streams of material **56** at printing site **60** spaced a distance away from first delivery device **58**. The flow rate of material **56** and the speed at which first delivery device **58** is moved relative to object **52** can be controlled to achieve a desired thickness for each printing site and/or layer of material forming object **52**.

[0029] While in some embodiments, material **56** is delivered to printing site **60** as a metal powder, according to other embodiments, material **56** may be a metal delivered in another form. For example, material **56** may be a solid metal delivered as a wire fed from first delivery device **58** to printing site **60**, or alternatively, may be a liquid metal delivered as a liquid metal stream or jet from first delivery device **58** to printing site **60**. Material **56** can be delivered in various other forms according to various alternative embodiments.

[0030] According to further embodiments, material **56** may be provided by material streams from several different supplies. For example, a primary material may be mixed with additives, such as particles configured to act as catalysts for nucleation, or grain refiners configured to retard the growth of dendritic grains. In other embodiments, material **56** may be provided by different elemental streams, with the flow rate of the different streams varied during the fabrication of object **52** to achieve different alloy compositions in different portions of object **52**.

[0031] According to one embodiment, first delivery device **58** is configured to provide a first material at a first printing site and a second material at a second printing site. For example, the amount of material, the rate of deposition of material, the composition of the material, or other parameters may be varied between the first material delivered to the first printing site and the second material delivered to the second printing site. Varying various parameters associated with the delivery of material to different printing sites enables variation of the microstructure (e.g., grain structure, etc.) between printing sites.

[0032] Referring further to FIG. **2**, in one embodiment, heating energy **62** is provided by a laser directed at printing site **60** by first delivery device **58**. The laser may be any suitable laser capable of providing the heating energy needed to melt material **56**. For example, the laser may be a fiber laser with an optical fiber doped with a rare-earth element (e.g., erbium, ytterbium, neodymium, etc.), another type of solid-state laser, or a gas laser. In some embodiments, first delivery device **58** may further provide a volume (e.g., envelope, sleeve, etc.) of a shielding gas surrounding the laser and/or material **56** that differs from the atmosphere in the interior of the printing device to provide a more favorable environment for the fabrication of object **52** (e.g., to limit oxidation, etc.).

[0033] The laser provided by first delivery device **58** is configured to generate a "melt pool" of molten material, and provide precise control of the size and depth of the melt pool. As such, a relatively narrow heat-affected zone surrounds the melt pool, thereby minimizing thermal distortion of the portions of object **52** surrounding printing site **60**. Printing site **60** can be heated by any method or combination of methods, including through the use of a laser. According to other embodiments, heating energy **62** can be provided via first delivery device **58** in another form, such as an electron beam or a micro-arc. According to still another embodiment, heating energy **62** can be delivered to printing site **60** through conduction by local resistance heating of object **52**, by thermal conduction from a (small) heat source contacting printing site **60**, or by controlling the temperature of material **56** delivered to printing site **60**.

[0034] In one embodiment, first delivery device **58** focuses heating energy **62** at printing site **60** (e.g., with a lens, etc.), and material **56** melts to form a melt pool. First delivery device **58** forms a bead of material (e.g., a weld bead, etc.) as it is moved relative to platform **54**. The bead includes material deposited at successive printing sites, and forms a layer of solidified material on the X-Y plane. The bead may be a continuous bead of material, or alternatively, a non-continuous bead of material. Successive layers of material are fused together to form object **52**. By controlling the delivery of heating energy **62** to printing site **60**, the melting of material **56** can be controlled. Although controlling only the delivery of heating energy **62** provides some control over the post-melting solidification of material **56** and of the resulting microstructure of object **52**, more precise control is possible, as in conventional metal formation, by also controlling the quenching (i.e., the cooling) of the molten metal.

[0035] According to one embodiment, first delivery device **58** is configured to vary the heating energy provided to first and second printing sites. For example, the amount of heating energy, the intensity of heating energy, the delivery method, or other parameters may be varied between the first and second printing sites. Varying various parameters associated with the delivery of heating energy to different printing sites enables variation of the microstructure (e.g., grain structure, etc.) between printing sites.

[0036] In one embodiment, the microstructure of object **52** is further controlled through cooling of the melt pool (e.g., material **56**) at printing site **60**. For example, a coolant **64** can be locally delivered by second delivery device **66**. Second delivery device **66** can be any mechanism suitable for the delivery of coolant **64** to printing site **60**. Coolant **64** can be delivered directly to printing site **60**, or alternatively, can be delivered indirectly to printing site **60** by, for example, cooling areas of object **52** surrounding printing site **60** (i.e., neighboring printing sites) or by cooling platform **54** supporting object **52**. By locally cooling printing site **60**, the microstructure of different portions of object **52** can be individually controlled and/or varied.

