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(71) Applicant: **DIVERGENT TECHNOLOGIES, INC.** [US/US]; 19601 Hamilton Avenue, Los Angeles, California 90502 (US).

(72) Inventors: **EL NAGA, Eahab Nagi**; 21119 Lighthill Drive, Topanga, California 90210 (US). **BUCKNELL, John Russell**; 701 Center Street, El Segundo, California 90245 (US). **YAP, Chor Yen**; 1655 Begonia Way, Gardena, California 90248 (US). **TENHOUTEN, Broc William**; 6501 Beachview Drive, Rancho Palos Verdes, California 90275 (US). **MARTINEZ, Antonio Bernerd**; 816 Maryland Street, El Segundo, California 90245 (US).

(74) Agent: **GELFOUND, Craig A.** et al.; c/o ARENT FOX LLP, 555 West Fifth St., 48th Floor, Los Angeles, California 90013 (US).

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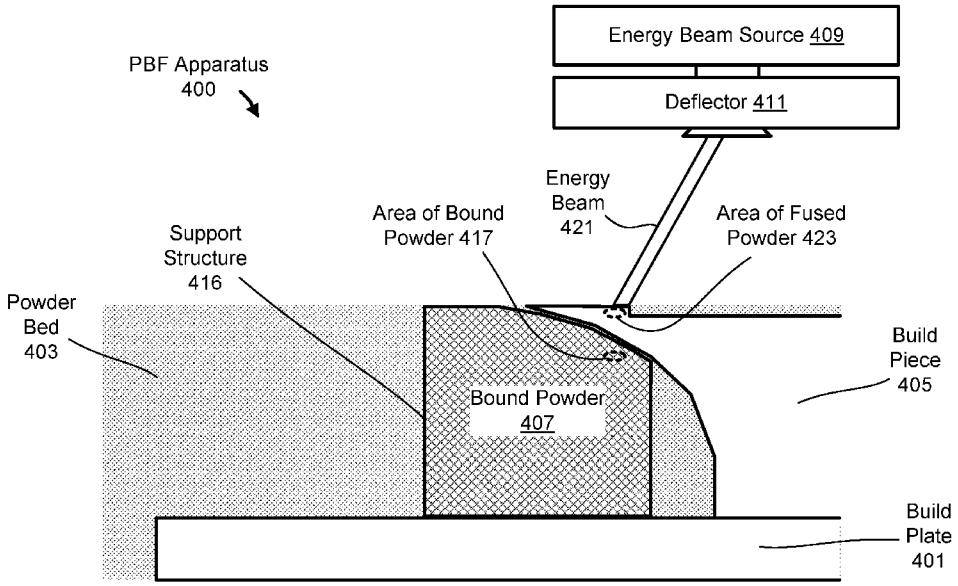


FIG. 4C

(57) Abstract: Systems and methods of support structures in powder-bed fusion (PBF) are provided. Support structures can be formed of bound powder, which can be, for example, compacted powder, compacted and sintered powder, powder with a binding agent applied, etc. Support structures can be formed of non-powder support material, such as a foam. Support structures can be formed to include resonant structures that can be removed by applying a resonance frequency. Support structures can be formed to include structures configured to melt when electrical current is applied for easy removal.

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SUPPORT STRUCTURES IN ADDITIVE MANUFACTURING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Patent Application No. 15/582,409, entitled "SUPPORT STRUCTURES IN ADDITIVE MANUFACTURING" and filed on April 28, 2017, which is expressly incorporated by reference herein in its entirety.

BACKGROUND

Field

[0002] The present disclosure relates generally to additive manufacturing, and more particularly, to support structures for additive manufacturing and removal of support structures from build pieces.

Background

[0003] Powder-bed fusion (PBF) systems can produce metal structures (referred to as build pieces) with geometrically complex shapes, including some shapes that are difficult or impossible to create with conventional manufacturing processes. PBF systems include additive manufacturing (AM) techniques to create build pieces layer-by-layer. Each layer or slice can be formed by a process of depositing a layer of metal powder and then fusing (e.g., melting and cooling) areas of the metal powder layer that coincide with the cross-section of the build piece in the layer. The process can be repeated to form the next slice of the build piece, and so on until the build piece is complete. Because each layer is deposited on top of the previous layer, PBF can be likened to forming a structure slice-by-slice from the ground up.

[0004] The shape of some build pieces in PBF can produce unwanted artifacts. These shapes include overhangs, or portions of the build piece formed by melting powder sections that reside over otherwise unfused powder. To mitigate the negative effects caused by these overhangs, support structures can be used. Conventional techniques for addressing overhangs with support structures, however, have significant drawbacks of their own that can substantially affect the quality of the resulting structures. These and other issues are addressed in the present disclosure.

SUMMARY

[0005] Several aspects of support structures and systems and methods for removal of support structures will be described more fully hereinafter.

[0006] In various aspects, an apparatus for powder-bed fusion can include a depositor that deposits multiple layers of a powder material, an energy beam source that generates an energy beam, a deflector that applies the energy beam to fuse the powder material in a first area in a first one of the layers, and a powder fixer that binds the powder material in a second area in a second one of the layers, the second area being underneath the first area.

[0007] In various aspects, an apparatus for powder-bed fusion can include a depositor that deposits multiple layers of a powder material, an energy beam that generates an energy beam, a deflector that applies the energy beam to fuse the powder material in a first area in a first one of the layers, and a support system that establishes support material, such as a foam, in a second area in a second one of the layers, the second area being underneath the first area.

[0008] In various aspects, a support structure to support a build piece formed in a powder-bed fusion system can include a base formed of fused powder in the powder bed underneath the build piece, and one or more extensions formed of fused powder extending from the base and configured to support the build piece.

[0009] In various embodiments, an apparatus for a powder-bed fusion system can include a support structure formed by the powder-bed fusion system, an electrical current source, a connection that connects the electrical current source to the support structure, and a controller that applies an electrical current from the electrical current source to the support structure through the connection.

[0010] In various embodiments, an apparatus for separating a support structure from a build piece of a powder-bed fusion system can include a vibrator that applies a resonant frequency to the support structure.

[0011] Other aspects will become readily apparent to those skilled in the art from the following detailed description, wherein is shown and described only several exemplary embodiments by way of illustration. As will be realized by those skilled in the art, concepts described herein are capable of other and different embodiments, and several details are capable of modification in various other respects, all without departing from the present disclosure. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Various aspects of the concepts described herein will now be presented in the detailed description by way of example, and not by way of limitation, in the accompanying drawings, wherein:

[0013] FIGS. 1A-D illustrate respective side views of an exemplary PBF system during different stages of operation.

[0014] FIG. 2 illustrates an exemplary drooping deformation in a PBF system.

[0015] FIG. 3 illustrates an exemplary embodiment of a bound-powder support structure.

[0016] FIGS. 4A-C illustrate an exemplary embodiment of a PBF apparatus for forming a support structure of bound powder.

[0017] FIG. 5 is a flowchart of an exemplary embodiment of a method of creating support structures of bound powder in a PBF apparatus.

[0018] FIG. 6 illustrates an exemplary embodiment of a configuration of a support structure.

[0019] FIG. 7 illustrates an exemplary embodiment of a PBF apparatus and method for compacting the powder with a mechanical roller.

[0020] FIG. 8 illustrates an exemplary embodiment of a PBF apparatus and method for compacting powder with a mechanical press.

[0021] FIG. 9 illustrates an exemplary embodiment of a PBF apparatus and method for sintering compacted powder.

[0022] FIG. 10 illustrates an exemplary embodiment of a PBF apparatus and method for applying a binding agent to the powder.

[0023] FIGS. 11A-C illustrate an exemplary embodiment of a PBF apparatus and method for non-powder support structures.

[0024] FIGS. 12A-C illustrate another exemplary embodiment of a PBF apparatus and method for non-powder support structures.

[0025] FIG. 13 is a flowchart of an exemplary embodiment of a method of forming non-powder support structures in a PBF apparatus.

[0026] FIGS. 14A-B illustrate an exemplary embodiment of a PBF apparatus and method.

[0027] FIG.15 is a flowchart of an exemplary embodiment of a method of forming non-powder support structures in a PBF apparatus.

[0028] FIG. 16 illustrates an exemplary embodiment of an anchored support structure.

[0029] FIG. 17 illustrates an exemplary embodiment of a floating support structure.

[0030] FIG. 18 illustrates an exemplary embodiment of a support structure including resonant structures in a half-wave resonator configuration.

[0031] FIG. 19 illustrates an exemplary embodiment of a support structure including resonant structures in another half-wave resonator configuration.

[0032] FIG. 20 illustrates an exemplary embodiment of a support structure including resonant structures in a quarter-wave resonator configuration.

[0033] FIG. 21 illustrates an exemplary embodiment of a support structure.

[0034] FIG. 22 illustrates an exemplary embodiment of a system including a vibrator that can apply a resonant frequency for removing support structures.

