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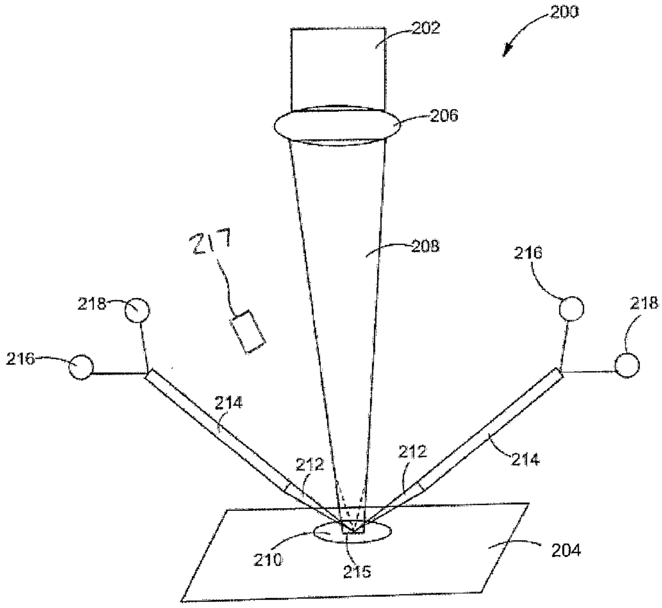

FIG. 13

(57) **Abstract:** Systems and methods for forming a three-dimensional build object on a substrate include controlling an energy beam source in a first mode during a first processing step during which additive material is deposited. Additionally, the method includes controlling the energy beam source in a second mode during a second processing step during which additive material is not deposited. During the first processing step, a feature may be formed by melting additive material as it is deposited into a target area. During the second processing step, the target area may be preheated or reheated to control temperature gradient

[Continued on next page]

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SYSTEMS AND METHODS FOR TEMPERATURE CONTROL IN AN ADDITIVE MANUFACTURING PROCESS

BACKGROUND

Technical Field

[0001] The present disclosure generally relates to additive manufacturing systems and methods and, more particularly, to systems and methods for controlling temperature in additive manufacturing processes.

Description of the Related Art

[0002] Traditionally, materials are processed into desired shapes and assemblies through a combination of rough fabrication techniques (e.g., casting, rolling, forging, extrusion, and stamping) and finish fabrication techniques (e.g., machining, welding, soldering, polishing). Producing a complex assembly in final, usable form ("net shape"), which often may require not only forming the part with the desired materials in the proper shapes but also providing the part with the desired combination of metallurgical properties (e.g., various heat treatments, work hardening, complex microstructure), typically requires considerable investment in time, tools, and effort.

[0003] One or more of the rough and finish processes may be performed using manufacturing centers, such as Computer Numerically Controlled (CNC) machine tools. CNC machine tools use precisely programmed commands to automate the manufacturing process. The commands may be generated using computer-aided design (CAD) and/or computer-aided manufacturing (CAM) programs. Examples of CNC machines include, but are not limited to, mills, lathes, mill-turns, plasma cutters, electric discharge machines (EDM), and water jet cutters. CNC machining centers have been developed which provide a single machine having multiple tool types that is capable of performing multiple different machining processes. Such machining centers may generally include one or more tool retainers, such as spindle retainers and turret retainers holding one or more tools, and a workpiece retainer, such as a pair of chucks. The workpiece retainer may be stationary or move (in translation and/or rotation) while a tool is brought into contact with the workpiece, thereby performing a subtractive manufacturing process during which material is removed from the workpiece.

[0004] Because of cost, expense, complexity, and other factors, additive manufacturing techniques have been developed that would replace all or part of the conventional subtractive manufacturing steps. In contrast to subtractive manufacturing processes, which focus on precise removal of material from a workpiece, additive manufacturing processes add material, typically in a computer-controlled environment, by creating successive layers of material to form a three-dimensional object, referred to herein as a “build object.” Additive manufacturing techniques may improve efficiency and reduce waste while expanding manufacturing capabilities, such as by permitting seamless construction of complex configurations which, when using conventional manufacturing techniques, would have to be assembled from a plurality of component parts. For the purposes of this specification and the appended claims, the term `plurality` consistently is taken to mean “two or more.” The opportunity for additive techniques to replace subtractive processes depends on several factors, such as the range of materials available for use in the additive processes, the size and surface finish that can be achieved using additive techniques, and the rate at which material can be added. Additive processes may advantageously be capable of fabricating complex precision net-shape components ready for use. In some cases, however, the additive process may generate “near-net shape” products that require some degree of finishing.

[0005] Additive manufacturing techniques include, but are not limited to, powder bed fusion processes such as laser sintering, laser melting, and electron beam melting; direct energy deposition processes such as laser engineered net shaping direct metal/material deposition, and laser cladding; material extrusion such as fused deposition modeling; material jetting including continuous or drop on demand; binder jetting; vat polymerization; and sheet lamination including ultrasonic additive manufacturing. In some direct energy deposition processes, powder is injected from one or more nozzles into a focused beam of a laser to melt a small pool of the substrate material. Powder contacting the pool will melt to generate a deposit on the substrate.

[0006] Direct energy deposition of and on brittle materials such as high carbon steels is difficult due to the high level of crack occurrence. Additionally, in some applications, the additive manufacturing process can generate high residual stresses as a result of the geometry being built, the build strategy employed, use of materials with very different thermal expansions, or other factors. To reduce cracking, the temperature gradient formed during the laser deposition process should be kept as small as possible. The first layer of the deposition exhibits greater thermal stresses than subsequent layers because the initial temperature of the substrate is at ambient temperature, hence the temperature gradient is the largest for this layer. As new layers of material are successively deposited, heat is conducted to the substrate, which acts as a heat sink. As the process progresses, heat accumulates in the substrate and the thermal gradient decreases reducing the risk of cracking. In some applications, cracking can be reduced by preheating and slowing the cooling rate of the material. Preheating reduces the thermal gradient which slows the cooling rate of the deposition and the region surrounding the deposition.

[0007] Heretofore, any such preheating has been achieved by heating the entire build object (with or without the substrate) in a furnace. While furnace heating provides a more uniform temperature distribution, it typically involves auxiliary equipment requiring transferring of the build object between the additive manufacturing machine and the furnace, thereby interrupting the additive manufacturing process. Furthermore, it is overly difficult and expensive to integrate a furnace into existing machinery used for direct energy deposition of additive material.

SUMMARY OF THE DISCLOSURE

[0008] The systems and methods disclosed herein selectively control heating and cooling rate of a substrate and/or build object during an additive manufacturing process. In some embodiments, the substrate and/or build object is preheated at a desired rate and to a desired temperature prior to deposition of additive material. In other embodiments, the substrate and/or build object is selectively reheated after deposition to control the rate at which the build object and/or substrate cools until a desired temperature is achieved.

[0009] According to certain aspects of the present disclosure, a method is provided of forming a three-dimensional build object on a substrate by successively depositing individual layers of additive material that are fused together. The method includes controlling an energy beam source in a first mode during a first processing step during which additive material is deposited onto a first area of the substrate, and controlling the energy beam source in a second mode during a second processing step during which additive material is not deposited onto the first area of the substrate.

[0010] According to additional aspects of the present disclosure, a method is provided of forming a three-dimensional build object on a substrate by successively depositing individual layers of additive material that are fused together, the method including controlling an energy beam source in a first mode during a first processing step in which additive material is deposited in a first area, the energy beam source in the first mode having a power density sufficient to melt the additive material, and controlling the energy beam source in a second mode during a second processing step in which additive material is deposited in the first area, the energy beam source in the second mode having a power density with a melting component sufficient to melt the additive material deposited during the second processing step, and a supplemental component in addition to the melting component.

[0011] According to further aspects of the present disclosure, additive manufacturing apparatus is provided for depositing additive material on a substrate to form a three-dimensional build object. The apparatus includes an energy beam source configured to direct an energy beam onto the substrate, the energy beam source having a first mode with a power density sufficient to melt the additive material, and a second mode with a power density insufficient to melt the additive material, a nozzle configured to deposit the additive material onto the substrate, and a controller operatively coupled to the energy source. The controller is programmed to control the energy beam source in the first mode during a first processing step during which additive material is deposited onto a first area of the substrate, and control the energy beam source in the second mode during a second processing step during which additive material is not deposited onto the first area of the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] For a more complete understanding of the disclosed methods and apparatus, reference should be made to the embodiment illustrated in greater detail on the accompanying drawings, wherein:

[0013] FIG. 1 is a front elevation of a computer numerically controlled machine in accordance with one embodiment of the present disclosure, shown with safety doors closed.

[0014] FIG. 2 is a front elevation of a computer numerically controlled machine illustrated in FIG. 1, shown with the safety doors open.

[0015] FIG. 3 is a perspective view of certain interior components of the computer numerically controlled machine illustrated in FIGS. 1 and 2, depicting a machining spindle, a first chuck, a second chuck, and a turret.

[0016] FIG. 4 a perspective view, enlarged with respect to FIG. 3 illustrating the machining spindle and the horizontally and vertically disposed rails via which the spindle may be translated.

[0017] FIG. 5 is a side view of the first chuck, machining spindle, and turret of the machining center illustrated in FIG. 1.

[0018] FIG. 6 is a view similar to FIG. 5 but in which a machining spindle has been translated in the Y-axis.

[0019] FIG. 7 is a front view of the spindle, first chuck, and second chuck of the computer numerically controlled machine illustrated in FIG. 1, including a line depicting the permitted path of rotational movement of this spindle.

[0020] FIG. 8 is a perspective view of the second chuck illustrated in FIG. 3, enlarged with respect to FIG. 3.

[0021] FIG. 9 is a perspective view of the first chuck and turret illustrated in FIG. 2, depicting movement of the turret and turret stock in the Z-axis relative to the position of the turret in FIG. 2.

[0022] FIG. 10 is a front view of the computer numerically controlled machine of FIG. 1 with the front doors open.

[0023] FIG. 11 is a perspective view of an exemplary tool changer of the machine of FIG. 1.

[0024] FIGS. 12(a) to 12(d) are perspective views showing operation of the tool changer of FIG. 11.

[0025] FIG. 13 is a schematic illustration of a material deposition assembly for use with the computer numerically controlled machine of FIG. 1.

[0026] FIG. 14 is a side elevation view of a material deposition assembly having a removable deposition head.

[0027] FIG. 15 is a side elevation view of an alternative embodiment of a material deposition assembly having a removable deposition head.

[0028] FIG. 16 is a side elevation view, in partial cross-section, of a lower processing head used in the material deposition assembly of FIG. 14.

[0029] FIG. 17 is a graphical representation illustrating use of a deposition laser with no powder flow to gradually increase the temperature of the substrate to a prescribed level prior to the start of deposition. The thermal history of a deposition with preheating can be compared to that of a deposition without preheating.

[0030] FIG. 18 is a graphical representation illustrating use of the deposition laser with no powder flow to gradually decrease the temperature of the substrate after a deposition step. The thermal history of a deposition with reheating can be compared to that of a deposition without reheating.

[0031] FIG. 19 is a graphical representation illustrating deposition with controlled heating and cooling rates by utilizing the preheating and reheating methodology verses a deposition with uncontrolled heating and cooling rates.

[0032] FIG. 20 is a flowchart schematically illustrating an exemplary method of preheating and/or reheating a feature of a build object.

[0033] FIG. 21 is a flowchart schematically illustrating an exemplary method of preheating and/or reheating multiple independent features of a build object.

[0034] FIG. 22 is a flowchart schematically illustrating an exemplary method of in situ preheating of a substrate and/or build object.

[0035] FIG. 23 schematically illustrates different configurations for an energy beam produced by an energy beam source.

[0036] It should be understood that the drawings are not necessarily to scale and that the disclosed embodiments are sometimes illustrated diagrammatically and in partial views. In certain instances, details which are not necessary for an understanding of the disclosed methods and apparatus or which render other details difficult to perceive may have been omitted. It should be understood, of course, that this disclosure is not limited to the particular embodiments illustrated herein.

DETAILED DESCRIPTION

[0037] Any suitable apparatus may be employed in conjunction with the methods disclosed herein. In some embodiments, the methods are performed using a computer numerically controlled machine, illustrated generally in FIGS. 1-10. A computer numerically controlled machine is itself provided in other embodiments. The machine 100 illustrated in FIGS. 1-10 is an NT-series or LT-series machine, versions of which are available from DMG Mori. Alternatively, DMG Mori's DMU-65 (a five-axis, vertical machine tool) machine tool, DMG Mori's LaserTec 4300 3D, or other machine tools having different orientations or numbers of axes, may be used in conjunction with the apparatus and methods disclosed herein. While systems and methods disclosed herein, directed towards methods for additive manufacturing, may be performed using such machines, the contents herein are not limited to being performed on such machines.

[0038] In general, with reference to the NT-series machine illustrated in FIGS. 1-3, one suitable computer numerically controlled machine 100 has at least a first retainer and a second retainer, each of which may be a tool retainer (such as a spindle retainer associated with spindle 144 or a turret retainer associated with a turret 108) or a workpiece retainer (such as chucks 110, 112). In the embodiment illustrated in the Figures, the computer numerically controlled machine 100 is provided with a spindle 144, a turret 108, a first chuck 110, and a second chuck 112. The computer numerically controlled machine 100 also has a computer control system operatively coupled to the first retainer and to the second retainer for controlling the retainers, as described in more detail below. It is understood that in some embodiments, the computer numerically controlled machine 100 may not contain all of the above components, and in other embodiments, the computer numerically controlled machine 100 may contain additional components beyond those designated herein.

[0039] As shown in FIGS. 1 and 2, the computer numerically controlled machine 100 has a machine chamber 116 in which various operations generally take place upon a workpiece (not shown). Each of the spindle 144, the turret 108, the first chuck 110, and the second chuck 112 may be completely or partially located within the machine chamber 116. In the embodiment shown, two moveable safety doors 118 separate the user from the machine chamber 116 to prevent injury to the user or interference in the operation of the computer numerically controlled machine 100. The safety doors 118 can be opened to permit access to the machine chamber 116 as illustrated in FIG. 2. The computer numerically controlled machine 100 is described herein with respect to three orthogonally oriented linear axes (X, Y, and Z), depicted in FIG. 4 and described in greater detail below. Rotational axes about the X, Y and Z axes are connoted "A," "B," and "C" rotational axes respectively.

[0040] The computer numerically controlled machine 100 is provided with a computer control system for controlling the various instrumentalities within the computer numerically controlled machine. In the illustrated embodiment, the machine is provided with two interlinked computer systems, a first computer system comprising a user interface system (shown generally at 114 in FIG. 1) and a second computer system (not illustrated) operatively connected to the first computer system. The second computer system directly controls the operations of the spindle, the turret, and the other instrumentalities of the machine, while the user interface 114 allows an operator to control the second computer system. Collectively, the machine control system and the user interface system, together with the various mechanisms for control of operations in the machine, may be considered a single computer control system.

[0041] The computer control system may include machine control circuitry having a central processing unit (CPU) connected to a main memory. The CPU may include any suitable processor(s), such as those made by Intel and AMD. By way of example, the CPU may include a plurality of microprocessors including a master processor, a slave processor, and a secondary or parallel processor. Machine control circuitry, as used herein, comprises any combination of hardware, software, or firmware disposed in or outside of the machine 100 that is configured to communicate with or control the transfer of data between the machine 100 and a bus, another computer, processor, device, service, or network. The machine control circuitry, and more specifically the CPU, comprises one or more controllers or processors and such one or more controllers or processors need not be disposed proximal to one another and may be located in different devices or in different locations. The machine control circuitry, and more specifically the main memory, comprises one or more memory devices which need not be disposed proximal to one another and may be located in different devices or in different locations. The machine control circuitry is operable to execute all of the various machine tool methods and other processes disclosed herein.

[0042] In some embodiments, the user operates the user interface system to impart programming to the machine; in other embodiments, programs can be loaded or transferred into the machine via external sources. It is contemplated, for instance, that programs may be loaded via a PCMCIA interface, an RS-232 interface, a universal serial bus interface (USB), or a network interface, in particular a TCP/IP network interface. In other embodiments, a machine may be controlled via conventional PLC (programmable logic controller) mechanisms (not illustrated).