[0037] The material at printing site **60** is locally cooled in a controlled manner, either through the direct or indirect cooling of the material. Local, controlled cooling allows the quenching of the material to be controlled to a greater degree than, for example, bulk cooling object **52**, or allowing object **52** to cool slowly to room temperature. Controlling the quenching of the material enables for the controlled formation of a desired microstructure (e.g., the transformation of austenite to martensite in steel, etc.) in object **52**. In some embodiments, the delivery of coolant **64** can be delayed to allow the material to remain at an elevated temperature for a period of time.

[0038] Printing site **60** can be locally cooled by thermal conduction to a small cooling probe such as a thermoelectric cooler, a heat pipe, a mini-cooling loop, or the like. In other embodiments, printing site **60** can be cooled by applying coolant **64** which absorbs energy from printing site **60**. Coolant **64** can respond to the absorbed heat by increasing its temperature (i.e., via its specific heat) and/or by undergoing a phase change (i.e., via latent heat). A vaporizable liquid coolant provides an effective embodiment of coolant **64**, because vaporization of the liquid provides an efficient way to absorb heat and because the coolant is directly removed from the site as it vaporizes, without leaving residuals. Coolant **64** can be a liquid with a relatively low boiling point, or alternatively, a liquid with a relatively high boiling point, with coolant **64** chosen such that the boiling point of coolant **64** corresponds to a desired quench temperature and/or cooling rate for the material at printing site **60**. Coolant **64** can be or include water, alcohol, an oil, a solvent, or a liquid metal, including, but not limited to, sodium, sodium-potassium alloy, sodium-lithium alloy, lithium, or a mixture of liquid metals. In some embodiments, the boiling point of coolant **64** can be varied by controlling the pressure of the interior of printing device **50**, by modifying the composition of coolant **64**, etc.

[0039] According to one embodiment, delivery device **66** is configured to deliver a high-speed stream of coolant **64** in the form of a vaporizable liquid to printing site **60**. According to another embodiment, delivery device **66** is an atomizer configured to deliver liquid coolant **64** as a mist. According to yet another embodiment, delivery device **66** is or includes a device such as a wick, brush, or tube that directs a low-speed stream of a liquid coolant to printing site **60**. According to a further embodiment, delivery device **66** can be a fan configured to direct a stream of coolant **64** in the form of a gas (e.g., air, an inert gas, etc.) at printing site **60** to cool material by convection. According to various alternative embodiments, combinations of one or more coolant delivery devices can be used to deliver coolant **64**.

[0040] In one embodiment, coolant **64** is not delivered directly to material to printing site **60**, but rather is provided as a part of a heat pipe or similar system incorporated into or separate from delivery device **66**. A heat pipe can include a casing with a first end proximate the melt pool at printing site **60** (e.g., on the surface of the object **52**). The first end of the heat pipe absorbs heat through the walls of the casing and vaporizes a liquefied coolant contained within the casing. The vaporized coolant releases latent heat at a second end and condenses back to a liquid. One or both ends of the heat pipe can include features such as a heat sink to facilitate the transfer of heat between the outside environment and the coolant contained within the heat pipe. The coolant contained within the heat pipe can be chosen to achieve a preferred heat transfer from printing site **60**. The internal pressure of the heat pipe can also be chosen and/or varied to control the phase changes of the coolant and further control the heat transfer from the printing site.

[0041] According to one embodiment, coolant **64** can be delivered continuously to printing site **60**. Alternatively, coolant **64** can be delivered intermittently (e.g., in a digital manner, etc.) to printing site **60** to achieve a desired microstructure. Various coolants, delivery devices, and delivery durations may be utilized for object **52** to form a metallic structure with varied microstructures. In some embodiments, delivery device **66** can be operated based on feedback data collected from sensors monitoring the fabrication of object **52**, as described in more detail below.

[0042] Printing device **50** may further include a system for removing coolant (e.g., vaporized or heated liquid coolant) from the surface of object **52** or the interior of printing device **50**, after the coolant has been utilized to cool printing site **60**. For example, printing device **50** may include a gas circulation system (e.g., incorporated into delivery device **66** or another component of the printing system) configured to remove gas from the interior of printing device **50** through an outlet duct and introduce gas to the interior of the printing device through an inlet duct. After being removed from the interior of printing device **50**, the gas may be scrubbed, cooled or otherwise processed and returned back to the interior of printing device **50**. Printing device **50** may include multiple inlet and outlet ducts such that the ducts can be opened, closed, or reversed to advantageously control the movement of gas within the interior of printing device **50** and across the surface of object **52**, including proximate printing site **60**.