[0035] FIG. 23 illustrates an exemplary embodiment of a support structure including portions configured to be melted by applying electrical current.

[0036] FIG. 24 illustrates an exemplary embodiment of an electrical current system for removing support structures.

[0037] FIG. 25 illustrates an exemplary embodiment of a support structure including portions configured to be excited by applying electrical current.

DETAILED DESCRIPTION

[0038] The detailed description set forth below in connection with the appended drawings is intended to provide a description of various exemplary embodiments of the concepts disclosed herein and is not intended to represent the only embodiments in which the disclosure may be practiced. The term "exemplary" used in this disclosure means "serving as an example, instance, or illustration," and should not necessarily be construed as preferred or advantageous over other embodiments presented in this disclosure. The detailed description includes specific details for the purpose of providing a thorough and complete disclosure that fully conveys the scope of the concepts to those skilled in the art. However, the disclosure may be practiced without these specific details. In some instances, well-known structures and components may be shown in block diagram form, or omitted entirely, in order to avoid obscuring the various concepts presented throughout this disclosure.

[0039] While this disclosure is generally directed to support structures for PBF systems, it will be appreciated that PBF systems may encompass a wide variety of AM techniques. Thus, the PBF process may include, among others, the following

printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). PBF fusing and sintering techniques may further include, for example, solid state sintering, liquid phase sintering, partial melting, full melting, chemical binding and other binding and sintering technologies. Still other PBF processes to which the principles of this disclosure are pertinent include those that are currently contemplated or under commercial development. While the specific details of each such process are omitted to avoid unduly obscuring key concepts of the disclosure, it will be appreciated that the claims are intended to encompass such techniques and related structures.

[0040] As discussed above, PBF systems can produce metal and polymer structures (referred to as build pieces) with geometrically complex shapes, including some shapes that are difficult or impossible to create with conventional manufacturing processes. PBF systems create build pieces layer-by-layer, i.e., slice-by-slice. Each slice can be formed by a process of depositing a layer of metal powder and fusing (e.g., melting and cooling) areas of the metal powder layer that coincide with the cross-section of the build piece in the slice. The process can be repeated to form the next slice of the build piece, and so on.

[0041] However, the shape of some build pieces can produce undesirable results in the finished piece. For example, some shapes include overhangs, which include portions of the build piece that are formed by melting powder on top of loose powder, i.e., powder that is not fused. A simple example of an overhang includes a common bowl, wherein a portion of the periphery of the bowl may be raised relative to a central portion of the bowl. In the context of AM, the raised portion of the bowl may be subject to the effects of gravity as well as thermal effects associated with temperature changes in the fusing process, which left unattended, may cause the raised portion to sag or otherwise deform.

[0042] In this regard, support structures can be used to mitigate or prevent problems associated with overhang areas. Described herein are various systems, apparatuses, and methods for creation of support structures in PBF systems and for removal of support structures from build pieces, as well as various novel configurations of support structures. In the context of AM and associated PBF techniques, support structures may be used to offset or otherwise mitigate the undesirable consequences of overhanging structures prone to deformation or other problems. Various

measures may be undertaken to remove the support material from the build piece after the build plate is rendered and solidified. Particularly in the context of complex geometrical structures, such an undertaking may present its own set of challenges.

[0043] As discussed in more detail below, some support structures can provide a mechanical link between the support plate (also referred to a build plate) and the build piece, stabilizing structures that are overhung relative to the main structure of the build piece. These types of support structures can be constructed, for example, much like the build piece itself, in that a plurality of layers of powder can be deposited in an area generally beneath and/or partially or fully surrounding an anticipated overhang, with each layer being fused to provide the requisite support for the overhang to be rendered in subsequent passes of the electron beam during ensuing print cycles. More specifically, pools of melted powder (i.e., melt pools) in a designated area can be established adjacent to prior sequential layers of melted and cooled powder, which can then collectively solidify together into a continuous structure. In some cases, this linking can be necessary due to the powder being an easily deformable solid. Because these types of support structures can be formed exclusively from melted powder, these support structures may be beneficial in cases in which it is desirable to prevent contamination of the powder by other materials, for example. Depending on the specific AM technique employed, the methods of forming mechanically linked layers may vary.

[0044] In some cases, instead of mechanical linking layers via fusing (e.g., melting and solidification), support structures may be formed by binding the powder. For example, mechanical compaction of the powder can be performed such that the compacted powder is sufficiently less deformable, and fused structures can be formed above the compacted powder. Thus the compacted powder can be described as being bound together. Compaction can be performed using a variety of methods including, for example, mechanical rolling, application of gas pressure, a mechanical press, etc. Because compacted-powder support structures can be formed exclusively of powder, these support structures may also be beneficial in cases in which it is desirable to prevent contamination of the powder by other materials, for example. In addition, support structures formed of compacted powder may be desirable in cases in which powder is recovered from the powder bed and reused because the compacted powder may be easily recyclable. In addition, compacted-

powder support structures can be easy to remove from build pieces, thus reducing the time and energy required to remove support structures and reducing the risk of damage to the build piece. In some cases, techniques using low levels of sintering can be performed to thermally heat and sinter the compacted area, which may provide a more stable support structure than mere compaction.

[0045] In some exemplary embodiments, a binding agent can be deposited in areas of powder to create a support structure. In some cases, the binding agent may be thermally crosslinked by energy beam heating. This binding agent can be placed by a print head that tracks across the powder bed behind the depositor, for example, depositing binding agent in regions under overhang areas of the build piece. Likewise, a binding agent can include a fluid or gel that can be deposited such that the powder is held to a sufficiently large degree to support the build piece (e.g., similar to wet sand being more bound together than dry sand). In some cases, the binding agent can include an adhesive agent, such as a resin.

[0046] In some exemplary embodiments described further below, the techniques of creating support structures by fusing, compacting, sintering, applying a binder, or other techniques described herein can be used to create support structures that can provide support by 'floating' the build piece above uncompacted powder. Creation of 'floating' support structures can allow less powder to be used to form the support structures, which may reduce build time, allow more powder to be recovered and reused, etc.

[0047] In other exemplary embodiments, support structures can be formed from materials other than the powder. For example, a support material, such as a dense foam, can be deposited in an area devoid of powder, and the deposited support material can form a support structure. In some cases, the support material may be deposited in a layer prior to, or concurrently with, the deposition of the layer of powder. For example, a separate support material depositor mechanism (*e.g.*, a separate or dedicated print head, automated constructor, computer-controlled robotic arm, etc.) can pass over the work area and deposit a layer of support material in the desired areas, then the powder depositor can pass over the work area and deposit the layer of powder in the remaining areas. In another example, an integrated print head may be capable of depositing either powder or support material as it passes over the work area, thus depositing specific material in specific locations.

[0048] In some examples, the powder depositor may deposit a layer of powder, and then a vacuum in the build chamber may remove powder from undesired areas. The newly-empty areas can then be filled with support material, such as foam or another space keeper. For example, the foam may be injected or placed as bricks / plates of a thickness configured to substantially conform to the thickness of the layer. While layer thickness may vary widely depending on the AM technique deployed, AM capabilities, etc. in one embodiment using selective layer sintering (SLS) the layer thickness ranges from approximately 0.060mm to 0.150 mm

[0049] In some cases, the support material can be deposited at a height greater than the height of the layer. For example, the entire support structure may be deposited at once at the beginning of the build. In this case, the powder depositor can be configured to deposit powder only in areas without support structures such that the depositor avoids the portions of the support structures above the layer currently being rendered. For example, the wiping/leveling system of the depositor can be configured to miss any areas that are built up with support material, until it is determined that the powder layer is at a level that is substantially even with or covers the support material.

[0050] In various embodiments, the support material can remain in the final part, or be dissolved away, for example.

[0051] Various exemplary embodiments disclosed herein are directed to novel configurations of support structures. In some embodiments, support structures can be configured to include resonant structures. Vibration of resonant support structures at its natural frequency may be sufficient to cause the support structure to break away from the 3-D build piece and/or the build plate, or, for instance, to substantially loosen the bond for a subsequent maneuver requiring less force. This breakage can be caused, for example, by the increased amplitude of the resonant oscillations of the applicable portion of the support structure inducing metal fatigue at the interface between the support structure and the build piece and/or build plate. Support structures can include a main body that contains an extrusion of fixed length, width and taper. The tapered ends of the extrusions can be connected to the 3-D build piece, the substrate plate, and/or to the support framework. In some cases, resonant support structures can include half-wave resonators, quarter-wave resonators, etc., which may allow metal fatigue to be induced more effectively.

[0052] After this stage of the AM operation is completed and the loose powders are removed, an excitation resonant frequency can be applied via mechanical conduction directly or indirectly through a medium to the build piece, the support structure, the build plate, etc. Mechanical excitation can be generated, for example, by ultrasound transducers, piezoelectric transducers, micro electro-mechanical systems, etc. The transducer can be attached to the build piece, the support structure, the build plate, or another suitable location for enabling the relevant portion of the support structure to receive the mechanical input. As noted above, the induced vibration can cause the support structure to vibrate with increasing amplitude until the ends break off from the build piece and the build plate.