[0043] As further illustrated in FIGS. 1 and 2, the computer numerically controlled machine 100 may have a tool magazine 142 and a tool changer 143. These cooperate with the spindle 144 to permit the spindle to operate with any one of multiple tools. Generally, a variety of tools may be provided; in some embodiments, multiple tools of the same type may be provided.

[0044] An exemplary embodiment of a tool changer 300 is illustrated in greater detail in FIGS. 11 and 12(a) to 12(d). The tool changer 300 includes a tool magazine 302 for holding a plurality of tools. The tool magazine 302 may include a magazine base 304 and an endless carrier 306 supported for rotation relative to the magazine base 304. A plurality of tool pots 308 are coupled to the endless carrier 306 at a predetermined pitch, each tool pot 308 being configured to detachably receive an associated tool. A rotary motor 310 is operably coupled to the endless carrier 306 to index the tool magazine 302 as desired.

[0045] The tool changer 300 also includes a tool carrier 312 for extracting a subsequent tool T2 from a tool delivery position A of the tool magazine 302 and transferring it to a tool change position B. As best shown in FIGS. 11 and 12a-d, the tool carrier 312 may include a transfer rail 314 coupled to the magazine base 304 and extending from the tool delivery position A to the tool change position B. A transfer support 316 is slidably coupled to the transfer rail 314 and configured to engage the subsequent tool T2 positioned at the tool delivery position A from the tool pot 308. A transfer motor 318 is operably coupled to the transfer support 316 to reciprocate the transfer support 316 between the tool delivery position A and the tool change position B, thereby to remove the subsequent tool T2 from the tool pot 308.

[0046] The illustrated tool changer 300 further includes a tool exchange assembly 320 for exchanging a preceding tool T1 held by the spindle 144 for the subsequent tool T2 presented at the tool change position B. the tool exchange assembly 320 may include an exchange shaft 322 supported by and rotatable relative to the magazine base 304 and an exchange arm 324 coupled to the exchange shaft 322. An exchange drive 326 is operably coupled to the exchange shaft 322 to move the exchange shaft 322 in both axial and rotational directions.

[0047] In operation, the tool changer 300 may be used to change the tool that is coupled to the spindle 144. The tool magazine 302 rotary-indexes the subsequent tool T2 to position it at the tool delivery position A, as shown in FIG. 12(a). The transfer support 316 engages the subsequent tool T2 positioned at the tool delivery position A and transfers it to the tool change position B, as shown in FIGS. 12(b) and 12(c). Next, the exchange arm 324 changes the preceding tool T1 attached to the spindle 144 to the subsequent tool T2 held by the transfer support 316, as shown in FIG. 12(d). Thereafter, the preceding tool T1 may be returned to a predetermined one of the tool pots 308 of the tool magazine 302, and the subsequent tool T2 attached to the spindle 144 may be used in a subsequent process.

[0048] The spindle 144 is mounted on a carriage assembly 120 that allows for translational movement along the X- and Z-axis, and on a ram 132 that allows the spindle 144 to be moved in the Y-axis. The ram 132 is equipped with a motor to allow rotation of the spindle in the B-axis, as set forth in more detail below. As illustrated, the carriage assembly has a first carriage 124 that rides along two threaded vertical rails (one rail shown at 126) to cause the first carriage 124 and spindle 144 to translate in the X-axis. The carriage assembly also includes a second carriage 128 that rides along two horizontally disposed threaded rails (one shown in FIG. 3 at 130) to allow movement of the second carriage 128 and spindle 144 in the

Z-axis. Each carriage 124, 128 engages the rails via plural ball screw devices whereby rotation of the rails 126, 130 causes translation of the carriage in the X- or Z-direction respectively. The rails are equipped with motors 170 and 172 for the horizontally disposed and vertically disposed rails respectively.

[0049] The spindle 144 holds the tool 102 by way of a spindle connection and a tool retainer 106. The spindle connection 145 (shown in FIG. 2) is connected to the spindle 144 and is contained within the spindle 144. The tool retainer 106 is connected to the spindle connection and holds the tool 102. Various types of spindle connections are known in the art and can be used with the computer numerically controlled machine 100. Typically, the spindle connection is contained within the spindle 144 for the life of the spindle. An access plate 122 for the spindle 144 is shown in FIGS. 5 and 6.

[0050] The first chuck 110 is provided with jaws 136 and is disposed in a stock 150 that is stationary with respect to the base 111 of the computer numerically controlled machine 100. The second chuck 112 is also provided with jaws 137, but the second chuck 112 is movable with respect to the base 111 of the computer numerically controlled machine 100. More specifically, the machine 100 is provided with threaded rails 138 and motors 139 for causing translation in the Z-direction of the second stock 152 via a ball screw mechanism as heretofore described. To assist in swarf removal, the second stock 152 is provided with a sloped distal surface 174 and a side frame 176 with Z-sloped surfaces 177, 178. Hydraulic controls and associated indicators for the chucks 110, 112 may be provided, such as the pressure gauges 182 and control knobs 184 shown in FIGS. 1 and 2. Each stock is provided with a motor (161, 162 respectively) for causing rotation of the chuck.

[0051] The turret 108, which is best depicted in FIGS. 5, 6 and 9, is mounted in a turret stock 146 (FIG. 5) that also engages rails 138 and that may be translated in a Z-direction, again via ball-screw devices. The turret 108 is provided with various turret connectors 134, as illustrated in FIG. 9. Each turret connector 134 can be connected to a tool retainer 135 or other connection for connecting to a tool. Since the turret 108 can have a variety of turret connectors 134 and tool retainers 135, a variety of different tools can be held and operated by the turret 108. The turret 108 may be rotated in a C' axis to present different ones of the tool retainers (and hence, in many embodiments, different tools) to a workpiece.

[0052] It is thus seen that a wide range of versatile operations may be performed. With reference to tool 102 held in tool retainer 106, such tool 102 may be brought to bear against a workpiece (not shown) held by one or both of chucks 110, 112. When it is necessary or desirable to change the tool 102, a replacement tool 102 may be retrieved from the tool magazine 142 by means of the tool changer 143. With reference to FIGS. 4 and 5, the spindle 144 may be translated in the X and Z directions (shown in FIG. 4) and Y direction (shown in FIGS. 5 and 6). Rotation in the B axis is depicted in FIG. 7, the illustrated embodiment permitting rotation within a range of 120 degrees to either side of the vertical. Movement in the Y direction and rotation in the B axis are powered by motors (not shown) that are located behind the carriage 124.

[0053] Generally, as seen in FIGS. 2 and 7, the machine is provided with a plurality of vertically disposed leaves 180 and horizontal disposed leaves 181 to define a wall of the machine chamber 116 and to prevent swarf from exiting this chamber.

[0054] The components of the machine 100 are not limited to the heretofore described components. For instance, in some instances an additional turret may be provided. In other instances, additional chucks and/or spindles may be provided. Generally, the machine is provided with one or more mechanisms for introducing a cooling liquid into the machine chamber 116.

[0055] In the illustrated embodiment, the computer numerically controlled machine 100 is provided with numerous retainers. Chuck 110 in combination with jaws 136 forms a retainer, as does chuck 112 in combination with jaws 137. In many instances these retainers will also be used to hold a workpiece. For instance, the chucks and associated stocks will function in a lathe-like manner as the headstock and optional tailstock for a rotating workpiece. Spindle 144 and spindle connection 145 form another retainer. Similarly, the turret 108, when equipped with plural turret connectors 134, provides a plurality of retainers (shown in FIG. 9).

[0056] The computer numerically controlled machine 100 may use any of a number of different types of tools known in the art or otherwise found to be suitable. For instance, the tool 102 may be a cutting tool such as a milling tool, a drilling tool, a grinding tool, a blade tool, a broaching tool, a turning tool, or any other type of cutting tool deemed appropriate in connection with a computer numerically controlled machine 100. Additionally or alternatively, the tool may be configured for an additive manufacturing technique, as discussed in greater detail below. In either case, the computer numerically controlled machine 100 may be provided with more than one type of tool, and via the mechanisms of the tool changer 143 and tool magazine 142, the spindle 144 may be caused to exchange one tool for another. Similarly, the turret 108 may be provided with one or more tools 102, and the operator may switch between tools 102 by causing rotation of the turret 108 to bring a new turret connector 134 into the appropriate position. In some examples, the turret may be provided with one or more of the gas delivery nozzles 401, 402, and 405.

[0057] The computer numerically controlled machine 100 is illustrated in FIG. 10 with the safety doors open. As shown, the computer numerically controlled machine 100 may be provided with at least a tool retainer 106 disposed on a spindle 144, a turret 108, one or more chucks or workpiece retainers 110, 112 as well as a user interface 114 configured to interface with a computer control system of the computer numerically controlled machine 100. Each of the tool retainer 106, spindle 144, turret 108 and workpiece retainers 110, 112 may be disposed within a machining area 190 and selectively rotatable and/or movable relative to one another along one or more of a variety of axes.

[0058] As indicated in FIG. 10, for example, the X, Y, and Z axes may indicate orthogonal directions of movement, while the A, B, and C axes may indicate rotational directions about the X, Y, and Z axes, respectively. These axes are provided to help describe movement in a three-dimensional space, and therefore, other coordinate schemes may be used without departing from the scope of the appended claims. Additionally, use of these axes to describe movement is intended to encompass actual, physical axes that are perpendicular to one another, as well as virtual axes that may not be physically perpendicular but in which the tool path is manipulated by a controller to behave as if they were physically perpendicular.

[0059] With reference to the axes shown in FIG. 10, the tool retainer 106 may be rotated about a B-axis of the spindle 144 upon which it is supported, while the spindle 144 itself may be movable along an X-axis, a Y-axis and a Z-axis. The turret 108 may be movable along an XA-axis substantially parallel to the X-axis and a ZA-axis substantially parallel to the Z axis.

The workpiece retainers 110, 112 may be rotatable about a C-axis, and further, independently translatable along one or more axes relative to the machining area 190. While the computer numerically controlled machine 100 is shown as a six-axis machine, it is understood that the number of axes of movement is merely exemplary, as the machine may be capable of movement in less than or greater than six axes without departing from the scope of the claims.

[0060] The computer numerically controlled machine 100 may include a material deposition assembly for performing additive manufacturing processes. An exemplary material deposition assembly 200 is schematically illustrated in FIG. 13 as including an energy beam 202 capable of being directed toward a substrate 204. The material deposition assembly 200 may be used in, for example, directed energy deposition. The substrate 204 may be supported by one or more of the workpiece retainers, such as chucks 110, 112. The material deposition assembly 200 may further include an optic 206 that may direct a concentrated energy beam 208 toward the substrate 204, however the optic 206 may be omitted if the concentrated energy beam 208 has sufficiently large energy density. The energy beam 202 may be a laser beam, an electron beam, an ion beam, a cluster beam, a neutral particle beam, a plasma jet, or a simple electrical discharge (arc). The concentrated energy beam 208 may have an energy density sufficient to melt a small portion of the growth surface substrate 204, thereby forming a melt-pool 210, without losing substrate material due to evaporation, splattering, erosion, shock-wave interactions, or other dynamic effects. The concentrated energy beam 208 may be continuous or intermittently pulsed.

[0061] The melt-pool 210 may include liquefied material from the substrate 204 as well as additive material. In an exemplary embodiment, the additive material may be provided as a feed powder that is directed onto the melt-pool 210 in a feed powder/propellant gas mixture 212 exiting one or more nozzles 214. The nozzles 214 may fluidly communicate with a feed powder reservoir 216 and a propellant gas reservoir 218. The nozzles 214 create a flow pattern of feed powder/propellant gas mixture 212 that may substantially converge into an apex 215 or region of smallest physical cross-section so that the feed powder is incorporated into the melt-pool 210. As the material deposition assembly 200 is moved relative to the substrate 204, the assembly traverses a tool path that forms a bead layer on the substrate 204.

Additional bead layers may be formed adjacent to or on top of the initial bead layer to fabricate solid, three-dimensional objects.

[0062] While the illustrated embodiment shows the additive material in the form of a powder, it may take other forms. For example, the additive material may be provided as a wire feed material, a foil material, or any other type of material known for use in additive manufacturing processes.

[0063] Depending on the materials used and the object tolerances required, it is often possible to form net shape objects, or objects which do not require further machining for their intended application (polishing and the like are permitted). Should the required tolerances be more precise than are obtainable by the material deposition assembly 200, a subtractive finishing process may be used. When additional finishing machining is needed, the object generated by the material deposition assembly 200 prior to such finishing is referred to herein as “near-net shape” to indicate that little material or machining is needed to complete the fabrication process.

[0064] The material deposition assembly 200 may be incorporated into the computer numerically controlled machine 100, as best shown in FIG. 14. In this exemplary embodiment, the material deposition assembly 200 includes a processing head assembly 219 having an upper processing head 219a and a lower processing head 219b. The lower processing head 219b is detachably coupled to the upper processing head 219a to permit the upper processing head 219a to be used with different lower processing heads 219b. The ability to change the lower processing head 219b may be advantageous when different deposition characteristics are desired, such as when different shapes and/or densities of the energy beam 202 and/or feed powder/propellant gas mixture 212 are needed.

[0065] More specifically, the upper processing head 219a may include the spindle 144. A plurality of ports may be coupled to the spindle 144 and are configured to interface with the lower processing head 219b when connected. For example, the spindle 144 may carry a feed powder/propellant port 220 fluidly communicating with a powder feed supply (not shown), which may include a feed powder reservoir and a propellant reservoir. Additionally, the spindle 144 may carry a shield gas port 222 fluidly communicating with a shield gas supply (not shown), and a coolant port 224 fluidly communicating with a coolant supply (not shown). The feed powder/propellant port 220, shield gas port 222, and coolant port 224 may be connected to their respective supplies either individually or through a harnessed set of conduits, such as conduit assembly 226.

[0066] The upper processing head 219a further may include a fabrication energy port 228 operatively coupled to a fabrication energy supply (not shown). In the illustrated embodiment, the fabrication energy supply is a laser connected to the fabrication energy port 228 by laser fiber 230 extending through a housing of the spindle 144. The laser fiber 230 may travel through a body of the spindle 144, in which case the fabrication energy port 228 may be located in a socket 232 formed in a bottom of the spindle 144. Therefore, in the embodiment of FIG. 14, the fabrication energy port 228 is disposed inside the socket 232 while the feed powder/propellant port 220, shield gas port 222, and coolant port 224 are disposed adjacent the socket 232. The upper processing head 219a may further include additional optics for shaping the energy beam, such as a collimation lens, a partially reflective mirror, or a curved mirror.

[0067] The upper processing head 219a may be selectively coupled to one of a plurality of lower processing heads 219b. As shown in FIG. 14, an exemplary lower processing head 219b may generally include a base 242, an optic chamber 244, and a nozzle 246. Additionally, a nozzle adjustment assembly may be provided to translate, rotate, or otherwise adjust the position and/or orientation of the nozzle 246 relative to the energy beam. The base 242 is configured to closely fit inside the socket 232 to permit releasable engagement between the lower processing head 219b and the upper processing head 219a. In the embodiment of FIG. 14, the base 242 also includes a fabrication energy interface 248 configured to detachably couple to the fabrication energy port 228. The optic chamber 244 may be either empty or it may include a final optic device, such as a focusing optic 250 configured to provide the desired concentrated energy beam. The lower processing head 219b may further include a feed powder/propellant interface 252, a shield gas interface 254, and a coolant interface 256 configured to operatively couple with the feed powder/propellant port 220, shield gas port 222, and coolant port 224, respectively.