[0043] According to one embodiment, delivery device **66** is configured to provide a first coolant to a first printing site and a second coolant to a second printing site. For example, the type of coolant, the amount of coolant, the timing or rate of delivery of coolant, the predefined delivery temperature of the coolant, the composition of the coolant, or other parameters may be varied between the first and second printing sites. In some embodiments, the delivery of heating energy (e.g., from delivery device **58**) may be interrupted during the delivery of the coolant. In some embodiments, the delivery of coolant can be nonsimultaneous with the delivery of heating energy at a site. In some embodiments, the delivery of coolant can begin after the delivery of heat energy begins at a site. In some embodiments the delivery of coolant can continue after the delivery of heat energy has stopped at a site. Varying various parameters associated with the delivery of coolant to different printing sites enables variation of the microstructure (e.g., grain structure, etc.) between printing sites.

[0044] In some embodiments, the microstructure of object **52** is further controlled by subjecting the material at printing site **60** to agitation, such as by sound waves (e.g., acoustic waves, ultrasonic waves, etc.). According to one embodiment, the waves are generated by agitation device **68** (e.g., agitator, wave generator, etc.) and directed at object **52**. Agitation device **68** is positioned and configured to direct the waves to printing site **60** to induce local vibration in object **52**. According to various alternative embodiments, agitation device **68** can be a piezoelectric transducer, a magnetostrictive transducer, a surface acoustic wave (SAW) generator, a bulk acoustic wave (BAW) generator, or a standing wave field generator (e.g., an ultrasonic wave field generator, etc.). According to one embodiment, as shown in FIG. **2**, agitation device **68** can be positioned remote from printing site **60** and can be configured such that the waves are steered to or focused at printing site **60**. Wave generation and steering and/or focusing can utilize a coherent array of wave generators (e.g., with phase and/or amplitude control of each); phase conjugation can be used to help control such remote wave delivery. According to another embodiment, agitation device **68** can be positioned proximate to printing site **60**.

[0045] In one embodiment, agitation device **68** provides ultrasonic vibrations to printing site **60**. Ultrasonic vibrations applied to a solidifying metal or alloy can decrease the size of the grains, increase the soundness of the grains, and/or decrease the occurrence of dendritic grain formation in the material. When molten material in the melt pool at printing site **60** is near the melting point (for a pure metal) or liquidus temperature (for an alloy), ultrasonic waves can influence the formation of solid nuclei, which leads to the corresponding formation of grains in the solidifying material, the grains being increased in number and decreased in size.

[0046] The amplitude and frequency of the waves produced by agitation device **68** can be controlled to produce grains of a desired size. According to one embodiment, agitation device **68** is configured to produce waves with a frequency selected based on a desired microstructure (e.g., grain size, etc.). The frequency produced by agitation device **68** can be maintained at a constant level for the entire fabrication process, or alternatively, can be altered to facilitate the growth of grains of different desired sizes in different portions of object **52**. The wavelength of the waves produced by agitation device **68** can also be configured to produce grains of a desired size. In some embodiments, the delivery of waves can be nonsimultaneous with the delivery of heating energy at a site. In some embodiments, the delivery of waves can begin after the delivery of heat energy begins at a site. In some embodiments, the delivery of waves can continue after the delivery of heat energy has stopped at a site, e.g., to perform ultrasonic peening. In some embodiments, agitation device **68** may be operated based on feedback data collected from sensors monitoring the fabrication of object **52**, as described in more detail below.

[0047] According to one embodiment, agitation device **68** is configured to provide differing waves to induce different vibrations at first and second printing sites. For example, the amplitude, wavelength, or other parameters associated with the delivery of the waves may be varied between the first and second printing sites. Varying various parameters associated with providing vibrations to different printing sites enables variation of the microstructure (e.g., grain structure, etc.) between printing sites.

[0048] According to one embodiment, the microstructure of object **52** can be further controlled by subjecting the material in the melt pool at printing site **60** to other processing or conditions. For example, magnet **69** can be provided proximate to printing site **60**. Magnet **69** produces a magnetic field that passes through printing site **60**. For magnetic materials (e.g., many steel alloys) the magnetic field influences the grain formation as the material in the melt pool solidifies and cools. Magnet **69** can be a permanent magnet generating a constant magnetic field, or may be a variable magnet (e.g., an electromagnet) that can be controlled to produce a variable magnetic field.