[0053] In various embodiments, further control of the support structure break-off can be achieved by a variant adaptation of this design with multiple resonant nodes. For instance, support extrusions of different lengths, widths, and/or tapers may be applied to different areas of the build piece. This can allow for the selective removal of supports by applying different excitation frequencies. A medium could also be used for complete or partial immersion of the build piece to speed the break-off process. Sound waves and heating may also be used to drive the break-off process.

[0054] In various embodiments, electric current can be used to remove the supports. For example, the support structure can be formed such that an interface (e.g., contact points) between the support structure and the build piece can heat substantially when an electrical current is applied. For example, the contact points can be tapered such that the contact points provide a relatively high electrical resistance compared to the remaining portions of the support structure and build piece. An electrical current can be applied across the tapered contact points to heat and melt the contact points to remove the support structure from the build piece.

[0055] FIGS. 1A-D illustrate respective side views of an exemplary PBF system 100 during different stages of operation. As noted above, the particular embodiment illustrated in FIGS. 1A-D is one of many suitable examples of a PBF system employing principles of this disclosure. It should also be noted that elements of FIGS. 1A-D and the other figures in this disclosure are not necessarily drawn to scale, but may be drawn larger or smaller for the purpose of better illustration of concepts described herein. PBF system 100 can include a depositor 101 that can deposit each layer of metal powder, an energy beam source 103 that can generate an energy beam, a deflector 105 that can apply the energy beam to fuse the powder material, and a

build plate 107 that can support one or more build pieces, such as a build piece 109. PBF system 100 can also include a build floor 111 positioned within a powder bed receptacle. The walls of the powder bed receptacle 112 generally define the boundaries of the powder bed receptacle, which is sandwiched between the walls 112 from the side and abuts a portion of the build floor 112 below. Build floor 111 can progressively lower build plate 107 so that depositor 101 can deposit a next layer. The entire mechanism may reside in a chamber 113 that can enclose the other components, thereby protecting the equipment, enabling atmospheric and temperature regulation and mitigating contamination risks. Depositor 101 can include a hopper 115 that contains a powder 117, such as a metal powder, and a leveler 119 that can level the top of each layer of deposited powder.

[0056] Referring specifically to FIG. 1A, this figure shows PBF system 100 after a slice of build piece 109 has been fused, but before the next layer of powder has been deposited. In fact, FIG. 1A illustrates a time at which PBF system 100 has already deposited and fused slices in multiple layers, e.g., 150 layers, to form the current state of build piece 109, e.g., formed of 150 slices. The multiple layers already deposited have created a powder bed 121, which includes powder that was deposited but not fused.

[0057] FIG. 1B shows PBF system 100 at a stage in which build floor 111 can lower by a powder layer thickness 123. The lowering of build floor 111 causes build piece 109 and powder bed 121 to drop by powder layer thickness 123, so that the top of the build piece and powder bed are lower than the top of powder bed receptacle wall 112 by an amount equal to the powder layer thickness. In this way, for example, a space with a consistent thickness equal to powder layer thickness 123 can be created over the tops of build piece 109 and powder bed 121.

[0058] FIG. 1C shows PBF system 100 at a stage in which depositor 101 is positioned to deposit powder 117 in a space created over the top surfaces of build piece 109 and powder bed 121 and bounded by powder bed receptacle walls 112. In this example, depositor 101 progressively moves over the defined space while releasing powder 117 from hopper 115. Leveler 119 can level the released powder to form a powder layer 125 that has a thickness of substantially equal to the powder layer thickness 123 (*see* FIG. 1B). Thus, the powder in a PBF system can be supported by a powder material support structure, which can include, for example, a build plate 107, a build floor 111, a build piece 109, walls 112, and the like. It should be noted that the

illustrated thickness of powder layer 125 (i.e., powder layer thickness 123 (FIG. 1B)) is greater than an actual thickness used for the example involving 150 previously-deposited layers discussed above with reference to FIG. 1A.

[0059] FIG. 1D shows PBF system 100 at a stage in which, following the deposition of powder layer 125 (FIG. 1C), energy beam source 103 generates an energy beam 127 and deflector 105 applies the energy beam to fuse the next slice in build piece 109. In various exemplary embodiments, energy beam source 103 can be an electron beam source, in which case energy beam 127 constitutes an electron beam. Deflector 105 can include deflection plates that can generate an electric field or a magnetic field that selectively deflects the electron beam to cause the electron beam to scan across areas designated to be fused. In various embodiments, energy beam source 103 can be a laser, in which case energy beam 127 is a laser beam. Deflector 105 can include an optical system that uses reflection and/or refraction to manipulate the laser beam to scan selected areas to be fused.

[0060] In various embodiments, the deflector 105 can include one or more gimbals and actuators that can rotate and/or translate the energy beam source to position the energy beam. In various embodiments, energy beam source 103 and/or deflector 105 can modulate the energy beam, e.g., turn the energy beam on and off as the deflector scans so that the energy beam is applied only in the appropriate areas of the powder layer. For example, in various embodiments, the energy beam can be modulated by a digital signal processor (DSP).

[0061] As shown in FIG. 1D, much of the fusing of powder layer 125 occurs in areas of the powder layer that are on top of the previous slice, i.e., previously-fused powder. An example of such an area is the surface of build piece 109. The fusing of the powder layer in FIG. 1D is occurring over the previously fused layers characterizing the substance of build piece 109. However, in some areas of powder layer 125, fusing can occur on top of loose powder –namely, over powder that was not fused-inadvertently or otherwise. For example, if the slice area is bigger than the previous slice area, at least some of the slice area will be formed over loose powder. Applying the energy beam to melt an area of powder over loose powder can be problematic. Melted powder is liquefied and generally denser than loose powder. The melted powder can seep down into the loose powder causing drooping, curling, or other unwanted deformations in the build piece 109. Because loose powder can have low thermal conductivity, higher temperatures than expected can result when

fusing powder in overhang areas because the low thermal conductivity can reduce the ability for heat energy to conduct away from the fused powder during fusing. Higher temperatures in these areas result in higher residual stresses after cooling and, more often than not, a poor quality build piece. In some cases, dross formations can occur in overhang areas thereby resulting in undesired surface roughness or other quality problems.

[0062] FIG. 2 illustrates a side view of an exemplary drooping deformation in a PBF system that can result in overhang areas. FIG. 2 shows a build plate 201 and a powder bed 203. In powder bed 203 is an actual build piece 205. A model build piece 207 is illustrated by a dashed line for the purpose of comparison. In one embodiment, model build piece 207 includes data from the data model created in CAD for use as an input to the AM processor to render the build piece. Model build piece 207 shows the desired shape of the build piece. Actual build piece 205 overlaps model build piece 207 in most places, i.e., in places that have no deformation. Thus, in areas to the right of overhang boundary 210, the solid line characterizing the actual build piece 205 overlaps with the dashed line defined in the model build piece 207. However, a drooping deformation occurs in an overhang area 209. In this example, overhang area 209 is formed from multiple slices fused on top of one another. In this case, the deformation worsens as overhang area 209 extends from the bulk of actual build piece 205. As the actual build piece 205 in FIG. 2 illustrates, some build piece shapes can therefore require the use of support structures in order to mitigate or prevent deformations and other problems that can result in overhang areas.

[0063] It should be noted that some problems, such as deformations, higher residual stresses, etc., can occur in areas in which powder in one layer is fused near the edge of the slice in the layer below, even though the fusing does not occur directly over loose powder. For example, unexpectedly high temperatures can result when fusing powder near the edge of a slice below because there is less fused material below to conduct heat away. These problems can be particularly severe where the slices below form a sharp edge. In this regard, support structures may be used to mitigate or prevent deformations and other problems that can result in these areas near overhang areas as well. As used herein, the terms “overhang area” and the like are intended to include areas near overhang areas and over fused powder, such as described above in areas adjacent the fusing of powder near the edge of a slice

below, in areas where slices form sharp corners or edges, and similar areas that can potentially result in the above-described array of unwanted overhang artifacts in the subject build piece.

[0064] FIGS. 3, 4A-C, and 5-10 illustrate example systems, methods, and configurations for bound powder support structures, in which particles of loose powder can be bound (e.g., with a binding agent, by compacting the loose powder, etc.) to provide a support structure. FIGS. 11A-C, 12A-C, 13, 14A-B, and 15 illustrate example systems and methods for support structures using materials other than powder, for example, a foam that can be deposited in areas void of powder, pre-formed support structures that can be positioned before powder is deposited, etc. FIGS. 16-25 illustrate example configurations for fused powder support structures and example systems and methods for removal of support structures.