[0068] The nozzle 246 may be configured to direct feed powder/propellant toward the desired target area. In the embodiment illustrated at FIG. 16, the nozzle 246 includes an outer nozzle wall 270 spaced from an inner nozzle wall 272 to define a powder/propellant chamber 274 in the space between the outer and inner nozzle walls 270, 272. The powder/propellant chamber 274 fluidly communicates with the feed powder/propellant interface 252 at one end and terminates at an opposite end in a nozzle exit orifice 276. In the exemplary embodiment, the nozzle exit orifice 276 has an annular shape; however other the nozzle exit orifice 276 may have other shapes without departing from the scope of the present disclosure. The powder/propellant chamber 274 and nozzle exit orifice 276 may be configured to provide one or more jets of feed powder/propellant at the desired angle of convergence. The nozzle 246 of the illustrated embodiment may deliver a single, conical-shaped jet of powder/propellant gas. It will be appreciated, however, that the nozzle exit orifice 276 may be configured to provide multiple discrete jets of powder/propellant gas. Still further, the resulting jet(s) of powder/propellant gas may have shapes other than conical.

[0069] The nozzle 246 may further be configured to permit the energy beam to pass through the nozzle 246 as it travels toward the target area. As best shown in FIG. 16, the inner nozzle wall 272 defines a central chamber 280 having a fabrication energy outlet 282 aligned with the optic chamber 244 and the optional focusing optic 250. Accordingly, the nozzle 246 permits the beam of fabrication energy to pass through the nozzle 246 to exit the lower processing head 219b.

[0070] In an alternative embodiment, an upper processing head 219a’ may have the fabrication energy port 228 provided outside of the housing of the spindle 144 as best shown in FIG. 15. In this embodiment, the fabrication energy port 228 is located on an enclosure 260 provided on a side of the spindle 144, and therefore, unlike the above embodiment, this port is not provided in the socket 232. The enclosure 260 includes a first mirror 262 for directing the fabrication energy toward a point below the socket 232 of the spindle 144. An alternative lower processing head 219b’ includes an optic chamber 244 that includes a fabrication energy receptacle 264 through which the fabrication energy may pass from the enclosure 260 to an interior of the optic chamber 244. The optic chamber 244 further includes a second mirror 266 for redirecting the fabrication energy through the nozzle 246 and toward the desired target location.

[0071] While the exemplary embodiments incorporate the fabrication energy into the processing head assembly 219, it will be appreciated that the fabrication energy may be provided independent of the processing head assembly 219. That is, a separate assembly, such as the turret 108, the first chuck 110, the second chuck 112, or a dedicated robot provided with the machine 100, may be used to direct the fabrication energy toward the substrate 204. In this alternative embodiment, the processing head assembly 219 would omit the fabrication energy port, fabrication energy interface, fabrication energy outlet, optic chamber, and focusing optic.

[0072] With the processing head assembly 219 having the upper processing head 219a configured to selectively couple with any one of several lower processing heads 219b, the computer numerically controlled machine 100 may be quickly and easily reconfigured for different additive manufacturing techniques. The tool magazine 142 may hold a set of lower processing heads 219b, wherein each lower processing head in the set has unique specifications suited for a particular additive manufacturing process. For example, the lower processing heads may have different types of optics, interfaces, and nozzle angles that alter the manner in which material is deposited on the substrate or energy is directed to the target area. When a particular part must be formed using different additive manufacturing techniques (or may be formed more quickly and efficiently when multiple different techniques are used), the tool changer 143 may be used to quickly and easily change the particular deposition head coupled to the spindle 144. In the exemplary embodiments illustrated in FIGS. 14 and 15, a single attachment step may be used to connect the energy, feed powder/propellant gas, shield gas, and coolant supplies to the deposition head. Similarly, detachment is accomplished in a single disconnect step. Accordingly, the machine 100 may be more quickly and easily modified for different material deposition techniques.

[0073] In certain additive manufacturing applications, it may be advantageous to control the temperature of the material and/or surrounding area when working with certain materials and/or build object geometries. Materials such as high carbon steel and titanium, for example, may be prone to cracking or other deformities when a high temperature gradient exists across the workpiece. As used herein, the term “high carbon steel” includes any steel having a carbon content equal to or greater than 0.2%. Additionally or alternatively, the shape or geometry of the desired final build object may require a build strategy that may, for example, overheat thin features while forming adjacent thicker features. Furthermore, with uncontrolled cooling, in some applications, the additive manufacturing process can generate high residual stresses as a result of the geometry being built, the build strategy employed, use of materials with very different thermal expansions, or other factors. By controlling the cooling rate, these stresses can be gradually released as the part cools.

[0074] The preheating and/or reheating processes may be controlled to achieve a desired temperature target. As used herein, the term “temperature target” is intended to encompass a desired temperature value and a rate of change of temperature. For example, the energy beam source may be controlled so that a selected area of the build object is maintained above a temperature target in the form of a desired temperature value. Alternatively, the energy beam source may be controlled so that a selected area of the build object achieves a temperature target in the form of a desired rate of cooling.

[0075] FIG. 17 schematically illustrates the thermal effect of the preheating cycle. Compared to the thermal history of the deposition without preheating, the preheating cycle greatly decreases the heating rate, reducing the thermal shock of the substrate material. This preheating cycle may be performed, for example, by applying the same energy beam source used during additive material deposition. During preheating, the energy beam source may be operated at a reduced power level when compared to the power level of the energy beam used during deposition. Preheating may be advantageous when the build object is formed of cast iron, high carbon steel, cobalt-chrome alloys, or any other materials that tend to have brittle modes of failure or are otherwise classified or known as marginally weldable materials. In some embodiments, preheating is controlled so that a maximum heating rate during the preheating cycle is no more approximately 7.8 K/minute, and an average heating rate during the preheating cycle is no more than approximately 3.4 K/minute.

[0076] Alternatively, other sources of heating the substrate and/or build object may be used, such as mechanical engagement to produce friction or an induction heater.

[0077] FIG. 18 schematically illustrates the thermal effect of a post-heating cycle. Reduced power energy beam passes may be used to reduce the cooling rate of the build object and/or substrate materials to prevent thermal shock and reduce residual stresses. Reheating may be advantageous when the build object is formed of titanium or other materials known to be problematic in terms of residual stress during welding and/or additive manufacturing processes. In some embodiments, reheating is controlled so that a cooling rate during the reheating cycle is no more than approximately 1.4 K/minute.

[0078] FIG. 19 schematically illustrates the thermal effect of both preheating and post-heating cycles in an additive manufacturing process.

[0079] The temperature of the build object may be measured using a temperature sensing device 217 (FIG. 13), which may be provided as one or more of any number of devices including but not limited to an IR camera, pyrometer, or thermocouple. Temperature measurement may not be necessary for all embodiments; specifically those utilizing simulation or experience to plan preheat or reheat cycles.

[0080] In some embodiments, a closed loop control system is used. The control system may vary time between cycles, duration of a cycle, and/or laser power to maintain the heating or cooling rate within specified bounds or to maintain temperature above a threshold value. Additional preheat cycles can also be triggered manually, by a time based sequence, or based on a methodology prescribed by simulation or experience.

[0081] In some embodiments, the energy beam may be diffused so that the local temperature directly under the laser does not overheat. This can be achieved by moving the laser out of focus, using a very high process speed, or changing the laser optics. In an exemplary embodiment, the laser may be diffused by replacing the deposition head used during deposition with another head having different optics. For example, the head used during preheating/reheating may generate a larger beam spot having a lower energy density. The beam spot may be sufficiently large that it does not melt, or minimally melts, the additive material and/or the substrate material. Alternatively, the same deposition head may be used but with the laser beam defocused (i.e., the substrate is not positioned at the focal point of the optics).

[0082] In some embodiments, the toolpath used by the laser during preheat and reheat cycles may be similar to the toolpath used in deposition based on the geometry of the build object. In other embodiments, the toolpath used during preheating/reheating is entirely different from that used during deposition. A larger area may be heated to reduce the thermal gradient within the build object or to control the rate of cooling of the build object or specific features thereof.

[0083] Preheating need not be performed before all depositions, but instead may be performed when moving to a new area of deposition on the same component, when returning to a section that has already cooled below acceptable temperature, or after one or more other intermediate machining steps. Reheating can be performed as an intermediate process step to maintain the temperature of a certain area or reduce the cooling rate of a certain feature before the process moves to another feature of a component. Whether to employ mid-process reheating and/or preheating may be feature and/or geometry dependent.

[0084] The cooling rate desired for different features of a build object may differ based on geometry. The desired cooling rate may be determined by experience, simulation, or the control system. Conversely, this methodology could be used to maintain uniform cooling over very different geometries of the same part to reduce residual stresses. In other embodiments, the overall temperature of the build object may be maintained above a desired value by reheating one or more specific features or areas, thereby cooling the entire build object at a more uniform rate.

[0085] Turning now to FIG. 20, an exemplary method 500 for additive manufacturing a build object is illustrated in a block diagram. The method 500 may utilize any of the aforementioned systems, methods, and apparatus described above, including any and all elements associated with or part of the machine 100. The method 500 may be specifically configured to perform a preheat and/or reheat cycle during the additive manufacturing process. At block 502 of the method 500, a substrate is preheated to a desired temperature. The method 500 continues at block 504, where a feature is deposited on the substrate, such as by any one of the additive manufacturing processes noted herein. At block 506 of the method 500, the feature is reheated to control cooling.

[0086] FIG. 21 illustrates an exemplary method 600 for additive manufacturing a build object having multiple features. Each feature may be selectively preheated and/or reheated throughout the additive manufacturing process to obtain the desired temperature either prior to or after deposition of additive material. For example, at block 602 of the method 600, a first substrate is preheated. The method 600 continues at block 604, where a first feature (identified as “feature A”) is deposited on the first substrate. At block 606, a second substrate is preheated. As used herein, the first and second substrates may be independent and distinct substrates, different areas of the same substrate, substrates that are formed independently of the deposited material, or formed by previously deposited material. At block 608 of the method, feature A is reheated to control cooling rate. Block 608 may be performed simultaneously or sequentially with block 606. The method 600 continues at block 610, where a second feature (identified as “feature B”) is deposited on the second substrate. At block 612, the method 600 may continue with another reheating of feature A to control cooling rate of feature A, while at block 614 feature B may be reheated to control cooling rate of feature B. Block 612 may be performed simultaneously or sequentially with block 614. As illustrated, therefore, the method of 600 alternates between preheat/reheating steps and depositing steps.

[0087] FIG. 22 illustrates an exemplary method 700 for additive manufacturing a build object with in situ heating of the build object and/or substrate. At block 702 of the method 700, a substrate is preheated to a desired temperature. At block 704, a feature is deposited on the preheated substrate. The method 700 continues at block 706 by machining (e.g., subtractive machining) the feature. At block 708, the area at which the feature was deposited is preheated, after which additional material is deposited at block 704 and additional machining of the feature is performed at block 706. Blocks 704, 706, and 708 may be repeated until the feature is complete, at which the process ends at block 710.

[0088] FIG. 23 illustrates energy beam configurations produced by an energy beam source that may be used to simultaneously performing preheating/reheating and material deposition. For example, an energy beam 800 is illustrated in FIG. 23 as having an inner region 802, an intermediate region 804, and an outer region 806. In the illustrated embodiment, the intermediate region 804 entirely surrounds the inner region 802, while the outer region 806 entirely surrounds the intermediate and inner regions 802, 804. The inner and intermediate regions 802, 804 may be configured so that the amount of energy delivered to these regions is sufficiently high to melt additive material deposited onto the substrate. The outer region 806 may be configured so that the amount of energy delivered to that region is relatively lower and suitable for preheating/reheating of the deposited feature. In this embodiment, the preheating/reheating process may be performed simultaneously with deposition of additive material, with the preheating/reheating being performed at a first area of the substrate and the additive material deposition being performed at a second area of the substrate.

[0089] Each of the regions 802, 804, 806 may be selectively turned on or off. Accordingly, FIG. 23 also illustrates seven different combinations of regions that can be used in this embodiment. A first beam configuration 810 includes only the inner region 802. A second beam configuration 812 includes the inner and intermediate regions 802, 804. A third beam configuration 814 includes only the intermediate region 804. A fourth beam configuration 816 includes the intermediate and outer regions 804, 806. A fifth beam configuration 818 includes only the outer region 806. A sixth beam configuration 820 includes the inner and outer regions 802, 806. A seventh beam configuration 822 includes the inner, intermediate, and outer regions 802, 804, 806.

INDUSTRIAL APPLICABILITY

[0090] Systems and methods are provided for forming a three-dimensional build object on a substrate by successively depositing individual layers of additive material that are fused together. The method may include controlling an energy beam source in a first mode during a first processing step during which additive material is deposited. Additionally, the method includes controlling the energy beam source in a second mode during a second processing step during which additive material is not deposited. During the first processing step, a feature may be formed by melting additive material as it is deposited into a target area. During the second processing step, the target area may be preheated or reheated to control temperature gradient.

[0091] In alternative embodiments, additive material may be deposited during the second processing step, in which case the energy beam source is controlled in the second mode to have a power density that greater than what would be needed for the amount of additive material deposited during the second processing step. That is, the energy beam source is controlled to have a power density with a melting component sufficient to melt the additive material being deposited during the second processing step, and also a supplemental component in addition to the melting component. The supplemental component may be used to preheat and/or reheat a target area on the substrate and/or build object. Power density of the energy beam may be measured in Kilo-Joules/gram of material added. In some embodiments, the power density of the energy beam is characterized as a multiple of that normally needed to melt the amount of additive material being deposited, such as 1.5 times, 2 times, 2.5 times, or other multiples.

[0092] In addition to preheating and reheating, the energy beam may also be used in post-cooling steps to effect desired characteristics in the finished build object. For example, the energy beam may be applied to specific features or the entire build object in an annealing process. Once additive material deposition and any preheating or reheating steps are complete and the build object has cooled to ambient temperature, the energy beam can be applied to selectively anneal or surface harden the build object.

[0093] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference. The description of certain embodiments as "preferred" embodiments, and other recitation of embodiments, features, or ranges as being preferred, is not deemed to be limiting, and the claims are deemed to encompass embodiments that may presently be considered to be less preferred. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended to illuminate the disclosed subject matter and does not pose a limitation on the scope of the claims. Any statement herein as to the nature or benefits of the exemplary embodiments is not intended to be limiting, and the appended claims should not be deemed to be limited by such statements. More generally, no language in the specification should be construed as indicating any non-claimed element as being essential to the practice of the claimed subject matter. The scope of the claims includes all modifications and equivalents of the subject matter recited therein as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the claims unless otherwise indicated herein or otherwise clearly contradicted by context. The description herein of any reference or patent, even if identified as "prior," is not intended to constitute a concession that such reference or patent is available as prior art against the present disclosure.

CLAIMS:

1. A method of forming a three-dimensional build object on a substrate by successively depositing individual layers of additive material that are fused together, the method comprising:

controlling an energy beam source in a first mode during a first processing step during which additive material is deposited onto a first area of the substrate; and

controlling the energy beam source in a second mode during a second processing step during which additive material is not deposited onto the first area of the substrate.

2. The method of claim 1, in which the second processing step comprises one of preheating prior to deposition or reheating after deposition.

3. The method of claim 1, in which the additive material comprises high carbon steel.

4. The method of claim 1, in which controlling the energy beam source in the second mode comprises close loop control of the energy beam source to obtain a temperature target.

5. The method of claim 4, in which the close loop control is based on a control variable selected from a group of control variables including energy beam duration value, surface temperature value, and energy beam power value.

6. The method of claim 1, in which controlling the energy beam source in the second mode comprises open loop control of the energy beam source to obtain a temperature target.

7. The method of claim 6, in which the open loop control is based on a predetermined methodology.

8. The method of claim 6, in which the temperature target comprises a cooling rate.

9. The method of claim 6, in which the temperature target comprises maintaining a temperature of the build object below a melting point of the additive material.

10. The method of claim 1, in which controlling the energy beam source in the second mode comprises diffusing an energy beam generated by the energy beam source.

11. The method of claim 1, in which:

controlling the energy beam source in the first mode comprises traversing the first area with an energy beam from the energy beam source at a first rate of speed; and

controlling the energy beam source in the second mode comprises traversing the first area with the energy beam from the energy beam source at a second rate of speed greater than the first rate of speed.