[0049] Referring further to FIG. **2**, in some embodiments, printing site **60** is monitored to provide feedback data to printing device **12**. The data may then be utilized by printing device **12** to control the printing process to achieve the desired microstructure in object **52**. According to one embodiment, printing device **50** may include image monitoring device **70**, and one or more sensors **72** to collect data from printing site **60**.

[0050] In one embodiment, image monitoring device **70** (e.g., an image capturing device, etc.) is configured to monitor the microstructure of object **52**. Image monitoring device **70** can be an optical microscope, an electron microscope, an x-ray microscope, etc. Optical microscopes can be used to examine relatively large microstructures, while electron microscopes and x-ray microscopes can be used to examine relatively small images (e.g., features or structures smaller than approximately one half micron). Image monitoring device **70** may include multiple devices, allowing the microstructure of object **52** to be examined at different scales simultaneously. Image monitoring device **70** captures an image (e.g., a still image or a video) of object **52**. The image may be transferred to an analysis device and be utilized to collect data concerning the microstructure at printing site **60**, such as an average grain size, or the formation of various phases of the material. According to one embodiment, image monitoring device **70** captures images of object **52** after the material at printing site **60** has solidified. Image monitoring device **70** may therefore be configured to capture images of an area trailing the current printing site **60**. Image monitoring device **70** may be configured to collect further visual data, such as by capturing an image of a portion of object **52** surrounding the current printing site **60**. The additional image data may be utilized, for example, to monitor the heat-induced distortions in the microstructure of object **52** surrounding printing site **60**, as caused by the heating energy provided to create the melt pool at printing site **60**.

[0051] Sensors **72** may be configured to collect a wide variety of data concerning the portions of object **52** at printing site **60**. According to one embodiment, sensor **72** can be or include a thermometer configured to monitor the temperature of printing site **60** or the portion of object **52** surrounding printing site **60**. For example, sensor **72** may be a contact thermometer, such as a thermocouple in direct contact with object **52**, or may be a non-contact thermometer, such as an infrared thermometer that is disposed away from object **52**. Sensor **72** may be an array of multiple thermometers configured to monitor the temperature at several locations at and/or surrounding printing site **60**. According to another embodiment, sensor **72** can be or include a vibration transducer configured to monitor the longitudinal or shear waves produced by agitation device **68**. According to other embodiments, sensor **72** may include multiple types of sensors that operate together to monitor multiple phenomena related to the solidification of the material forming object **52**.

[0052] Referring now to FIG. **3**, a portion of printing device **80** is shown according to one embodiment as a laser deposition device. Printing device **80** forms object **82** supported by a platform **84** in a manner similar to the printing device **50** shown and discussed with respect to FIG. **2**. Object **82** is formed from a material **86** delivered from a first delivery device **87** to printing site **90**. Material **86** is melted by heating energy **92** delivered to printing site **90** from a second delivery device **89**. According to one embodiment, material **86** is manipulated during and/or after the application of heating energy **92** with substances such as coolant **94** delivered to printing site **90** from third delivery device **97**, energy such as vibrations generated by agitation device **98**, or by a magnetic field generated by magnet **99**. The delivery of material **86** and heating energy **92** via separate delivery devices **87** and **89** may advantageously provide for the improved melting of material **86** and/or creation of a melt pool at printing site **90**.

[0053] According to one embodiment, the additive manufacturing system is configured to provide, or define, different microstructure at or within different portions of an object. For example, as discussed in greater detail below, one or more image capture devices, sensors, etc. may be configured to provide feedback regarding the formation of an object, and in response, one or more parameters associated with the delivery of material, heating energy, vibrations, coolant, etc. can be varied between printing sites.

[0054] After being formed with a printing process, the fabricated object may be subjected to further processing, such as heat treating (e.g., annealing, tempering, etc.) and the like. Such post-printing processing enables further altering of the microstructure and the mechanical properties of the material beyond what may be possible during the 3D printing process.

[0055] Referring now to FIG. **4**, a schematic top view of a portion of printed metal object **100** is shown according to one embodiment. Material from delivery device **102** is melted and solidified at printing site **104**. In one embodiment, as delivery device **102** is moved relative to object **100**, bead **106** of solidified material is formed on the surface of object **100** (the surface of the object being material printed at previous print sites and/or in previous layers). By controlling the delivery of material and heating energy to printing site **104**, as well as the delivery of ultrasonic or acoustic waves and the rate of cooling through the delivery of a coolant, the mechanical properties of object **100** can be controlled. The heat affected zone **108** can be minimized by providing heating energy to printing site **104** in the form of a laser or an electron beam. Locally controlling the heating energy, material, agitation, cooling, and other factors, as opposed to subjecting the entirety of object **100** to "bulk" conditions (e.g., with a bulk cooling process, etc.), allows the mechanical properties of object **100** to be varied between different areas/printing sites of object **100**. Mechanical properties may be further controlled within different portions of printing site **104** (e.g., local cooling or quenching of material may generate a microstructure in center **110** of printing site **104** that is different than the microstructure at the periphery of printing site **104**).