[0065] FIG. 3 illustrates a side view of an exemplary embodiment of a bound-powder support structure 300. FIG. 3 shows a build plate 301 and a powder bed 303. In powder bed 303 is a build piece 305 that includes an overhang area 307. In powder bed 303, under the portion of build piece 305 in overhang area 307, there is a region of bound powder 309. As described above, bound powder can be, for example, compacted powder, partially sintered powder, powder with a binding agent applied, etc. Bound powder 309 can form support structure 300 that supports the portion of build piece 305 in overhang area 307. In this way, for example, support structure 311 formed of bound powder 309 mitigates or prevents deformations and other unwanted artifacts of build piece 305.

[0066] Bound powder can be formed in various ways. In various embodiments, bound powder can be formed by compacting loose powder by, for example applying pressure on the surface of the loose powder. In this way, loose powder can be compacted, or bound, together. Because compacted powder has a greater density than that of loose powder, it is not surprising that compacted powder represents an improvement as a support mechanism for overhanging build pieces.

[0067] In various embodiments, compacted powder can be sintered to further increase the binding of the powder. Additionally, a binding agent can be applied to bind loose powder. For example, a liquid or gel may be applied to increase the cohesiveness of loose powder. In some examples, the binding agent can include an adhesive to further increase the cohesiveness.

[0068] FIGS. 4A-C illustrate respective side views of an exemplary embodiment of a PBF apparatus 400 for forming a support structure of bound powder, such as support structure 300 (FIG. 3). FIGS. 4A-C show a build plate 401 and a powder bed 403. In powder bed 403 is a build piece 405 and bound powder 407. PBF apparatus 400 can include an energy beam source 409, a deflector 411, and a depositor 413. PBF apparatus 400 can also include a powder fixer 415.

[0069] FIG. 4A shows an example operation of PBF apparatus 400 to form bound powder 407 within a work area generally characterized by powder bed 403. Depositor 413 can move across the work area to deposit a layer of powder. Powder fixer 415 can move across the work area following depositor 413 (see the bolded arrows designated rightward motion of the components) and bind powder in an area of the layer deposited by the depositor to create bound powder 407, which can form a support structure 416. In this regard, bound powder 407 can be built up in slices similar to the fusing of slices to form build piece 405, except that instead of fusing the powder, powder fixer 415 binds the powder. In various embodiments, powder fixer 415 can bind the powder by, for example, compacting the powder, sintering the compacted powder, applying a binding agent to the powder, and related techniques, as will be discussed in further detail below.

[0070] FIG. 4B shows a state of PBF apparatus 400 after bound powder 407 has been formed under an overhang area of build piece 405. FIG. 4B shows a state in which powder fixer 415 has moved across the work area and has finished binding bound powder 407 in the current layer. As can be seen in FIG. 4B, there is an area of bound powder 417 underneath an area of powder to be fused 419.

[0071] FIG. 4C shows a state of PBF apparatus 400 in which a layer of powder is being fused. Energy beam source 409 creates an energy beam 421, and deflector 411 applies the energy beam to an area of powder deposited by depositor 413. In this regard, energy beam 421 is applied to area of powder to be fused 419 to create an area of fused powder 423. Area of fused powder 423 is above area of bound powder 417. As is evident from the shape of build piece 405, the problems associated with drooping, gravity, temperature fluctuations and other anomalies are substantially eliminated by virtue of support structure 416 enclosing bound powder 407.

[0072] FIG. 5 is a flowchart of an exemplary embodiment of a method of creating support structures of bound powder in a PBF apparatus. A PBF apparatus can deposit (501) a first layer of powder material and can bind (502) powder material in an area of the

first layer. The PBF apparatus can deposit (503) a second layer of powder material above the first layer. The PBF apparatus can generate (504) an energy beam and can apply (505) the energy beam to fuse powder material in an area of the second layer above the bound powder material in the first layer. For example, in FIG. 4C, energy beam 421 is applied to the layer of powder to fuse area of fused powder 423, which is over area of bound powder 417.

[0073] FIG. 6 illustrates a side view of an exemplary embodiment of a configuration of a support structure 600 in an overhang area 607 of powder bed 603. FIG. 6 shows a build plate 601, the powder bed 603, and a build piece 605. A portion of build piece 605 can be in an overhang area 607. In this example, support structure 600 can be formed of a region of bound powder 609. In this configuration, support structure 600 does not extend down to build plate 601. Furthermore, in this configuration support structure 600 does not form an attachment to build piece 605 (in contrast to other exemplary embodiments, e.g., FIG. 16 described below, in which the support structure is attached, or 'anchored,' to a portion of the build piece that is not in an overhang area). Thus, support structure 600 is supported solely by loose powder. However, support structure 600 can support build piece 605 because, as discussed above, the support structure can 'float' on loose powder in powder bed 603. More specifically, bound powder 609 can be formed to cover wider area than overhang area 607, such that deformation forces in the downward direction acting on build piece 605 can be distributed to a greater area of loose powder. In this way, the force can be distributed in such a way that the loose powder underneath support structure 600 can provide an adequately non-deformable link between the support structure 600 and build plate 601. Therefore, support structure 600 can effectively support portions of build piece 605 in overhang area 607 even though the support structure does not extend all of the way to build plate 601. In the configuration of FIG. 6, for example, an area of fused powder 611 is above an area of bound powder 613, which is above an area of not-fused and not-bound powder 615.

[0074] Support structures that are supported solely by loose powder can be referred to as floating support structures. It should be noted that floating support structures such as the example shown in FIG. 6 can be formed using various techniques, e.g., formed using bound powder techniques such as compacting, compacting and sintering, applying a binder, etc., and/or formed using non-powder support materials (described in more detail below). Floating support structures can allow less powder

to be used to form the support structures, which among other benefits, reduces build time and allows more powder to be recovered and reused. These factors collectively result in cost savings, manufacturing efficiency, and potential time to market advantages.

[0075] In addition, floating support structures may allow additional build pieces to be built more efficiently during a single PBF AM run. For example, additional build pieces may be built in the spaces of loose powder below anchored support structures, i.e., in the spaces in which other support structures would ordinarily extend through to reach down to the build plate. In another exemplary embodiment involving a bound powder region 609 having a comparatively large area 613, a second adjacent component (not shown) may be constructed adjacent build piece 605 using an opposite side of bound powder region 609 as a support structure for overhang support. These exemplary embodiments potentially allow for a much greater ability to render more types of build pieces in a comparatively shorter time.

[0076] FIGS. 7 and 8 are side views illustrating exemplary embodiments of PBF systems and methods for bound-powder support structures in which binding the powder includes compacting the powder. These types of support structures can be referred to as compacted-powder support structures. For example, mechanical compaction of the powder can be performed such that the compacted powder is sufficiently less deformable, and fused structures can be formed above the compacted powder. Thus the compacted powder is effectively bound together. Because compacted-powder support structures can be formed exclusively of powder, these support structures may also be beneficial in cases in which it is desirable to prevent contamination of the powder by other materials, for example. In addition, support structures formed of compacted powder may be desirable in cases in which powder is recovered from the powder bed and reused because the compacted powder may be easily recovered and reused. Further, compacted-powder support structures are comparatively easier to remove from build pieces, thus reducing the time and energy required to remove support structures. These benefits may likewise result in reduced cost and increased efficiency and capacity on the factory floor.

[0077] It should be noted that by compacting the powder, the top surface of the compacted powder may be lower than the top surface of the non-compacted powder in the layer. However, in various embodiments, the next layer of powder deposited by the powder depositor can fill in the extra space such that the top surface of the next

powder layer is level (*see*, e.g., bound powder 707 compared with powder bed 73 in FIG. 7). In this case, the level of the top surface of a support structure formed of compacted powder may not differ from the level of the top surface of the powder bed by more than a small amount.

[0078] FIG. 7 illustrates an exemplary embodiment of a PBF apparatus 700 and method in which binding the powder includes compacting the powder with a mechanical roller. FIG. 7 shows a build plate 701 and a powder bed 703. In powder bed 703 is a build piece 705 and bound powder 707. PBF apparatus 700 can include an energy beam source 709, a deflector 711, and a depositor 713. PBF apparatus 700 can also include a mechanical roller 715 that can operate as a powder fixer, such as powder fixer 415 (*see* FIGS. 4A-B), by compacting the powder.

[0079] Depositor 713 can move across the work area to deposit a layer of powder. Mechanical roller 715 can move across the work area following depositor 713 in sequence with depositor 713 (see rightmost arrows). To this end, mechanical roller 715 can be lowered in an area of the layer deposited by the depositor 713 to roll over the area, thus compacting the powder in the area to create bound powder 707, which can form a support structure 717. In this regard, bound powder 707 can be built up in slices similar to the fusing of slices to form build piece 705, except that instead of fusing the powder, mechanical roller 715 compacts the powder.

[0080] FIG. 8 illustrates an exemplary embodiment of a PBF apparatus 800 and method in which binding the powder includes compacting the powder with a mechanical press. FIG. 8 shows a build plate 801 and a powder bed 803. In powder bed 803 is a build piece 805 and bound powder 807. PBF apparatus 800 can include an energy beam source 809, a deflector 811, and a depositor 813. PBF apparatus 800 can also include a mechanical press 815 that can operate as a powder fixer, such as powder fixer 415 (*see* FIGS. 4A-B), by compacting the powder.