12. The method of claim 1, in which the additive material comprises cast iron.

13. The method of claim 1, in which:

the energy beam source includes a first energy beam region having a first power level sufficient to melt the additive material, and a second energy beam region having a second power level insufficient to melt the additive material;

controlling the energy beam source in the first mode comprises directing the first energy beam region toward the first area; and

controlling the energy beam source in the second mode comprises directing the second energy beam region toward the first area.

14. A method of forming a three-dimensional build object on a substrate by successively depositing individual layers of additive material that are fused together, the method comprising:

controlling an energy beam source in a first mode during a first processing step in which additive material is deposited in a first area, the energy beam source in the first mode having a power density sufficient to melt the additive material; and

controlling the energy beam source in a second mode during a second processing step in which additive material is deposited in the first area, the energy beam source in the second mode having a power density with a melting component sufficient to melt the additive material deposited during the second processing step, and a supplemental component in addition to the melting component.

15. The method of claim 14, in which the energy beam source includes a first energy beam region having a first power level sufficient to melt the additive material, and a second energy beam region having a second power level insufficient to melt the additive material;

controlling the energy beam source in the first mode comprises directing the first energy beam region toward the first area; and

controlling the energy beam source in the second mode comprises directing the second energy beam region toward the first area.

16. Additive manufacturing apparatus for depositing additive material on a substrate to form a three-dimensional build object, the apparatus comprising:

an energy beam source configured to direct an energy beam onto the substrate, the energy beam source having a first mode with a power density sufficient to melt the additive material, and a second mode with a power density insufficient to melt the additive material;

a nozzle configured to deposit the additive material onto the substrate; and

a controller operatively coupled to the energy source, the controller programmed to:

control the energy beam source in the first mode during a first processing step during which additive material is deposited onto a first area of the substrate; and

control the energy beam source in the second mode during a second processing step during which additive material is not deposited onto the first area of the substrate.

17. The apparatus of claim 16, in which:

the energy beam source includes a first energy beam region having a first power density sufficient to melt the additive material, and a second energy beam region having a second power density insufficient to melt the additive material; and

the controller is further programmed to:

control the energy beam source in the first mode by directing the first energy beam region toward the first area; and

control the energy beam source in the second mode by directing the second energy beam region toward the first area.

18. The apparatus of claim 16, in which the second energy beam region surrounds the first energy beam region.

19. The apparatus of claim 16, in which the additive material comprises high carbon steel.

20. The apparatus of claim 16, in which the additive material comprises cast iron.

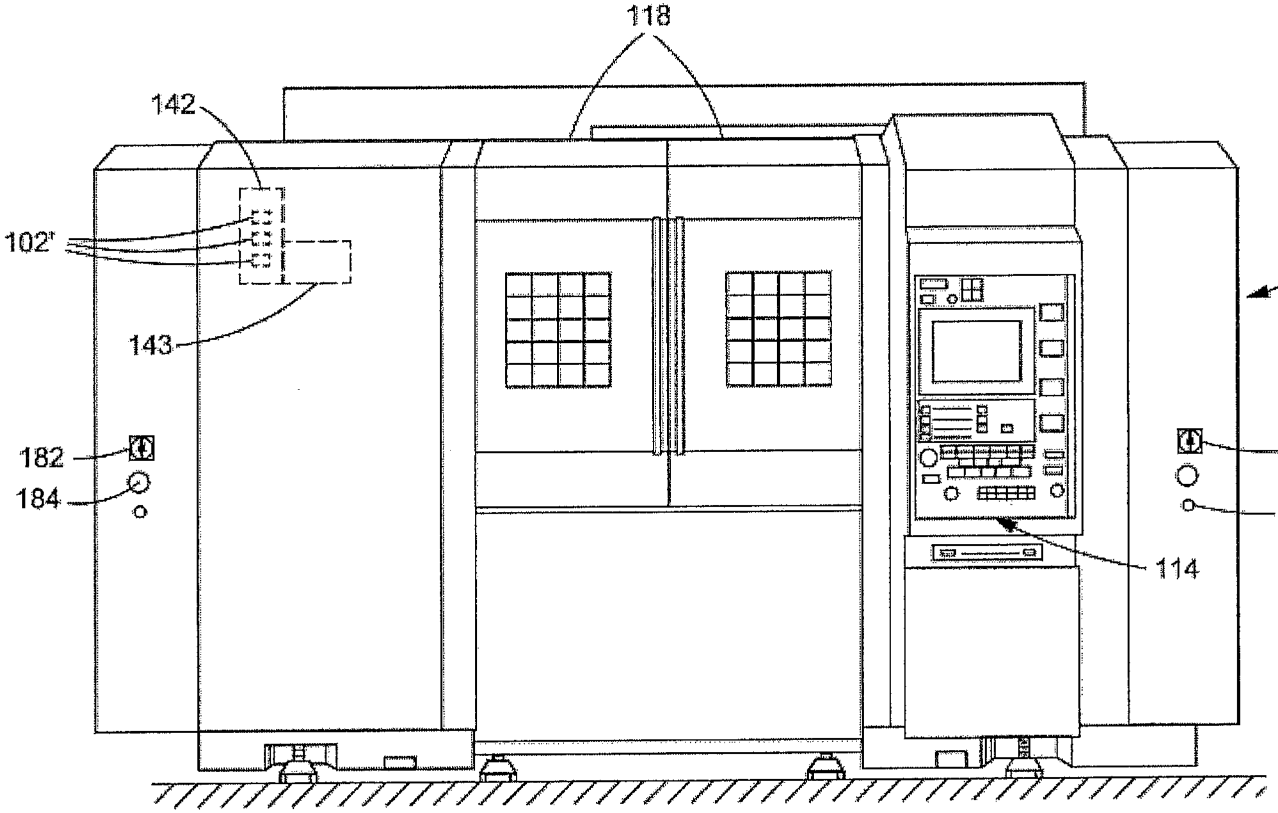

FIG. 1

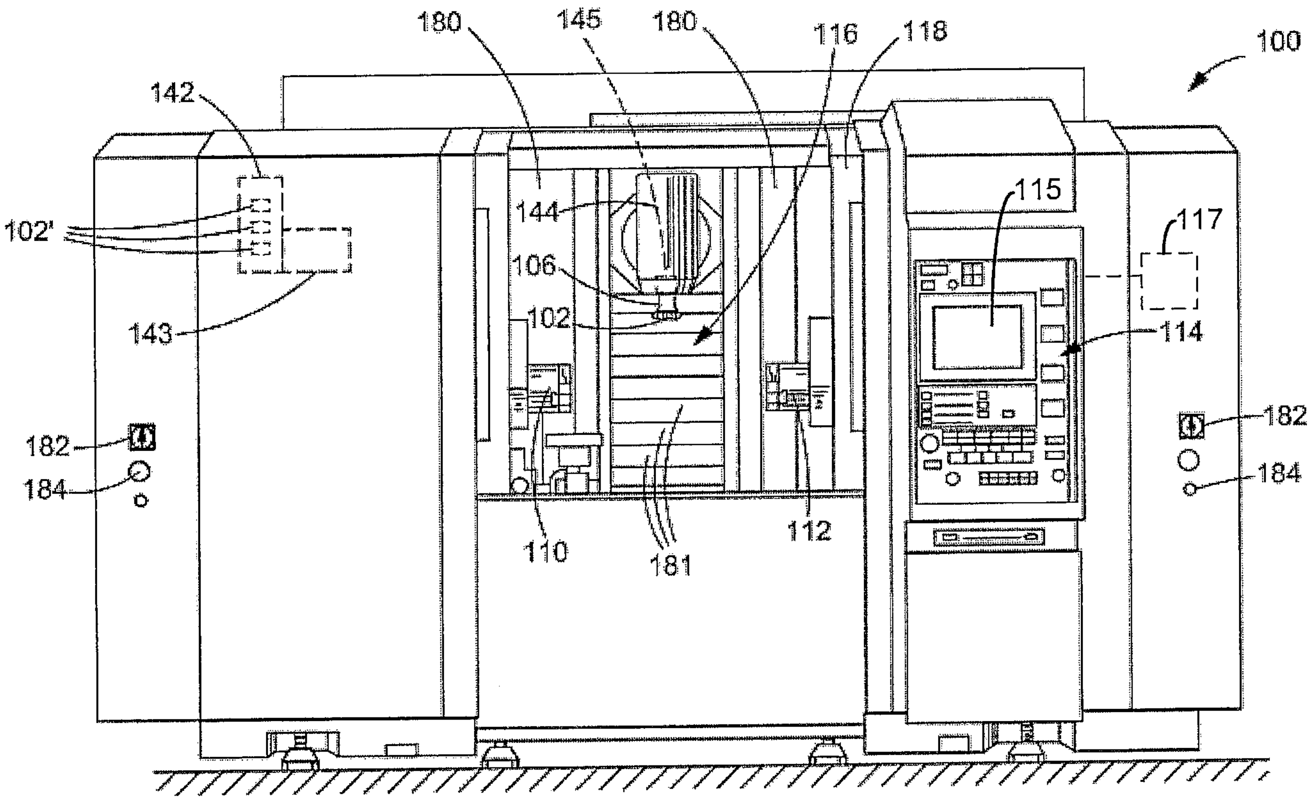
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FIG. 2

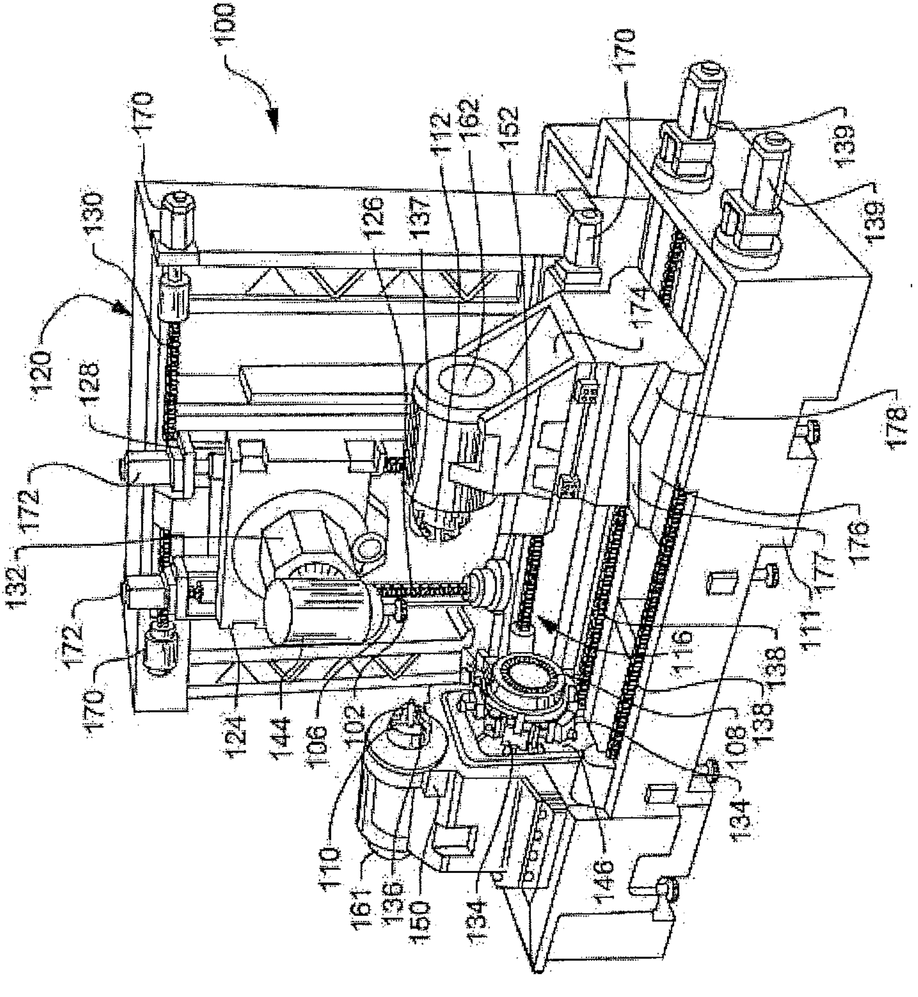
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FIG. 3

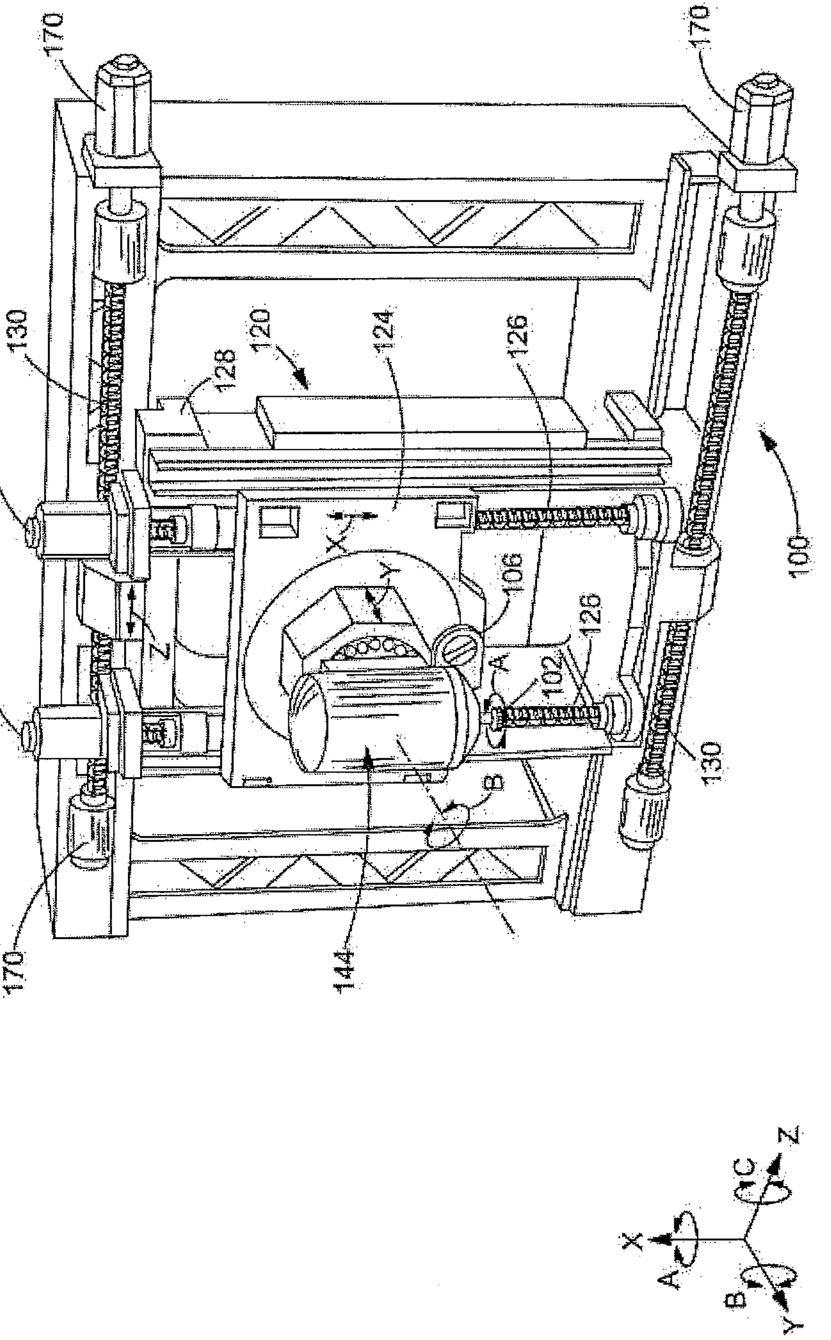
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FIG. 4