[0056] Referring now to FIG. **5**, an example microstructure of an object formed by the printing devices disclosed herein is shown. A desired microstructure is created by locally controlling the heating energy, material, agitation, cooling, and other factors as the material is printed, thereby allowing the fabricated object to have desired mechanical properties (e.g., strength, toughness, ductility, hardness, etc.). According to one embodiment, the microstructure is configured to have a relatively small grain structure including a multitude of small grains **120** (e.g., crystallites) separated by grain boundaries **122**. Grain boundaries **122** represent disconnects between crystal lattices of neighboring grains **120**, and impede the movement of dislocations through the material. A fine grain structure increases the number of grain boundaries **122**, and increases the yield strength of the material. A large grain structure, conversely, lowers the yield strength of the material, but increases ductility and electrical and thermal conductivity. Local control of heating energy, material, agitation, cooling, and other factors allows the grain structure to be written, or printed, as desired, allowing different portions of the manufactured object to have different mechanical properties. The local control of the printing process may also be used to vary the mechanical properties of the material in other ways, such as by varying the presence and/or concentrations of different phases of the material, the presence and/or concentration of dislocations, pinning points, impurities, etc.

[0057] Referring now to FIG. **6**, a schematic block diagram of printing system **130** is shown according to one embodiment. Printing system **130** includes 3D printing device **132** operated by control system **134**. Printing device **132** forms an object using digital data, such as a 3D computer-aided design (CAD) model. Printing device **132** can be the same or similar to any of the other printing devices discussed herein. Furthermore, printing system **130** may include one or more auxiliary systems **136** (e.g., computer systems, etc.).

[0058] According to one embodiment, control system **134** includes processor **140** and memory **142**. Processor **140** may be implemented on a chip, integrated circuit, circuit board, etc., as a general purpose processor, an application specific integrated circuit (ASIC), one or more field programmable gate arrays (FPGAs), a group of processing components, or other suitable electronic processing components. Memory **142** can be or include one or more devices (e.g., RAM, ROM, Flash memory, hard disk storage, etc.) for storing data and/or computer code for completing and/or facilitating the various processes described herein. Memory **142** can be or include non-transient volatile memory or non-volatile memory or non-transitory computer readable storage media. Memory **142** can include database components, object code components, script components, or any other type of information structure for supporting the various activities and information structures described herein. Memory **142** can be communicably connected to the processor and include computer code or instructions executable by the processor for executing one or more processes described herein. Control system **134** can include one or more modules configured to use data and code stored in memory **142** to execute a process via processor **140**.

[0059] Control system **134** further includes input device **144** and output device **146**. Input device **144** can be a mouse, keyboard, trackball, touchscreen or any other device that allows a user to input instructions to control system **134**. Input device **144** can be used, for example, in combination with a graphical user interface to allow a user to control various parameters associated with the operation and monitoring of printing device **132** or auxiliary systems **136**. Output device **146** can be a visual output device, such as a monitor (e.g., a CRT monitor, LCD monitor, LED monitor, etc.), an audio device, or another device.

[0060] Control system **134** can receive additional instructions or data from auxiliary system **136**. Auxiliary system **136** can be, for example, an external drive or storage device containing the CAD model and other control data. The CAD model can be generated with any suitable CAD program and can be stored in any suitable digital file format. The geometry of the CAD model is analyzed and divided into a multitude of slices, layers, or portions that correspond to portions to be printed by printing device **132**.

[0061] As shown in FIG. **6**, printing device **132** includes positioning system **150**, material delivery system **152**, heating energy delivery system **154**, coolant delivery system **156**, and agitation system **158**. Positioning system **150** controls the positions of the delivery devices relative to the platform on which the object is fabricated, and can be or include any of the positioning systems discussed herein. Positioning system **150** controls the delivery devices to form a bead of material in a desired path on the X-Y plane. In some embodiments, multiple passes of the delivery device in the X-Y (horizontal) plane forms a slice or layer of the object as defined by the CAD model. Movement of the delivery devices in the Z (vertical) direction positions the delivery devices to form successive layers. According to one embodiment, positioning system **150** may further control the position of the platform on which the object is formed, either in addition to or instead of controlling the position of the delivery devices. Positioning system **150** may further control the orientation of the delivery devices and/or the platform through rotation about one or more axis (e.g., the X-axis, Y-axis, Z-axis, etc.).