[0081] Depositor 813 can move across the work area to deposit a layer of powder. Likewise, mechanical press 815 can move across the work area following depositor 813 (as designated by the bolded arrow). In some instances depending on the input requirements to the AM device as determined, e.g., by the code received from the slicer program, mechanical press 815 may be lock step with depositor 813 except for its variations in vertical motion and can be lowered in an area of the layer deposited by the depositor to apply pressure on the area, thus compacting the powder in the area to create bound powder 807, which in turn can form a support structure 817. In

this regard, bound powder 807 can be built up in slices similar to the fusing of slices to form build piece 805, except that instead of fusing the powder, mechanical press 815 compacts the powder.

[0082] In various embodiments, compaction can be performed by any method for applying pressure to the powder bed, for example, a nozzle blowing gas, an expanding balloon membrane, and a variety of chemical reactions, among other techniques.

[0083] FIG. 9 illustrates a side view of an exemplary embodiment of a PBF apparatus 900 and method in which binding the powder further includes sintering compacted powder with a heater. FIG. 9 shows a build plate 901 and a powder bed 903. In powder bed 903 is a build piece 905 and bound powder 907. PBF apparatus 900 can include an energy beam source 909, a deflector 911, and a depositor 913. PBF apparatus 900 can also include a heater press 915 that can operate to compact the powder and to further bind compacted powder by sintering the compacted powder. Although the example of FIG. 9 shows an integrated heater and press, it should be understood that a separate heater could be used to sinter powder that has been previously compacted by methods such as those described above with reference to FIGS. 7 and 8, for example.

[0084] Depositor 913 can move across the work area to deposit a layer of powder. Heater press 915 can move across the work area following depositor 913, as shown in prior embodiments and conceptually illustrated by the arrows, and can be lowered in an area of the layer deposited by the depositor to apply pressure on the area, thus compacting the powder in the area, and to heat the area of compacted powder to sinter the compacted powder, to create bound powder 907, which can form a support structure 917.

[0085] In some cases, techniques using low levels of sintering can be performed to thermally heat and sinter the compacted area. While this configuration may provide a more stable support structure, in some instances it may be more difficult to remove from the build piece due to the strength of its bond. Reusability may also be reduced since the materials have been exposed to sintering, albeit at comparatively low levels. These potential benefits and risks can be assessed to make an informed judgment about the appropriate process to employ for a given project involving PBF AM techniques.

[0086] FIG. 10 illustrates a side view of an exemplary embodiment of a PBF apparatus 1000 and method in which binding the powder includes applying a binding agent to

the powder. FIG. 10 shows a build plate 1001 and a powder bed 1003. In powder bed 1003 is a build piece 1005 and bound powder 1007. PBF apparatus 1000 can include an energy beam source 1009, a deflector 1011, and a depositor 1013. PBF apparatus 1000 can also include an applicator 1014 that can operate as a powder fixer, such as powder fixer 415, by applying a binding agent to the powder.

[0087] Depositor 1013 can move across the work area to deposit a layer of powder. Here again, applicator 1014 can move across the work area following depositor 1013 and can apply a binding agent 1015 with a nozzle 1016 in an area of the layer deposited by the depositor to apply pressure on the area, thus binding the powder in the area to create bound powder 1007, which can form a support structure 1017. In this regard, bound powder 1007 can be built up in slices similar to the fusing of slices to form build piece 1005, except that instead of fusing the powder, applicator 1014 binds the powder with a binding agent.

[0088] In various embodiments, the binding agent may include a fluid or gel that can be deposited such that the powder is held to a sufficiently large degree to support the build piece (e.g., similar to wet sand being more bound together than dry sand). In various embodiments, the binding agent can include an adhesive agent, such as a resin. In some cases, the binding agent may include a material that can be thermally crosslinked by energy beam heating. In various embodiments, the binding agent could be applied by a print head that tracks across the powder bed behind the depositor 1013.

[0089] FIGS. 11A-C, 12A-C, 13, 14A-B, and 15 will now be described. These figures illustrate exemplary embodiments of systems and methods for support structures using materials other than powder, which can be referred to as non-powder support structures. Some examples of non-powder support structures include pre-formed support structures of various materials (e.g., metal, ceramic, etc.) that can be positioned before powder is deposited. Other examples of non-powder support structures can include high-density foams, fast-hardening gels, etc., that can be injected into areas devoid of powder before, during, or after powder is deposited, as explained in more detail below.

[0090] FIGS. 11A-C, 12A-C, and 13 illustrate exemplary embodiments of systems and methods for non-powder support structures in which non-powder support material can be formed in an area of a layer and powder can be deposited in the remaining area of the layer.

[0091] FIGS. 11A-C illustrate an exemplary embodiment of a system and method in which non-powder support material can first be established in an area of a layer, and then powder can be deposited in the remaining area of the layer. For example, a separate support material depositor can pass over the work area and deposit a layer of support material in the desired areas, then the powder depositor can pass over the work area and deposit the layer of powder in the remaining areas.

[0092] FIGS. 11A-C illustrate an exemplary PBF apparatus 1100 for forming a support structure of support material that does not include powder. FIGS. 11A-C show a build plate 1101 and a powder bed 1103. In powder bed 1103 is a build piece 1105 and support material 1107. PBF apparatus 1100 can include an energy beam source 1109, a deflector 1111, and a depositor 1113. PBF apparatus 1100 can also include a support system 1115.

[0093] FIG. 11A shows an exemplary operation of PBF apparatus 1100 to form support material 1107. Support system 1115 can move across the work area to deposit a layer of support material 1107 in an area of the layer, which can form a support structure 1117. Depositor 1113 can move across the work area following support system 1115 and deposit powder in a remaining area of the layer. However, in this embodiment depositor 1113 does not deposit support material 1107.

[0094] As shown in FIG. 11B, after the layer of support material 1107 has been formed, depositor 1113 can continue to move, thus crossing over the support material. In this example, depositor 1113 can continue to release powder, and the leveler of the depositor can sweep across the top surface of support material 1107 to clear the powder from the surface. In other embodiments, the depositor can interrupt the supply of powder as the depositor crosses over support material, for example.

[0095] FIG. 11C shows a state in which support system 1115 has moved across the work area and has finished depositing support material 1107 in the current layer. Depositor 1113 can continue to move across the work area and deposit powder in the remaining area that does not include support material 1107.

[0096] In various embodiments, the entire support structure may be deposited at once at the beginning of the build. For example, support system 1115 can include an automated robotic arm that can be programed to position entire pre-formed support structures at the proper locations on build plate 1101 prior to the depositing of the first layer of powder. In this case, the support material can be deposited at a height greater than the height of the powder layers, until enough powder layers have been deposited to

cover the support structure. Depositor 1113 can be configured to deposit powder only in areas without support structures such that the depositor avoids the portions of the support structures above the current layer. In various embodiments, the leveler of depositor 1113 can be configured to avoid areas that with support material protrude above the current layer of powder, until the powder layer is at a level that covers, or has reached the surface of, the support structure.

[0097] In an exemplary embodiment as noted above, the automated robotic arm is configured to place support structures at strategic locations on build plate 1101. In another exemplary embodiment, the robotic arm may be built in to the PBF apparatus and as such, can operate under control of the same processing and timing mechanisms and in synchronization with the other components for layering and placement, such as depositor 1113 and, where implemented, support system 1115.

[0098] FIGS. 12A-C illustrate an exemplary embodiment of a PBF apparatus 1200 and method for non-powder support structures in which non-powder support material and powder can be alternately deposited during a single pass over the work area defined substantially by the surface area of build plate 1201 or some subset thereof. FIGS. 12A-C show a build plate 1201 and a powder bed 1203. In powder bed 1203 is a build piece 1205 and support material 1207. PBF apparatus 1200 can include an energy beam source 1209, a deflector 1211, and a depositor 1213, each of which may function in a manner consistent with prior embodiments. PBF apparatus 1200 can also include a support system 1215 that is integrated with depositor 1213 as an integrated layer system 1216.

[0099] FIG. 12A shows an example operation of PBF apparatus 1200 to form support material 1207. Integrated layer system 1216 can move across the work area to deposit a layer of powder in designated areas in which powder should be deposited. Specifically, when integrated layer system 1216 is above an area that has been designated for the deposition of powder, depositor 1213 of the integrated layer system can release powder, and support system 1215 can interrupt the release of support material to enable application of the correct amount of powder at that point. Thus, in this configuration, integrated layer system 1216 acts to selectively apply powder to designated portions of the work area.