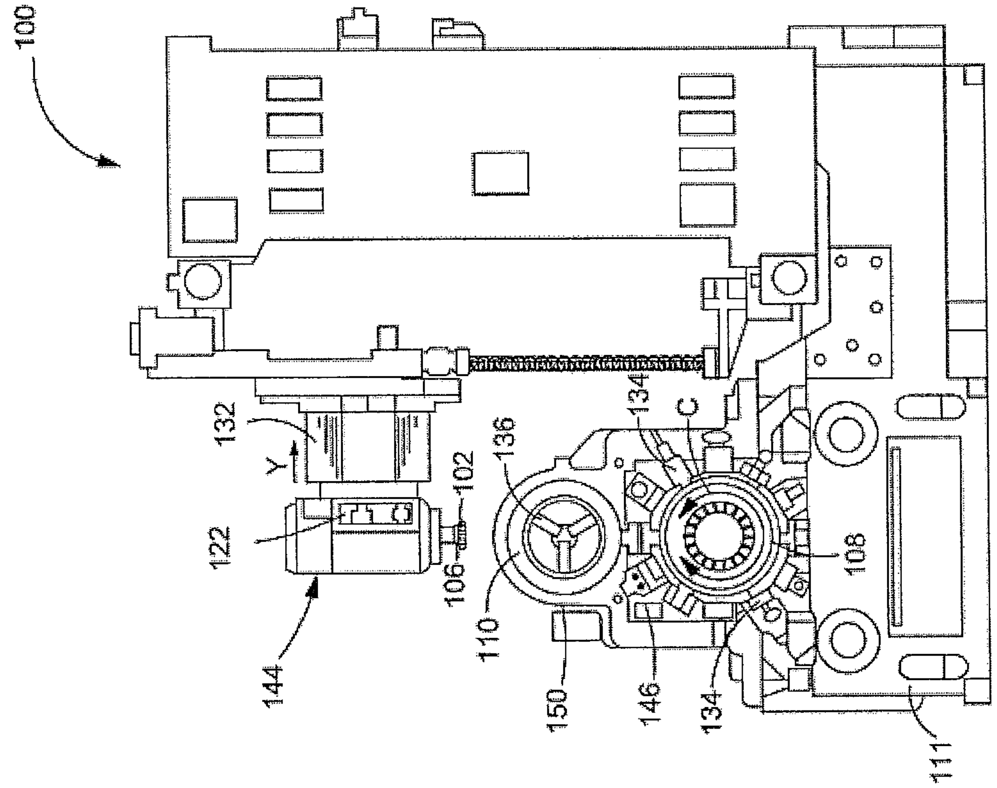

FIG. 5

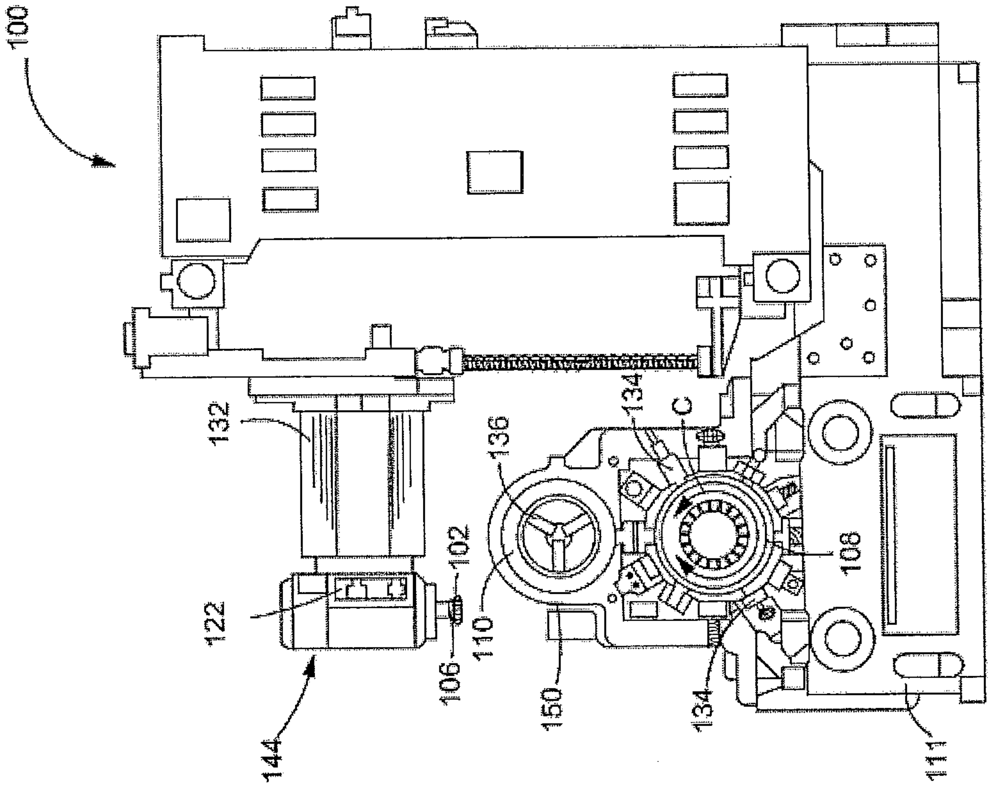

FIG. 6

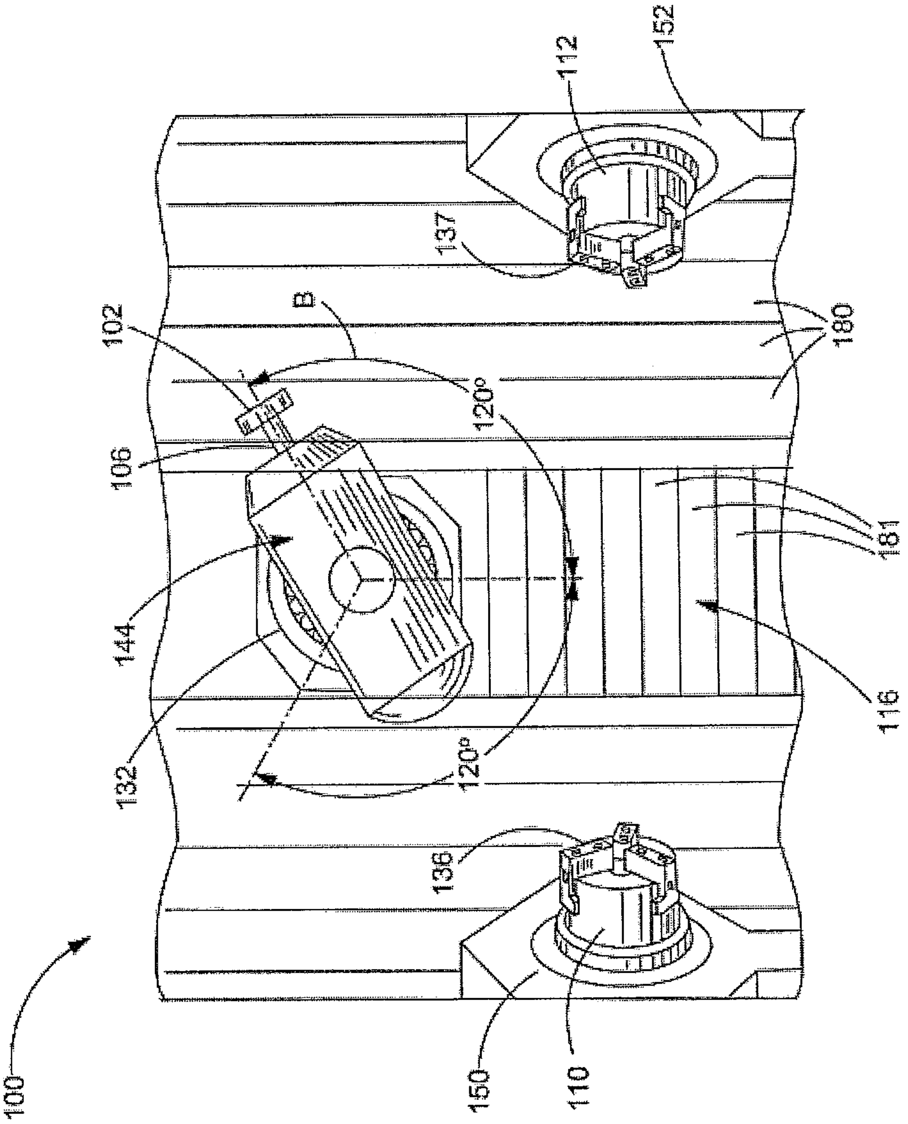

FIG. 7

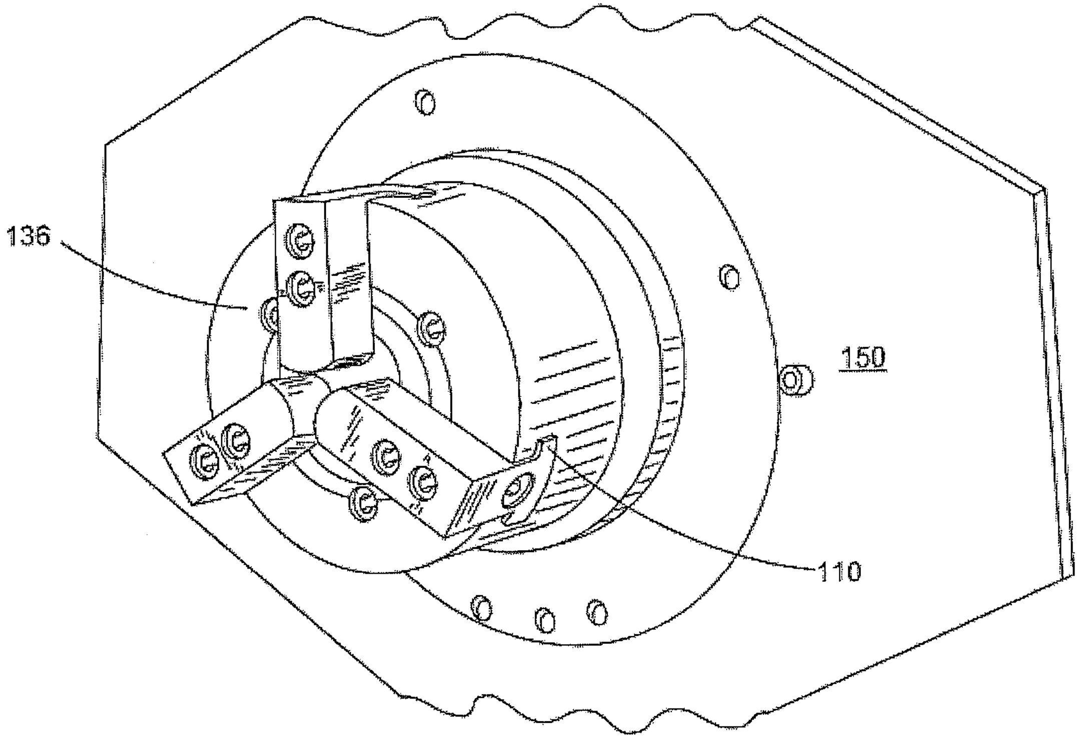

FIG. 8

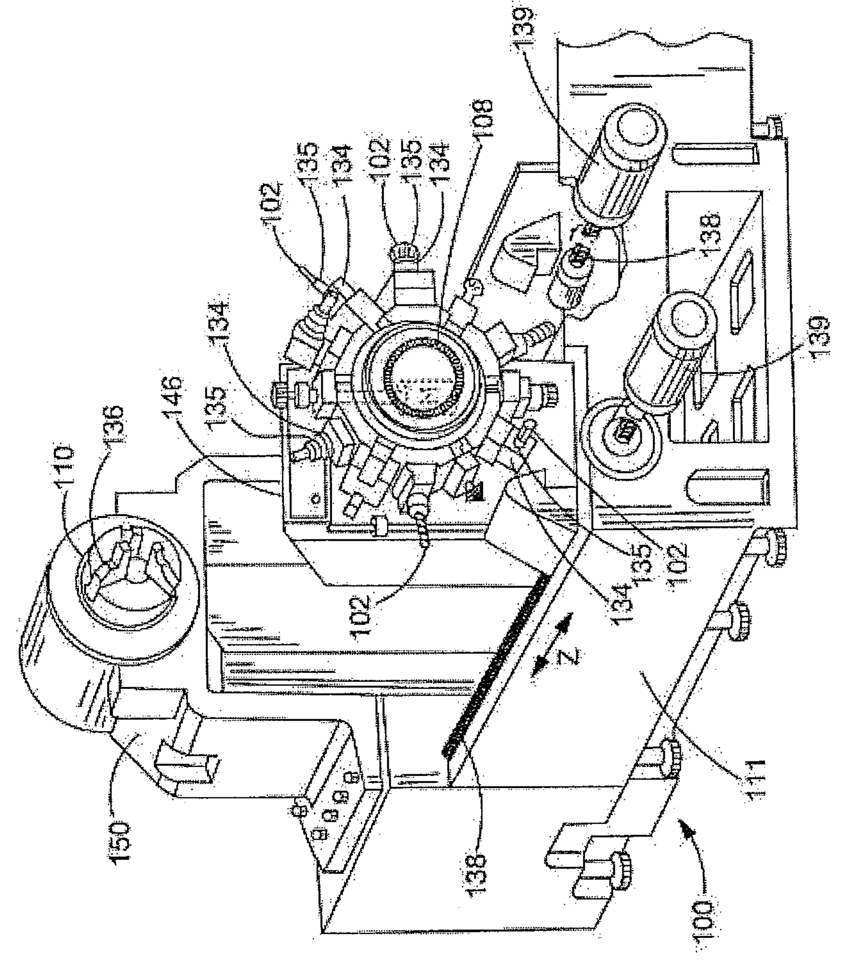
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FIG. 9