[0062] Material delivery system **152** controls the delivery of material from a supply to the printing site via a material delivery device, and can include any of the material delivery devices discussed herein. Material delivery system **152** can, for example, control the flow rate of a powdered or a liquid metal or the feed rate for a solid wire to the printing site. Material delivery system **152** can control the delivery ratio of two or more materials to a printing site to alter the composition of the material of different portions of the fabricated object. As such, different materials can be delivered to different printing sites of an object.

[0063] Heating energy delivery system **154** controls the delivery of heating energy to the printing site via a heating energy delivery device, and can include any of the heating energy delivery devices discussed herein. Heating energy delivery system **154** can control the operation of a laser, including focusing the laser at the printing site and controlling the power output of the laser. The heating energy delivery system **154** can operate the laser to provide continuous heating energy to the printing site, or can activate and deactivate the laser to provide intermittent heating energy to the printing site. According to other embodiments, heating energy delivery system **154** can be configured to control an electron beam or another heating energy delivery device, such as resistance heater configured to supply an electrical voltage applied to the object to heat the printing site by resistance heating.

[0064] Coolant delivery system **156** controls the delivery of coolant (e.g., a liquid or gas coolant) to the printing site via a coolant delivery device to reduce the temperature of the material at a desired rate, and can include any of the coolant delivery devices discussed herein. For example, coolant delivery system **156** can control the flow rate of a high pressure stream of a liquid coolant directed at the printing site or at a portion of the fabricated object proximate to the printing site. Coolant delivery system **156** can vary the type of coolant delivered or the rate/amount of coolant delivered depending on the material used and the desired cooling time. In some embodiments, the delivery of coolant can be delayed to allow the material to remain at an elevated temperature for a period of time.

[0065] Agitation system **158** controls the generation and delivery of sound energy to the printing site. Agitation system **158** can operate an agitation device (e.g., agitator, wave generator, etc.) to generate ultrasonic or acoustic waves at a desired amplitude and frequency, and can include any of the agitation devices discussed herein. Agitation system **158** can be configured to continuously generate waves, or alternatively, can be configured to engage and disengage the agitation device to intermittently generate waves.

[0066] Printing device **132** can further include other systems **159**. Other systems **159** can be utilized to, for example, control a magnet (e.g., an electromagnet) to generate a desired magnetic field at the printing site, or any other suitable device. Furthermore, it should be noted that according to various alternative embodiments, one or both of systems **156**, **158** may be omitted.

[0067] Printing device **132** further includes a monitoring system **160** for monitoring the operation of the other systems of printing device **132** and the object fabricated by printing device **132**. Monitoring system **160** can be configured to visually monitor the printing site and the portions of the object surrounding the printing site. Monitoring system **160** can adjust the focus and/or magnification of a monitoring device (e.g., an optical microscope, electron microscope, etc.) to obtain an image of the microstructure of the material. In one embodiment, monitoring system **160** is configured to collect other data, such as pressure data (e.g., to monitor ultrasonic vibrations) and temperature, with a variety of sensors. The sensors can be positioned on the surface of the fabricated object or away from the object. The sensors are configured to collect data from the printing site, a portion of the object near the printing site, an area of the object away from the printing site, or the interior of the printing device. Data collected by monitoring system **160** is used to provide feedback on the formation of the object. The data can be used to adjust the parameters of one of the other systems (e.g., positioning system **150**, material delivery system **152**, heating energy delivery system **154**, coolant delivery system **156**, agitation system **158** or other systems **159**) to adjust the microstructure of the object. The adjustments can be initiated automatically (e.g., by processor **140**) or alternatively can be initiated manually (e.g., by a user with input device **144**). For example, in one embodiment, processor **140** receives inputs from monitoring system **160** (e.g., temperature data, pressure data, etc.), and provides control signals to one or more of systems **150**, **152**, **154**, **156**, **158**, and **159** based on the inputs.