[00100] FIG. 12B shows an example operation when integrated layer system 1216 has traversed an area in which support material should be deposited. In this case, support system 1215 of integrated layer system 1216 can deposit support material

1207 in the area of the layer, which can form a support structure 1217. Specifically, when integrated layer system 1216 is above an area for support material, depositor 1213 of the integrated layer system interrupts the release of powder, and support system 1215 is concurrently or substantially immediately thereafter enabled to release support material.

[00101] FIG. 12C shows a state in which integrated layer system 1216 has moved across the area for support material and continues to deposit powder in the remaining area for powder.

[00102] Integrated layer system 1216, in sum, constitutes support system 1215 and depositor 1213 operating in a selective mode under software or dedicated hardware control to deposit a given material depending on the location of the system 1216 relative to the work area. However, this configuration is not intended to be limiting, as any number of equally suitable means to perform the identified functions may be contemplated by those skilled in the art upon perusal of the present disclosure.

[00103] FIG. 13 is a flowchart of an exemplary embodiment of a method of forming non-powder support structures in a PBF apparatus, such as in FIGS. 11A-C and 12A-C. A PBF apparatus can establish (1301) non-powder support material in an area of a first layer and can deposit (1302) powder material in the remaining area of the first layer. The PBF apparatus can deposit (1303) a second layer of powder material above the first layer. The PBF apparatus can generate (1304) an energy beam and can apply (1305) the energy beam to fuse powder material in an area of the second layer above the non-powder support material in the first layer.

[00104] FIGS. 14A-B and 15 illustrate exemplary embodiments of systems and methods for non-powder support structures in which powder can first be deposited over an entire layer, the powder in an area of the layer can be removed to form a void in the layer, and then non-powder support material can be established in the void area.

[00105] In some cases, the powder depositor may deposit a layer of powder, and then a vacuum in the build chamber may remove powder from areas that should be empty. The empty areas can then be filled with support material, such as foam or another space keeper. For example, the foam may be injected or placed as bricks / plates of a height configured to fit in the layer. Other mechanical-based powder removal means may be used.

[00106] FIGS. 14A-B illustrate an exemplary embodiment of a PBF apparatus 1400 and method. FIGS. 14A-B show a build plate 1401 and a powder bed 1403. In powder

bed 1403 is a build piece 1405 and support material 1407. PBF apparatus 1400 can include an energy beam source 1409, a deflector 1411, and a depositor 1413. PBF apparatus 1400 can also include a support system 1414 that can include a vacuum 1415 and a material nozzle 1416.

[00107] FIG. 14A shows an example operation of PBF apparatus 1400 in which depositor 1413 moves across the work area and deposits a layer of powder, and support system 1414 moves across the work area in sequence behind the depositor. Support system 1414 in this example is configured to remove powder deposits from designated portions of the work area using a vacuum mechanism and concurrently or immediately thereafter to deposit support material onto the designated portions. In FIG. 14A, support system 1414 is operational but is not activated to perform its functions due to its determined position over the work area. FIG. 14B shows an example of a later state in which support system 1414 passes above an area in which support material should be deposited. As support system 1414 passes above the area, vacuum 1415 can remove deposited powder via suctioning, and material nozzle 1416 can deposit support material 1407 in the area, which can form a support structure 1417.

[00108] In various embodiments, the support material can be deposited at a height greater than the height of the layer. For example, the entire support structure may be deposited at once at the beginning of the build. In this case, the powder depositor can be configured to deposit powder only in areas without support structures such that the depositor avoids the portions of the support structures above the current layer. For example, the wiping/leveling system of the depositor could be configured to miss any areas that are built up with support material, until, for example, the powder layer is at a level that covers the support material.

[00109] In various embodiments, the support material could remain in the final part, or be dissolved away, for example.

[00110] FIG.15 is a flowchart of an exemplary embodiment of a method of forming non-powder support structures in a PBF apparatus, such as in FIGS. 14A-B. A PBF apparatus can deposit (1501) a first layer of powder material. The PBF can then remove (1502) powder material in an area of the first layer and can establish (1503) non-powder support material in the area of removed powder. The PBF apparatus can then deposit (1504) a second layer of powder material above the first layer. The PBF apparatus can generate (1505) an energy beam and can apply (1506) the energy

beam to fuse powder material in an area of the second layer above the non-powder support material in the first layer.

[00111] FIGS. 16-25 illustrate example configurations for support structures and example systems and methods for removal of support structures. In these examples, fused-powder support structures will be described. As mentioned above, fused-powder support structures, i.e., support structures that can be formed exclusively of melted powder, may be beneficial in cases in which, for example, it is desirable to prevent contamination of the powder by other materials. However, it should be understood that the example configurations could be formed from other types of support structures, such as bound-powder support structures, non-powder support structures, etc.

[00112] FIG. 16 illustrates an example support structure 1600 that does not extend all of the way down to the build plate, and that is attached to a portion of the build piece outside of an overhang area. These types of support structures can be referred to as anchored support structures.

[00113] FIG. 16 shows a build plate 1601, a powder bed 1603, and a build piece 1605. The build piece 1605 is curved like an arch, thereby necessitating some modicum of support in an overhang area 1607. A portion of build piece 1605 can be in an overhang area 1607. Similar to floating support structures, support structure 1600 does not extend down to build plate 1601. However, in contrast to floating support structures, support structure 1600 forms an attachment to build piece 1605 at a portion of the build piece outside of overhang area 1607. In this configuration, the attachment is made in two attachment areas 1609, where the attachment can be seen to occur outside the overhang area 1607. Attachment areas 1609 can provide highly effective support using support structures to a variety of structural build pieces including, for example, build piece 1605. Support structure 1600 facilitates a supportive connection to sustain the structural integrity of build piece 1605. Support structure 1600 can effectively support portions of build piece 1605 in overhang area 1607 even though the support structure does not extend all of the way to build plate 1601. Similar to floating support structures, anchored support structures can result in an area of fused powder in the overhang area of the build piece that is above an area of bound powder, which is above an area of not-fused and not-bound powder. Integrity of the support may be facilitated by the strategic

placement of the support structures at attachment areas 1609 outside the overhang area.

[00114] Anchored support structures can share many of the same advantages as floating support structures. For example, anchored support structures can allow less powder to be used to form the support structures, which may reduce build time, allow more powder to be recovered and reused, etc., and may allow additional build pieces to be built more efficiently during a single PBF printing run. In addition, because of the added support provided by attachment to the build piece, anchored support structures may potentially be made smaller than a floating support structure, thus allowing a greater amount of loose powder to be used for other build pieces or recovered and reused.

[00115] FIG. 17 illustrates an example support structure 1700 that does not extend all of the way down to the build plate and also does not include attachment points to the build piece at locations outside of an overhang area. FIG. 17 shows a build plate 1701, a powder bed 1703, and a build piece 1705. A portion of build piece 1705 can be in an overhang area 1707. In this case, the entire build piece 1705 is in overhang area 1707. Support structure 1700 does not extend down to build plate 1701. However, support structure 1700 can support build piece 1705 because the support structure can 'float' on loose powder in powder bed 1703. As described above with respect to FIG. 6, bound powder 1709 can be formed to cover wider area than overhang area 1707, such that deformation forces in the downward direction from build piece 1705 can be distributed to a greater area of loose powder. In this way, the force can be distributed in such a way that the loose powder underneath support structure 1700 can provide an adequately non-deformable link between the support structure and build plate 1701. Therefore, support structure 1700 can effectively support portions of build piece 1705 in overhang area 1707 even though the support structure does not extend all of the way to build plate 1701. As in the example of FIG. 6., the configuration of FIG. 17 results in an area of fused powder of the build piece that is above an area of bound powder, which is above an area of not-fused and not-bound powder.

[00116] In various embodiments, support structure 1700 can form an attachment with build piece 1705, and in various embodiments support structure 1700 may not form an attachment with build piece 1705. For example, in embodiments in which the support structure is formed using fused powder, the support structure can be

attached to the build piece. In embodiments in which the support structure is formed using compacted powder, the support structure can be unattached to the build piece. In embodiments in which the support structure is formed using powder that is bound with a binding agent, such as a non-adhesive liquid or gel, the support structure can be unattached to the build piece. In embodiments in which the support structure is formed using powder that is bound with a binding agent, such as an adhesive liquid or gel, the support structure can be unattached to the build piece.

[00117] As mentioned above with reference to FIG. 6, floating support structures may offer advantages such as allowing less powder to be used to form the support structures, which may reduce build time, allow more powder to be recovered and reused, allow more loose powder to be used to create other build pieces, etc. For example, floating support structures may allow additional build pieces to be built more efficiently during a single PBF printing run by arranging multiple floating support structures vertically in the powder bed to support multiple smaller (i.e., shorter) build pieces during a printing run that includes a larger (i.e., taller) build piece. In this way, for example, multiple build pieces could be printed in a vertical stack. This could allow a larger amount of the powder bed to be used for printing build pieces, leading to a more efficient printing process with more build pieces printed per printing run.

[00118] FIGS. 18-22 illustrate example configurations for support structures including resonant structures and systems and methods for removing these types of support structures.