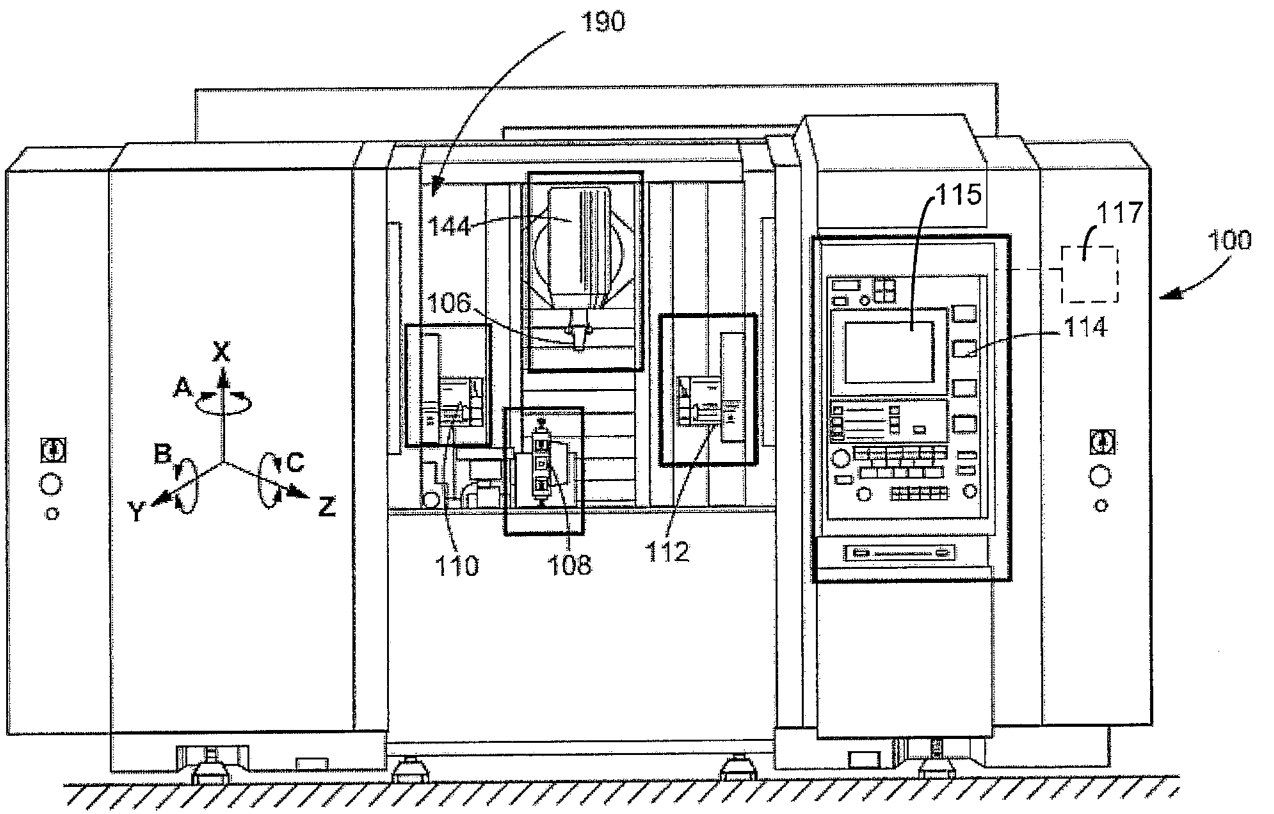


FIG. 10

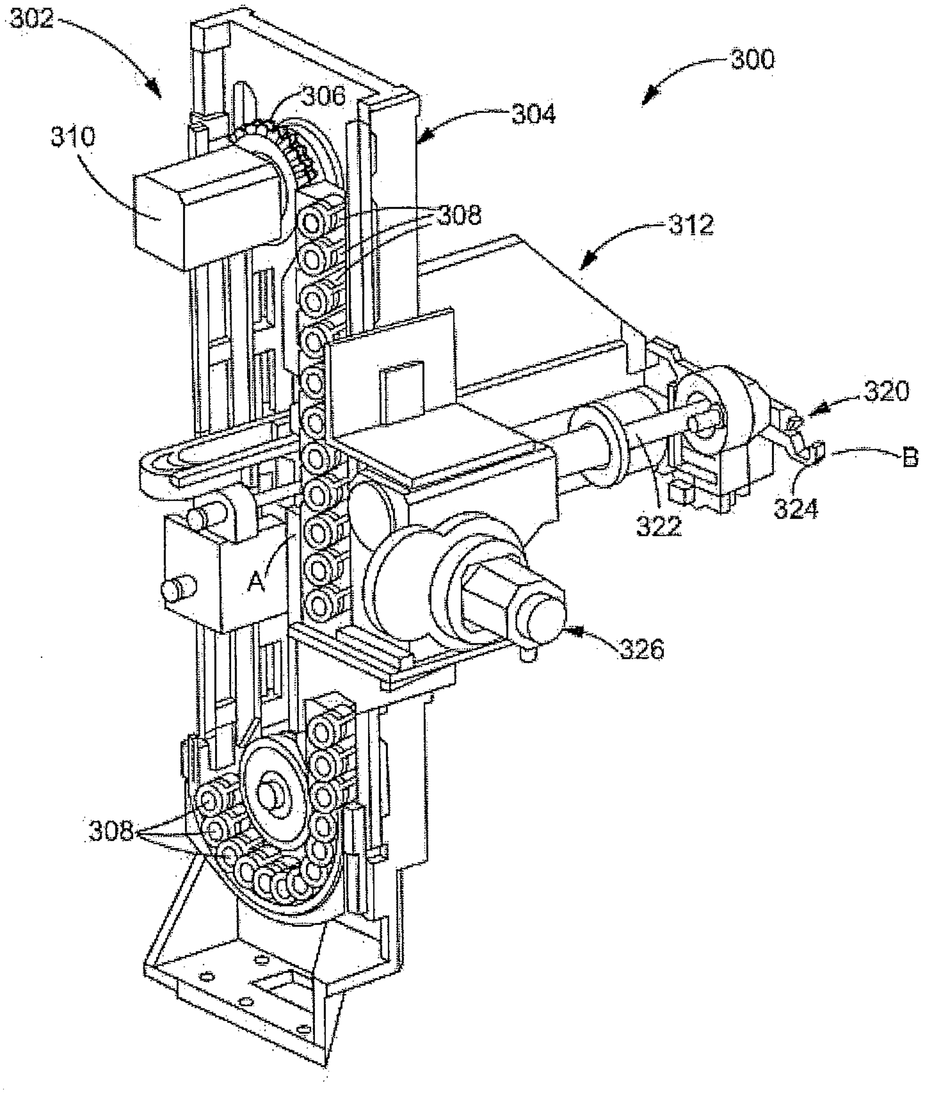


FIG. 11

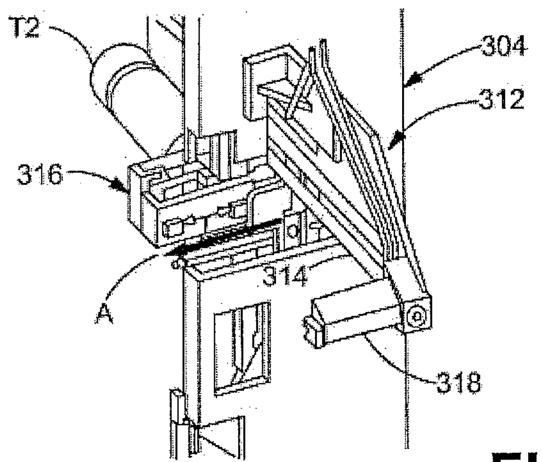


FIG. 12(a)

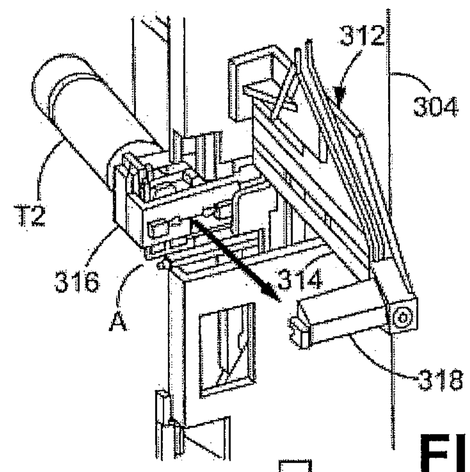


FIG. 12(b)

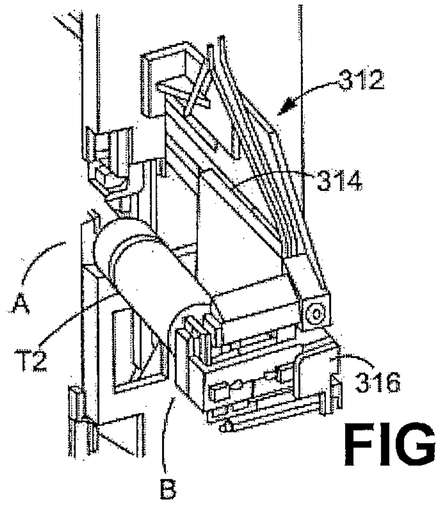


FIG. 12(c)

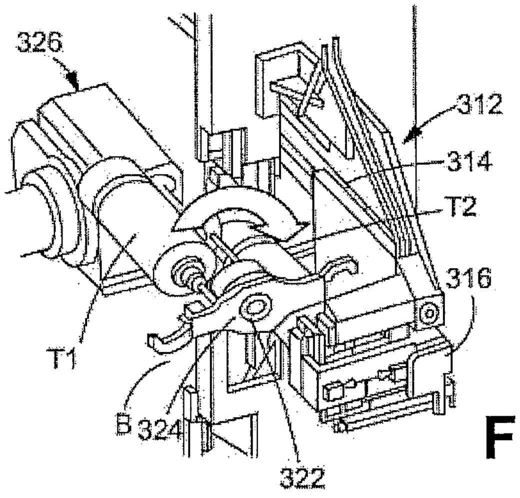


FIG. 12(d)

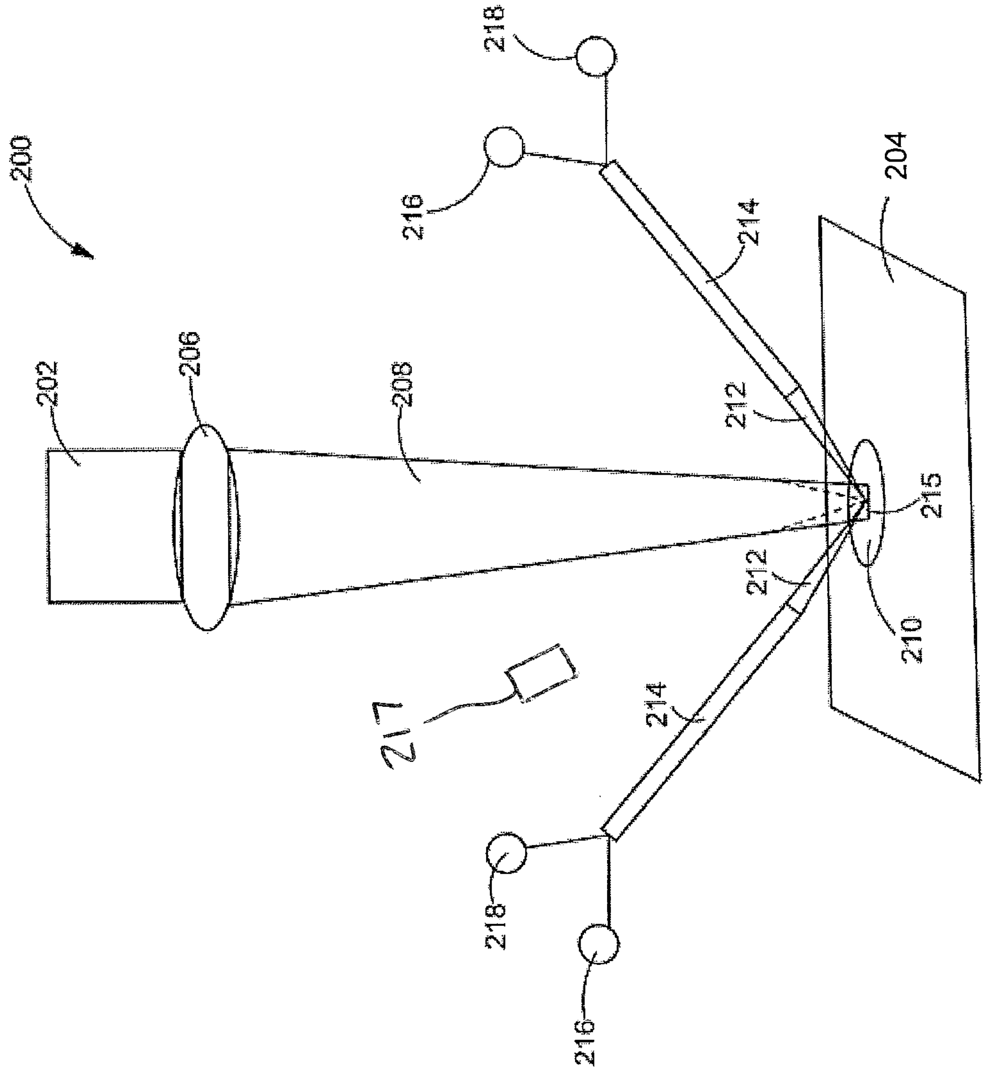


FIG. 13

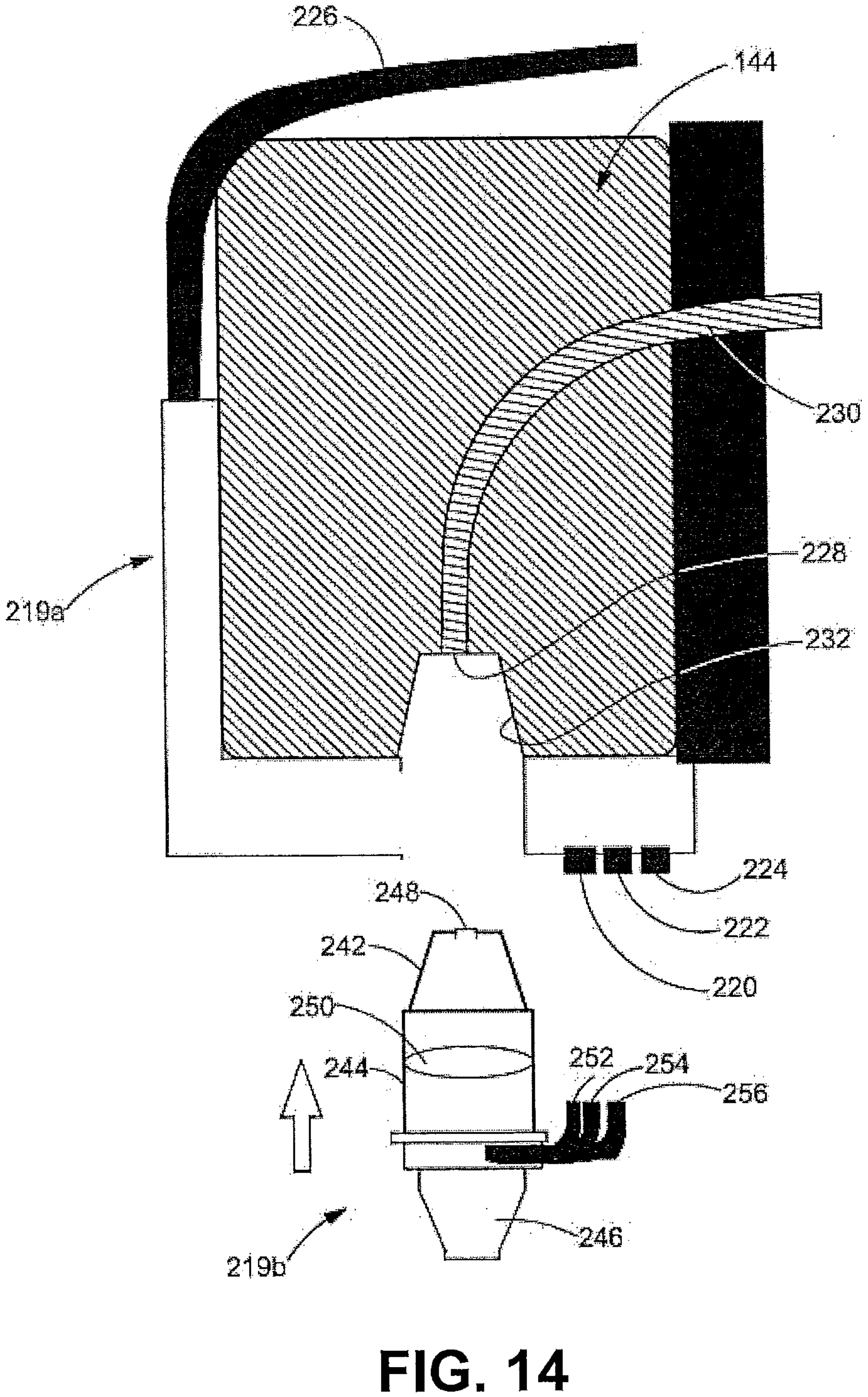

226
144
230
228
232
219a
224
222
220
248
242
250
244
252
254
256
246
219b

FIG. 14

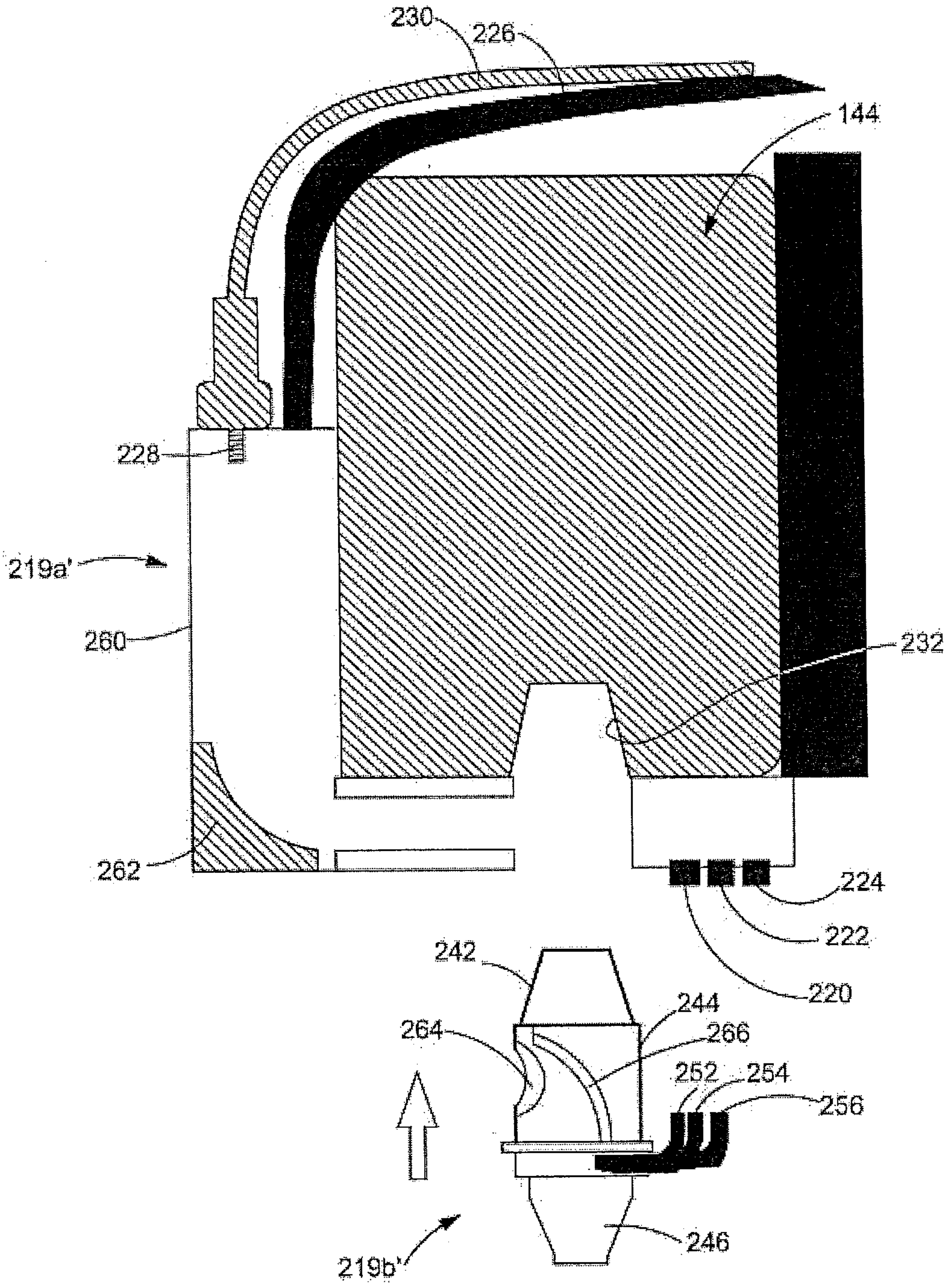

230
226
144
228
219a'
260
232
262
224
222
220
242
244
264
266
252
254
256
246
219b'