[0068] Referring now to FIG. **7**, method **170** of fabricating a 3D metal structure with an additive manufacturing system is shown according to one embodiment. A material (e.g., material **56** or material **86**) is delivered to a printing site (**172**). According to various embodiments, the amount, location, type, etc. of material provided can be controlled, and can vary within and between printing sites. Heating energy (e.g., heating energy **62** or heating energy **92**) is delivered to the printing site (**174**). As discussed above, heating energy can be provided in a variety of ways, and the amount of heating energy and other parameters can be varied within and between printing sites. The printing site is agitated (e.g., by way of ultrasonic or acoustic waves generated by agitation device **68** or agitation device **98**) (**176**). For example, various types of ultrasonic waves can be continuously and/or intermittently provided, and various characteristics of the waves (e.g., frequency, amplitude, etc.) can be varied within and between printing sites. The resulting properties of the fabricated metal structure are then monitored and the data is utilized to adjust the control parameters for the delivery of material, heating energy, and agitation to the printing site, or alternatively, to a subsequently printed portion of the printing site or a subsequently printed printing site (**178**). The process can then continue for subsequent printing sites until the object is formed.

[0069] Referring now to FIG. **8**, method **180** of fabricating a 3D metal structure using an additive manufacturing system is shown according to another embodiment. Material (e.g., material **56** or material **86**) is delivered to a printing site (**182**). Heating energy (e.g., heating energy **62** or heating energy **92**) is delivered to the printing site (**184**). The delivery of material and/or heating energy to the printing site can be controlled in a manner similar to that discussed with respect of FIG. **7**. A coolant (e.g., coolant **64** or coolant **94**) is delivered to the printing site (**186**). The amount, location, type etc. of coolant provided can be varied within and between printing sites. The resulting properties of the fabricated metal structure are then monitored and the data is utilized to adjust the control parameters for the delivery of material, heating energy, and coolant to the printing site, or alternatively, to a subsequently printed portion of the printing site or a subsequently printed printing site (**188**).

[0070] Referring now to FIG. **9**, method **190** of fabricating a 3D metal structure using an additive manufacturing system is shown according to another embodiment. Material (e.g., material **56** or material **86**) is delivered to a printing site (**192**). Heating energy (e.g., heating energy **62** or heating energy **92**) is delivered to the printing site (**194**). The printing site is agitated (e.g., by way of ultrasonic or acoustic waves generated by agitation device **68** or agitation device **98**) (**195**). A coolant (e.g., coolant **64** or coolant **94**) is delivered to the printing site (**196**). Other process parameters, such as the delivery of a magnetic field, etc. to the printing site can further be controlled (**197**). The resulting properties of the fabricated metal structure are then monitored and the data is utilized to adjust the control parameters for the delivery of material, heating energy, agitation, coolant and other processes (**198**). The method illustrated in FIG. **9** may control the delivery of material, heating energy, agitation, coolant, or other processes in a manner similar to that discussed with respect of FIGS. **7** and **8**.

[0071] While the systems and methods described herein relate to the fabrication of a metal part with laser deposition or similar technology, the local control of printing variables, along with monitoring and feedback systems, may be useful for other additive manufacturing processes involving metals or non-metals. For example, a selective laser sintering process may be utilized to form an object, and the process can be monitored to detect the size and concentration of pores in the fabricated object. This data may then be utilized to control, for example, the power output of the laser to achieve a desired final product. The systems and methods disclosed herein may be used in combination with other fabrication techniques according to various other alternative embodiments.

[0072] The present disclosure contemplates methods, systems, and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure may be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a machine, the machine properly views the connection as a machine-readable medium. Thus, any such connection is properly termed a machine-readable medium. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0073] Although the figures may show a specific order of method steps, the order of the steps may differ from what is depicted. Also two or more steps may be performed concurrently or with partial concurrence. Such variation will depend on the software and hardware systems chosen and on designer choice. All such variations are within the scope of the disclosure. Likewise, software implementations could be accomplished with standard programming techniques with rule based logic and other logic to accomplish the various connection steps, processing steps, comparison steps and decision steps.

[0074] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

1. A method of fabricating a three dimensional structure, comprising:
- delivering a metal material to a printing site; and
- defining a microstructure of the metal material at the printing site by:
  - controlling the delivery of heating energy to the printing site; and
  - controlling the delivery of ultrasonic vibrations to the printing site.

2. The method of claim **1**, wherein delivering the metal material to the printing site includes delivering a metal powder to the printing site.

3. The method of claim **1**, wherein delivering the metal material to the printing site includes delivering a metal wire to the printing site.

4. The method of claim **1**, wherein delivering the metal material to the printing site includes using a liquid metal jet.

5. (canceled)

6. The method of claim **1**, wherein the heating energy is delivered to the printing site by a laser.

7. The method of claim **1**, wherein the heating energy is delivered to the printing site by an electron beam.

8-18. (canceled)

19. The method of claim **1**, further comprising monitoring a temperature at the printing site and controlling delivery of at least one of the heating energy and the ultrasonic vibrations based on the temperature.