[00119] In various embodiments, support structures can be configured to include resonant structures. Vibration of resonant support structures in its natural frequency can cause the support structure to more easily break away from the 3-D build piece and/or the build plate. This can be due, for example, to metal fatigue at the interface between the support structure and the build piece and/or build plate.

[00120] FIG. 18 illustrates an example support structure 1800 including resonant structures in a half-wave resonator configuration with upward extensions to interface with the build piece. FIG. 18 shows a build plate 1801, a powder bed 1803, and a build piece 1805. Support structure 1800 can include a base 1807 and upward extensions 1809. The ends of upward extensions 1809 can form attachments with build piece 1805 at the interface, which can support the build piece. Each upward extension 1809 can be a resonant structure, i.e., can resonate at a resonance frequency. In this example,

upward extensions 1809 can be of equal length and can have the same resonance frequency. Furthermore, in this example, each upward extension 1809 can be a half-wave resonator, such that application of a resonance frequency would cause a large amplitude swing to be generated at the end of each upward extension, which is the location of the interface between the upward extension and build piece 1805. In this way, for example, applying a resonance frequency can cause a large stress on the ends of upward extension 1809 as the ends attempt to vibrate while being attached to build piece 1805. The stress caused by applying the resonance frequency can cause the ends of upward extensions 1809 to break away from build piece 1805, thus removing support structure 1800 from the build piece.

[00121] In this example, support structure 1800 includes extensions of fixed length, width and taper. In various embodiments, extensions may have different lengths and/or widths, and can have different resonant frequencies, for example, which can allow different portions of the support structure to be removed using different frequencies. In various embodiments, extensions may have different tapers, or no taper, for example.

[00122] FIG. 19 illustrates an example support structure 1900 including resonant structures in a half-wave resonator configuration with upward extensions to interface with the build piece and downward extensions to interface with the build plate. FIG. 19 shows a build plate 1901, a powder bed 1903, and a build piece 1905. Support structure 1900 can include a base 1907, upward extensions 1909, and downward extensions 1911. The ends of upward extensions 1909 can taper down and form attachments with build piece 1905 at the build piece interface, which can support the build piece. The ends of downward extensions 1911 can form attachments with build plate 1901 and the build plate interface, which can support the support structure 1900. Each upward extension 1909 and each downward extension 1911 can be a resonant structure, i.e., can resonate at a resonance frequency. In this example, upward extensions 1909 and downward extensions 1911can be of equal length and can have the same resonance frequency. Furthermore, in this example, each upward extension 1909 and downward extension 1911 can be a half-wave resonator, such that application of a resonance frequency would cause a large amplitude swing to be generated at the end of each upward extension and at the end of each downward extension. In this way, for example, applying a resonance frequency can cause a large stress on the ends the extensions as the ends attempt to

vibrate while being attached at the interfaces. The stress caused by applying the resonance frequency can cause the ends to break away from the interfaces, thus removing support structure 1900 from build piece 1905 and build plate 1901.

[00123] In this example, support structure 1900 includes extensions of fixed length, width and taper. In various embodiments, extensions may have different lengths and/or widths, and can have different resonant frequencies, for example, which can allow different portions of the support structure to be removed using different frequencies. In various embodiments, extensions may have different tapers, or no taper, for example.

[00124] FIG. 20 illustrates an example support structure 2000 including resonant structures in a quarter-wave resonator configuration with upward extensions to interface with the build piece and downward extensions to interface with the build plate. FIG. 20 shows a build plate 2001, a powder bed 2003, and a build piece 2005. Support structure 2000 can include a base 2007, upward extensions 2009, and downward extensions 2011. The ends of upward extensions 2009 can taper down and form attachments with build piece 2005 at the build piece interface, which can support the build piece. The ends of downward extensions 2011 can taper down and form attachments with build plate 2001 and the build plate interface, which can support the support structure 2000. In addition, the base of each upward extension 2009 and the base of each downward extension 2011 can taper at the attachment to base 2007.

[00125] Each upward extension 2009 and each downward extension 2011 can be a resonant structure, i.e., can resonate at a resonance frequency. In this example, upward extensions 2009 and downward extensions 2011can be of equal length and can have the same resonance frequency. Furthermore, in this example, each upward extension 2009 and downward extension 2011 can be a quarter-wave resonator, such that application of a resonance frequency would cause a large amplitude swing to be generated at the end of each upward extension and each downward extension and also at the base of each upward extension and the base of each downward extension. In this way, for example, applying a resonance frequency can cause a large stress on the ends and the bases of the extensions as the ends and bases attempt to vibrate while being attached at interfaces. The stress caused by applying the resonance frequency can cause the ends and bases of the extensions to break away from the interfaces, thus removing support structure 2000 from build piece 2005 and build plate 2001.

[00126] In this example, support structure 2000 includes extensions of fixed length, width and taper. In various embodiments, extensions may have different lengths and/or widths, and can have different resonant frequencies, for example, which can allow different portions of the support structure to be removed using different frequencies. In various embodiments, extensions may have different tapers, or no taper, for example.

[00127] It should be noted that various concepts described herein can be combined and modified, as one skilled in the art would readily understand. To illustrate this point, FIG. 21 shows an example configuration of a support structure that includes resonant structures and a floating base.

[00128] FIG. 21 illustrates an example support structure 2100 according to various embodiments. FIG. 21 shows a build plate 2101, a powder bed 2103, and a build piece 2105. Support structure 2100 can include a base 2107 and upward extensions 2109. Base 2107 can be configured to float on the loose powder below, similar to embodiments described above with reference to FIGS. 6 and 17. Upward extensions 2009 can be resonant structures similar to embodiments described above with reference to FIGS. 18-20.

[00129] After the printing operation is completed and the loose powders are removed, an excitation resonant frequency can be applied to remove the support structure.

[00130] FIG. 22 illustrates an example system and method including a vibrator 2200 that can apply a resonance frequency for removing support structures including resonant structures. FIG. 22 shows a build plate 2201 and a build piece 2205 that have been removed from a powder bed after printing. FIG. 22 includes a support structure 2207 with a base 2209 and upward extensions 2211, similar to support structure 1800 of FIG. 18. Each upward extension 2211 can be a resonant structure, i.e., can resonate at a resonance frequency.

[00131] Vibrator 2200 can be coupled to base 2209 such that a resonance frequency can be applied to cause upward extensions 2211 to vibrate. In various embodiments, the resonance frequency can be applied via mechanical conduction directly or indirectly through a medium to the build piece, the support structure, the build plate, etc. Mechanical excitation can be generated, for example, by ultrasound transducers, piezoelectric transducers micro electro-mechanical systems, etc., of vibrator 2200. The transducer can be attached to build piece 2205, support structure 2207, build plate 2201, etc. The induced vibration can cause the support structure to vibrate

with increasing amplitude until the ends break off from the build piece and the build plate.

[00132] In various embodiments, further control of the support structure break-off can be achieved by a variant adaptation of this design with multiple resonant nodes. For instance, support extrusions of different lengths, widths, and/or taper may be applied to different areas of the build piece. This can allow for the selective removal of supports by applying different excitation frequencies. A medium could also be used for complete or partial immersion of the build piece to speed the break-off process. Sound waves and heating may also be used to drive the break-off process.

[00133] In various embodiments, support structure can be formed such that an interface (e.g., contact points) between the support structure and the build piece can heat substantially when an electrical current is applied. This can allow easy removal of the support structure via the application of electrical current.

[00134] FIG. 23 illustrates an example support structure 2300 including portions configured to be melted by applying electrical current to remove the support structure. FIG. 23 shows a build plate 2301, a powder bed 2303, and a build piece 2305. Support structure 2300 can include a base 2307 and upward extensions 2309. The ends of upward extensions 2309 can form attachments with build piece 2305 at the interface, which can support the build piece. Each upward extension 2309 can be configured such that an electrical current applied across the attachments between the upward extension and build piece 2305 can cause the attachments to melt. In this way, for example, applying an electrical current can cause the ends of upward extensions 2309 to melt away from build piece 2305, thus removing support structure 2300 from the build piece.

[00135] In various embodiments, support structures can includes extensions of fixed length, width and taper. In various embodiments, extensions may have different lengths and/or widths. In various embodiments, the contact points can be tapered such that the contact points provide a relatively high electrical resistance compared to the remaining portions of the support structure and build piece. In various embodiments, extensions may have different tapers, or no taper, for example.

[00136] FIG. 24 illustrates an example system and method including a current system 2400 for removing support structures that include portions configured to be melted by applying electrical current to remove the support structure. FIG. 24 shows a build plate 2401 and a build piece 2405 that have been removed from a powder bed after

printing. FIG. 24 includes a support structure 2407 with a base 2409 and upward extensions 2411. Each upward extension 2411 can be configured such that the ends melt when a current is applied across them.