FIG. 15

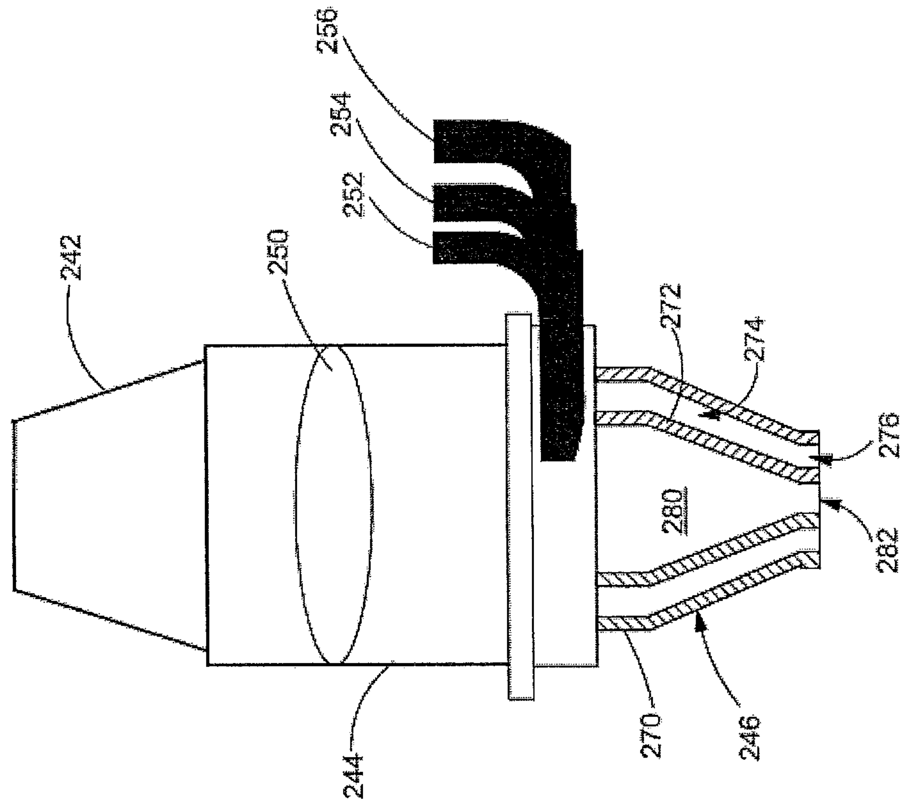


FIG. 16

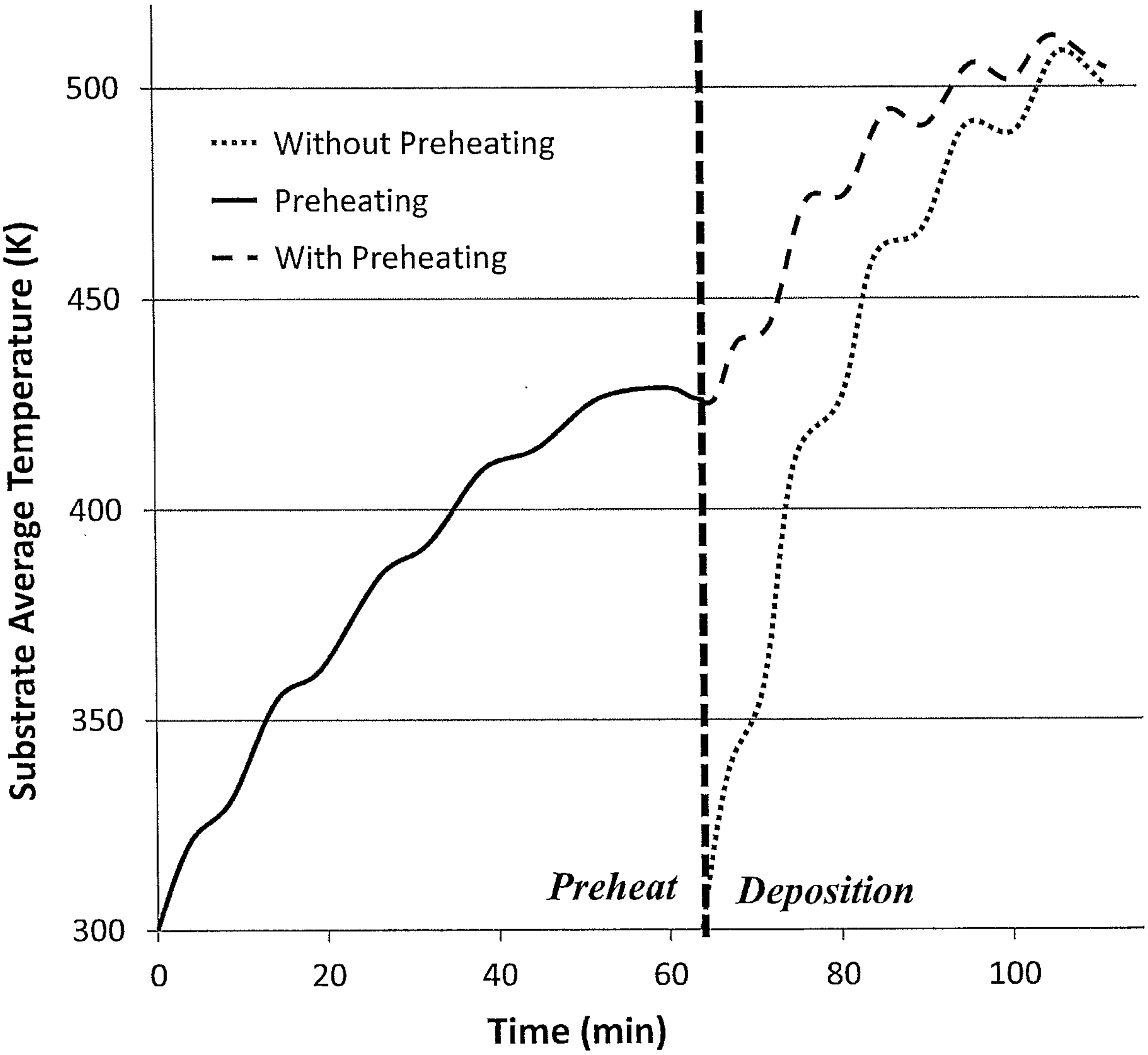

Without Preheating
Preheating
With Preheating
Substrate Average Temperature (K)
300
350
400
450
500
Preheat
Deposition
0
20
40
60
80
100
Time (min)

FIG. 17

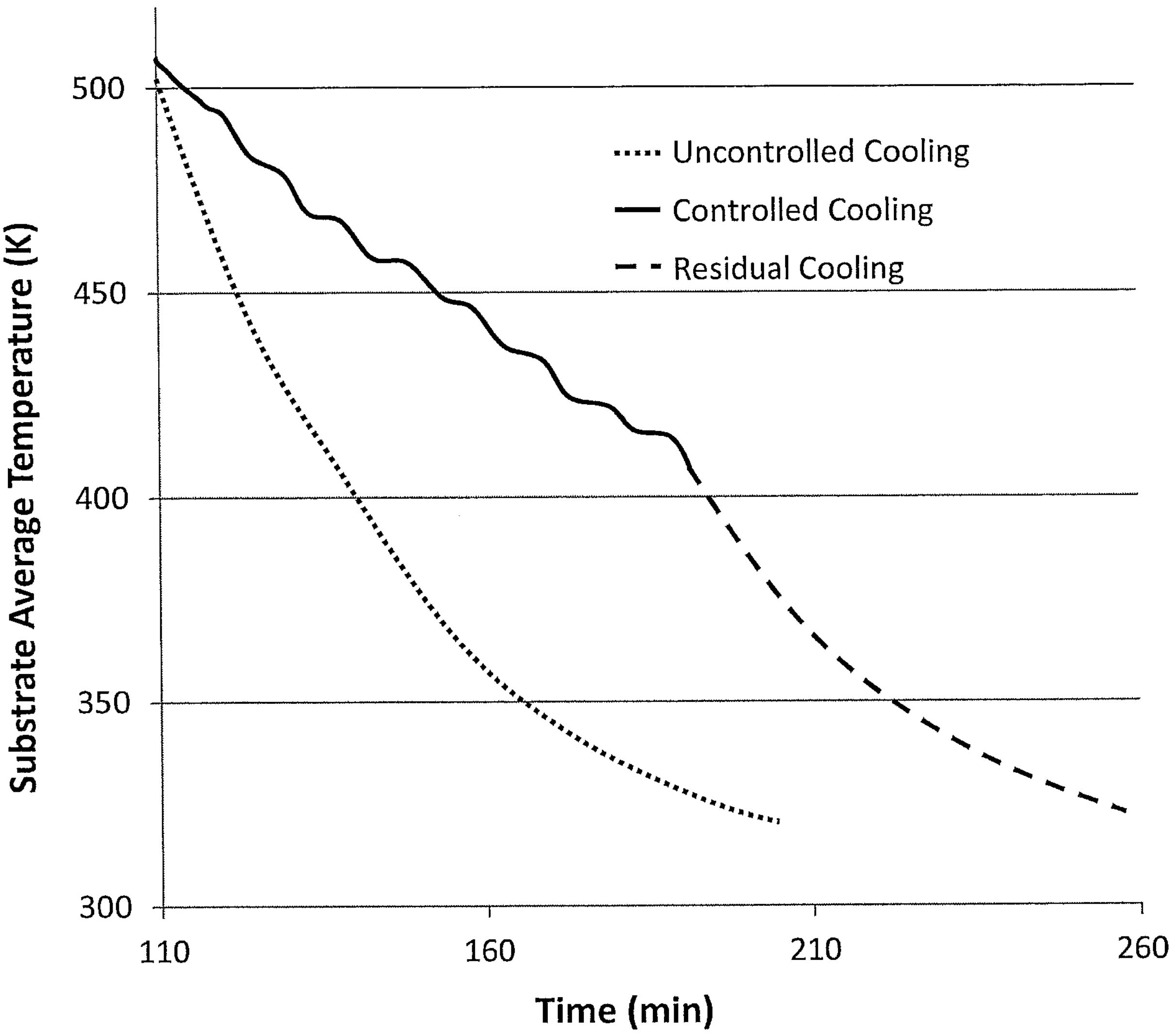

Substrate Average Temperature (K)
500
450
400
350
300
110
160
210
260
Time (min)
Uncontrolled Cooling
Controlled Cooling
Residual Cooling

Fig. 18

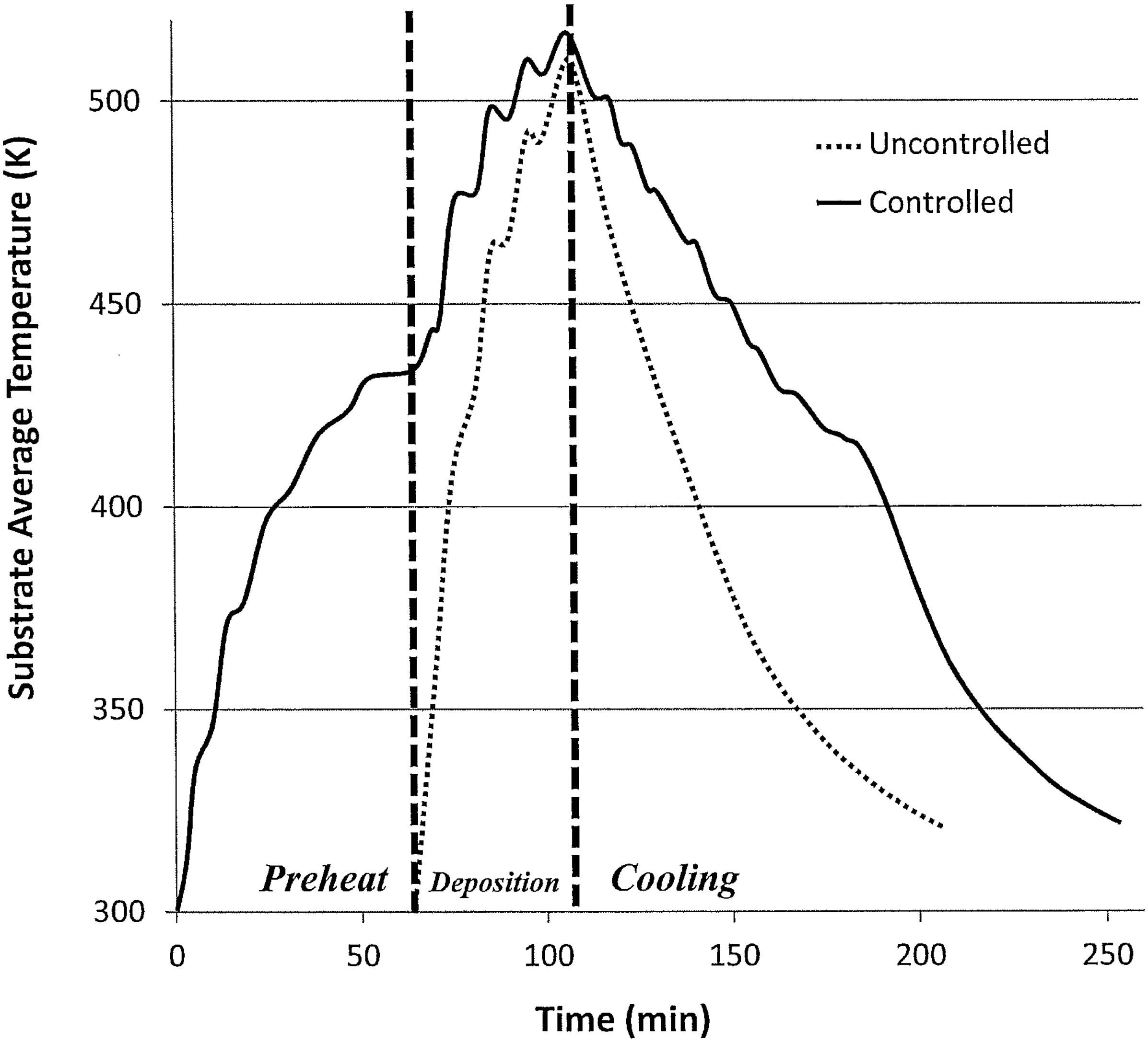

Substrate Average Temperature (K)
300
350
400
450
500
Time (min)
0
50
100
150
200
250
Uncontrolled
Controlled
Preheat
Deposition
Cooling