20-22. (canceled)

23. The method of claim **1**, wherein defining the microstructure includes defining a grain boundary.

24. The method of claim **1**, wherein defining the microstructure includes defining a grain size.

25. The method of claim **1**, wherein defining the microstructure includes defining a pinning point for the microstructure.

26-27. (canceled)

28. The method of claim **1**, further comprising delivering a vaporizable coolant to the printing site.

29-47. (canceled)

48. The method of claim **28**, further comprising varying the pattern of delivery of the vaporizable coolant between different portions of the metal at the printing site.

49. The method of claim **28**, further comprising varying an amount of vaporizable coolant delivered to different portions of the metal at the printing site.

50-51. (canceled)

52. A method of fabricating a three dimensional structure, comprising:
- delivering a metal material to a printing site;
- delivering heating energy to the printing site;
- delivering a vaporizable coolant to the printing site; and
- defining a microstructure for the three dimensional structure based on providing the heating energy to the metal material at the printing site and vaporizing the vaporizable coolant.

53-76. (canceled)

77. The method of claim **52**, wherein the boiling point of the vaporizable coolant corresponds to a predetermined quenching temperature for the metal delivered to the printing site.

78. The method of claim **52**, further comprising modifying the boiling point of the vaporizable coolant.

79. The method of claim **78**, wherein modifying the boiling point of the vaporizable coolant includes modifying the composition of the vaporizable coolant.

80. The method of claim **78**, wherein modifying the boiling point of the vaporizable coolant includes modifying a pressure of a delivery environment for the vaporizable coolant.

81. (canceled)

82. The method of claim **52**, further comprising varying the pattern of delivery of the vaporizable coolant between different portions of the metal at the printing site.

83-90. (canceled)

91. The method of claim **52**, wherein the printing site is a first printing site, the metal material is a first portion of metal material, the heating energy is a first amount of heating energy, and the vaporizable coolant is a first vaporizable coolant, and further comprising:

delivering a second portion of metal material to a second printing site;

delivering a second amount of heating energy to the second printing site; and

delivering a second vaporizable coolant to the second printing site.

92. The method of claim **91**, wherein the first portion of metal material differs from the second portion of metal material in at least one of an amount of metal and a type of metal.

93. The method of claim **91**, wherein the first amount of heating energy differs from the second amount of heating energy in at least one of a duration of delivery of heating energy and an intensity of delivery of heating energy.

94. The method of claim **91**, wherein the first vaporizable coolant varies from the second vaporizable coolant in at least one of a type of coolant, a temperature of coolant, and an amount of coolant.

95. A method of fabricating a three dimensional structure, comprising:

delivering a first metal material to a first printing site;

delivering a first amount of heating energy to the first printing site;

delivering a first vaporizable coolant to the first printing site;

agitating the first printing site; and

forming a first portion of a printed metal structure by providing the first amount of heating energy to the first metal material at the first printing site and vaporizing the first vaporizable coolant while agitating the first printing site.

96-104. (canceled)

105. The method of claim **95**, wherein agitating the first printing site includes delivering ultrasonic vibrations to the first printing site by a transducer.

106. The method of claim **95**, wherein agitating the first printing site includes delivering bulk acoustic waves.

107. The method of claim **95**, wherein agitating the first printing site includes delivering surface acoustic waves.

108. The method of claim **95**, wherein agitating the first printing site includes delivering ultrasonic vibrations to the first printing site by phase conjugation.

109-110. (canceled)

111. The method of claim **95**, wherein agitating the first printing site includes generating a standing wave ultrasonic field.

112-115. (canceled)

116. The method of claim **95**, further comprising varying the pattern of delivery of the first vaporizable coolant between different portions of the first printing site.

117. The method of claim **95**, further comprising varying an amount of the first vaporizable coolant delivered to different portions of the first printing site.

118-121. (canceled)

122. The method of claim **95**, further comprising delivering a second metal material, a second amount of heating energy, and a second vaporizable coolant to a second printing site, and agitating the second printing site.

123. The method of claim **122**, wherein the first metal material differs from the second metal material in at least one of an amount of material delivered and a type of material delivered.

124. The method of claim **122**, wherein the first amount of heating energy differs from the second amount of heating energy.

125. The method of claim **122**, wherein the first vaporizable coolant differs from the second vaporizable coolant in at least one of type of coolant, a temperature of coolant, and amount of coolant delivered.

126-242. (canceled)

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