FIG. 19

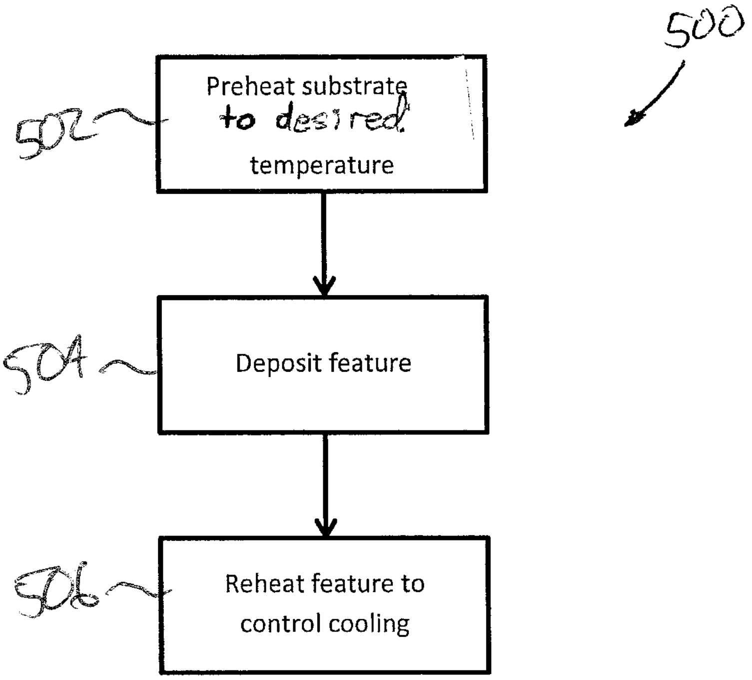
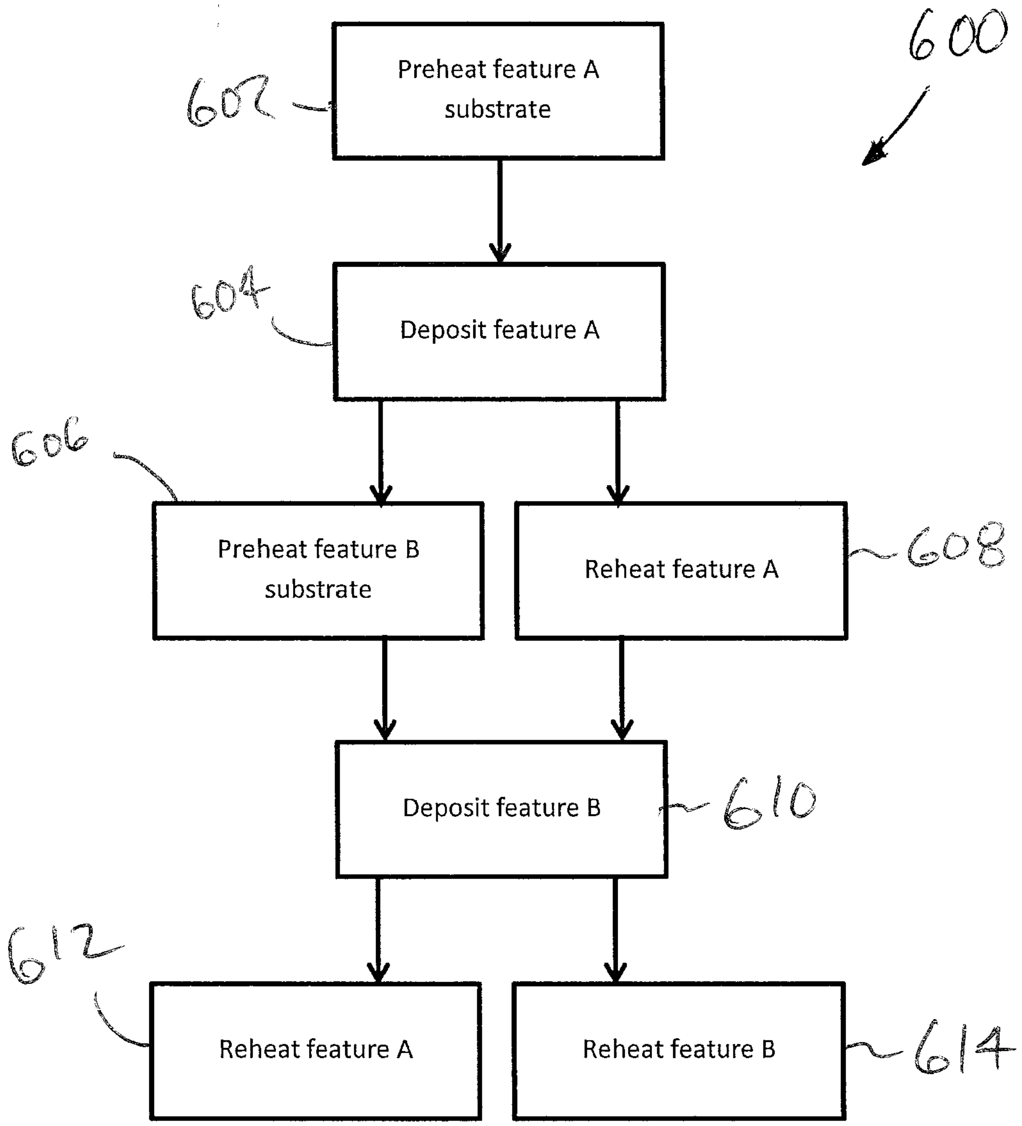

500
502
Preheat substrate to desired temperature
504
Deposit feature
506
Reheat feature to control cooling

FIG. 20



600
602
Preheat feature A substrate
604
Deposit feature A
606
Preheat feature B substrate
Reheat feature A
608
Deposit feature B
610
612
Reheat feature A
Reheat feature B
614

FIG. 21

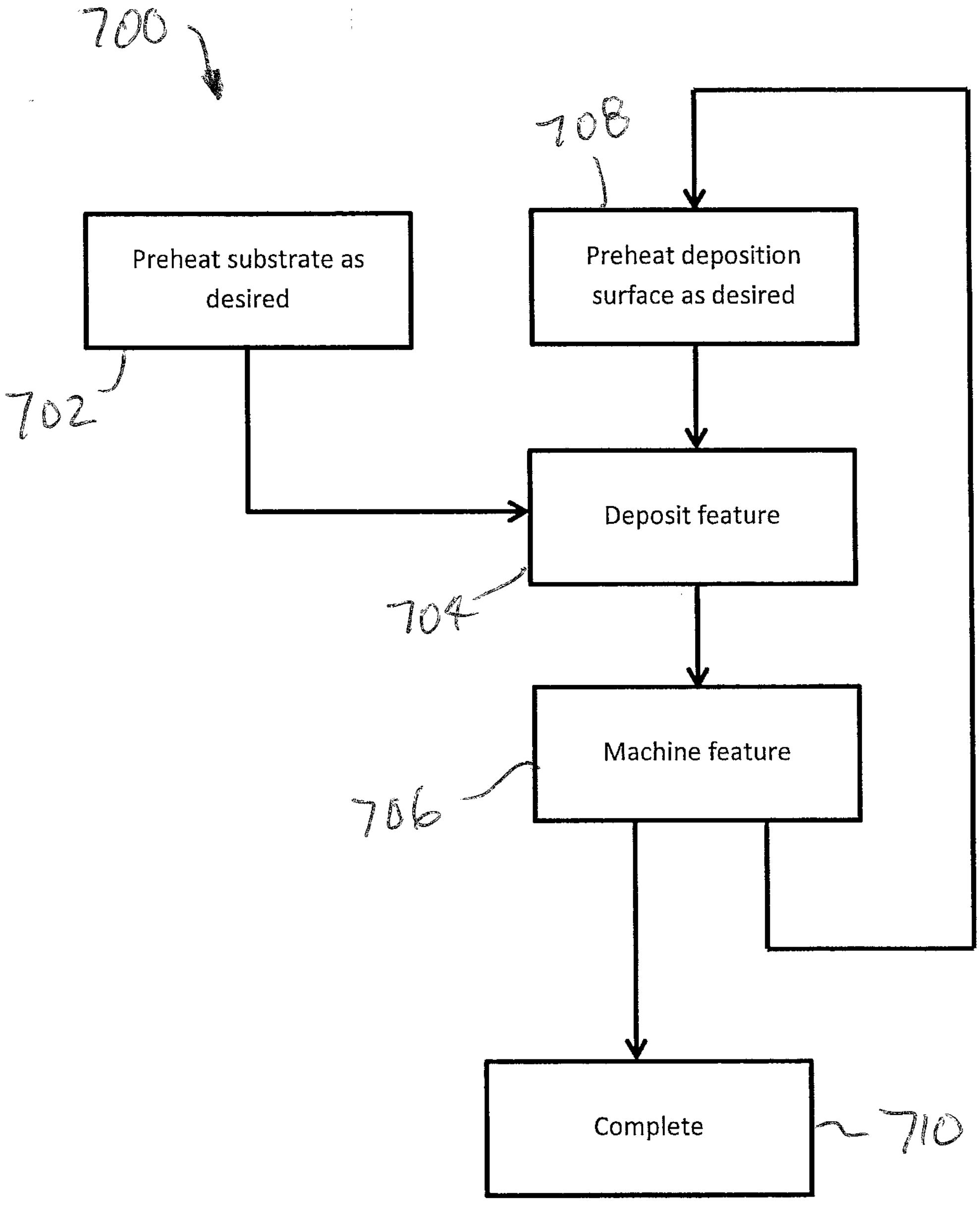

700
708
Preheat substrate as desired
Preheat deposition surface as desired
702
Deposit feature
704
Machine feature
706
Complete
710

FIG. 22

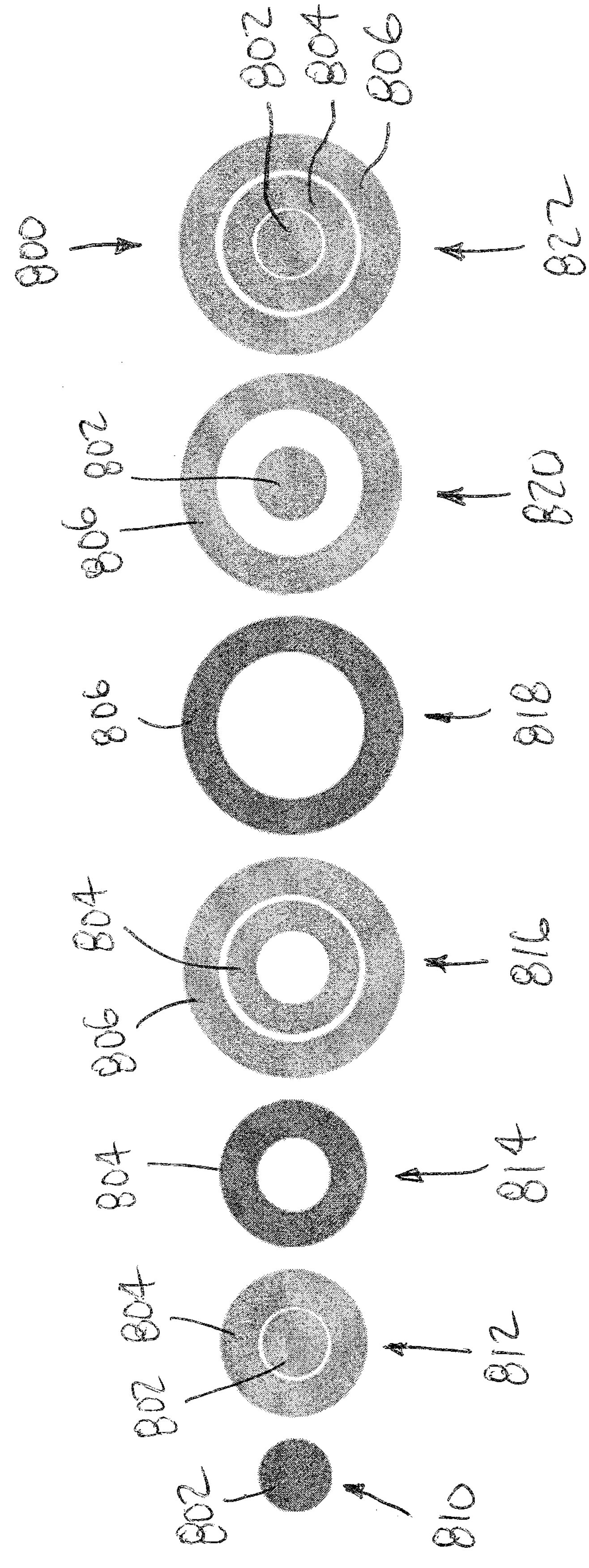

810
802
812
802
804
814
804
816
806
804
818
806
820
806
802
800
822
802
804
806

FIG. 23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB2017/000869

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. B22F3/105(2006.01)i, B22F3/16(2006.01)i, B33Y30/00(2015.01)i, B33Y40/00(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)

Int.Cl. B22F3/105, B22F3/16, B33Y30/00, B33Y40/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2017
Registered utility model specifications of Japan 1996-2017
Published registered utility model applications of Japan 1994-2017

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2012/0308781 A1 (PANASONIC CORPORATION) 2012.12.06, Claims, [0076]-[0078], Fig.1,3-5,14 & WO 2011/102382 A1	1-2,13,16-17
Y		3-7,9-12,19-20
A		8,14-15,18
Y	JP 2007-016312 A (HIROSHIMA INDUSTRIAL PROMOTION ORGANIZATION) 2007.01.25, Claims, [0031] (No Family)	3,19
Y	US 2012/0300799 A1 (HIGH Q LASER GMBH) 2012.11.29, Claims & WO 2011/101329 A2	4-7,9
Y	JP 2013-021079 A (SEIKO EPSON CORPORATION) 2013.01.31, [0040] (No Family)	10

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

* Special categories of cited documents:
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"E" earlier application or patent but published on or after the international filing date
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"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

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"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
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"&" document member of the same patent family

Date of the actual completion of the international search
21.09.2017

Date of mailing of the international search report
03.10.2017

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2012/102655 A1 (ARCAM AB) 2012.08.02, Claims & JP 2014-508668 A & US 2013/0300035 A1	11
Y	JP 2015-189035 A (CMET INC.) 2015.11.02, Claims (No Family)	12,20
A	EP 1600282 A1 (3D SYSTEMS, INC.) 2005.04.07, Claims, [0024]-[0036], FIG 5 & JP 2005-335392 A & US 2005/0263934 A1	1-20
A	US 2014/0348692 A1 (COMPAGNIE GENERALE DES ESTABLISSEMENTS MICHELIN) 2014.11.27, Claims, [0031], Fig.1 & WO 2013/092997 A1 & CN 104010749 A	1-20
A	WO 2008/013483 A1 (ARCAM AB) 2008.01.31, All pages & JP 2009-544501 A	1-20
A	US 2003/0206820 A1 (OPTOMEC DESIGN COMPANY) 2003.11.06, Claims, [0132], FIG.11 & WO 2001/002160 A1 & WO 2005/107981 A2	1-20
P,A	US 2017/0036299 A1 (TECHNOLOGY RESEARCH ASSOCIATION FOR FUTURE ADDITIVE MANUFACTURING) 2017.02.09, Claims & WO 2016/151740 A1	1-20
A	JP 2001-047520 A (TOYOTA JIDOSHA KABUSHIKI KAISHA) 2001.02.20, Claims, Fig. 1,3 (No Family)	14-15