[00137] Current system 2400 include a current source 2413, a controller 2415 (e.g. a switch), and electrical leads 2417. Electrical leads 2417 can be coupled to base 2409 and build piece 2405 such that an electrical current from current source 2413 flows through the ends of upward extensions 2411 when controller 2415 is closed. In this way, the ends of upward extensions 2411 can be melted and support structure 2407 can be removed from build piece 2405.

[00138] FIG. 25 an example support structure 2500 including portions configured to be excited by applying electrical current to remove the support structure, and an example system and method for removing these types of support structures. FIG. 25 shows a build plate 2501, a powder bed 2503, and a build piece 2505. Support structure 2500 can include a base 2507 and upward extensions 2509. The ends of upward extensions 2509 can form attachments with build piece 2505 at the interface, which can support the build piece. A coil 2511 can be formed to wrap around each upward extension 2509. Coils 2511 can be metal coils that can be formed, for example, by fusing metal powder. In this example, each upward extension 2509 can be configured to be excited by an application of electrical current through the corresponding coil 2511. For example, each upward extension 2509 and coil 2511 can be configured as a solenoid structure, such that application of an alternating electrical current to the coil causes the upward extension to move up and down along the axis of the coil. In this way, for example, the attachment between each upward extension 2509 and build piece 2505 can be weakened and broken to remove support structure 2500.

[00139] In this example, support structure 2500 includes extensions and coils configured as a solenoid structure. In various embodiments, support structures can include other types of elements that may be excited to weaken the attachment between the support structure and the build piece and/or the build plate. Such elements may include, for example, a combination of electrically conductive portions formed, for example, by fusing metal powder, and electrically insulating portions formed, for example, by applying an insulating binding agent, by depositing an insulating non-powder support material, etc. In this way, for example, many different types of elements

may be formed that would allow the support structure to be more easily removed from the build piece and/or build plate.

[00140] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these exemplary embodiments presented throughout this disclosure will be readily apparent to those skilled in the art, and the concepts disclosed herein may be applied to other support structures and systems and methods for removal of support structures. Thus, the claims are not intended to be limited to the exemplary embodiments presented throughout the disclosure, but are to be accorded the full scope consistent with the language claims. All structural and functional equivalents to the elements of the exemplary embodiments described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed under the provisions of 35 U.S.C. §112(f), or analogous law in applicable jurisdictions, unless the element is expressly recited using the phrase "means for" or, in the case of a method claim, the element is recited using the phrase "step for."

WHAT IS CLAIMED IS:

1. An apparatus for powder-bed fusion, comprising:

a depositor that deposits a plurality of layers of a powder material;

an energy beam source that generates an energy beam;

a deflector that applies the energy beam to fuse the powder material in a first area in a first one of the layers; and

a powder fixer that binds the powder material in a second area in a second one of the layers, wherein the second area is underneath the first area.

2. The apparatus of claim 1, wherein a third one of the layers includes a third area of powder material underneath the second area, and the deflector and the powder fixer are configured such that the powder material in the third area is not fused and not bound.

3. The apparatus of claim 1, wherein the powder fixer includes a compactor that compacts the powder material in the second area.

4. The apparatus of claim 3, wherein the compactor includes a mechanical roller.

5. The apparatus of claim 3, wherein the compactor includes a mechanical press.

6. The apparatus of claim 1, wherein the powder fixer includes a heater that partially sinters the powder material in the second area.

7. The apparatus of claim 1, wherein the powder fixer includes an applicator that applies a binding agent to the powder material in the second area.

8. The apparatus of claim 7, wherein the binding agent includes a liquid.

9. The apparatus of claim 7, wherein the binding agent includes a gel.

10. The apparatus of claim 7, wherein the binding agent includes a resin.

11. The apparatus of claim 7, wherein the applicator includes a nozzle that deposits the binding agent, wherein the nozzle tracks behind the depositor.

12. An apparatus for powder-bed fusion, comprising:

a depositor that deposits a plurality of layers of a powder material;

an energy beam that generates an energy beam;

a deflector that applies the energy beam to fuse the powder material in a first area in a first one of the layers; and

a support system that establishes support material in a second area in a second one of the layers, wherein the second area is underneath the first area.

13. The apparatus of claim 12, wherein the support material includes a foam.

14. The apparatus of claim 12, wherein the support system is configured to use the depositor to establish the support material in the second area of the second one of the layers.

15. The apparatus of claim 12, wherein the support system includes a vacuum that removes the powder material in the second area prior to the establishment of the support material.

16. A support structure to support a build piece formed in a powder-bed fusion system, comprising:

a base formed of fused powder in the powder bed underneath the build piece; and

one or more extensions formed of fused powder extending from the base and configured to support the build piece.

17. The support structure of claim 16, wherein the one or more extensions have a resonance frequency transverse to the first direction.

18. The support structure of claim 16, wherein each of the one or more extensions includes a tapered portion at an end of the extension furthest from the base.

19. The support structure of claim 16, wherein each of the one or more extensions includes a tapered portion at an end of the extension closest to the base.

20. The support structure of claim 16, wherein the support structure further comprises:

one or more second extensions extending from the base in a direction opposite to a direction the one or more extensions extend from the base.

21. The support structure of claim 20, wherein the one or more second extensions have a resonance frequency that corresponds to the resonance frequency of the one or more extensions.

22. The support structure of claim 16, further comprising a coil formed of fused powder, wherein the coil is wrapped around one of the one or more extensions.

23. The support structure of claim 16, further comprising the build piece, wherein the build piece includes one or more attachment points configured to attach to the one or more extensions.

24. An apparatus for a powder-bed fusion system, comprising:

a support structure formed by the powder-bed fusion system;

an electrical current source;

a connection that connects the electrical current source to the support structure; and

a controller that applies an electrical current from the electrical current source to the support structure through the connection.

25. The apparatus of claim 24, wherein the connection includes a contact configured to contact the support structure, the apparatus further comprising a second contact configured to contact a build piece supported by the support structure, wherein the build piece is supported by the support structure at one or more attachment points, and the electrical current is configured to pass through the one or more attachment points and melt at least a portion of the support structure.

26. The apparatus of claim 25, further comprising the build piece.

27. The apparatus of claim 24, wherein the connection includes a first contact configured to contact a first location on the support structure, the apparatus further comprising a second contact configured to contact a second location on the support structure, such that the electrical current is applied across an electromechanical transducer of the support structure.

28. An apparatus for separating a support structure from a build piece of a powder-bed fusion system, comprising:

a vibrator that applies a resonant frequency to the support structure.

29. The apparatus of claim 28, wherein the vibrator comprises a piezoelectric transducer.

30. The apparatus of claim 28, wherein the vibrator is configured to vibrate at less than an ultrasonic frequency.

31. A method of powder-bed fusion, comprising:

depositing first and second layers of a powder material;

generating an energy beam;

applying the energy beam to fuse the powder material in a first area in the first layer; and

binding the powder material in a second area in the second layer, wherein the second area is underneath the first area.

32. The method of claim 31, further comprising depositing a third layer of the powder material without fusing a third area of powder material underneath the second area and without binding the third area.

33. The method of claim 31, wherein binding the powder material includes compacting the powder material in the second area.

34. The method of claim 33, wherein compacting the powder material includes a mechanically rolling the powder material in the second area.

35. The method of claim 33, wherein compacting the powder material includes a mechanically pressing the powder material in the second area.

36. The method of claim 31, wherein binding the powder material includes partially sintering the powder material in the second area.

37. The method of claim 31, wherein binding the powder material includes applying a binding agent to the powder material in the second area.

38. The method of claim 37, wherein the binding agent includes a liquid.

39. The method of claim 37, wherein the binding agent includes a gel.

40. The method of claim 37, wherein the binding agent includes a resin.

41. The method of claim 37, wherein applying the binding agent includes depositing the binding agent with a nozzle that tracks behind the depositor.

42. A method of powder-bed fusion, comprising:

depositing first and second layers of a powder material;

generating an energy beam;

applying the energy beam to fuse the powder material in a first area in the first layer; and

establishing support material in a second area in the second layer, wherein the second area is underneath the first area.

43. The method of claim 42, wherein the support material includes a foam.

44. The method of claim 42, wherein the first and second layers are deposited using a depositor, and establishing the support material includes using the depositor to establish the support material.

45. The method of claim 42, further comprising removing the powder material in the second area prior to establishing the support material.

46. A method for separating a support structure from a build piece of a powder-bed fusion system, comprising:

connecting the support structure to a ground; and

applying an electrical current to the support structure.

47. The method of claim 46, wherein applying the electrical current includes applying the electrical current across an attachment point between the build piece and the support structure that melts at least a portion of the support structure.

48. The method of claim 46, wherein applying the electrical current includes applying the electrical current across an electromechanical transducer of the support structure.

49. A method for separating a support structure from a build piece of a powder-bed fusion system, comprising:

applying a resonant frequency to the support structure.

50. The method of claim 49, further comprising attaching a piezoelectric transducer to the support structure.

51. The method of claim 49, wherein the resonant frequency is less than an ultrasonic frequency.

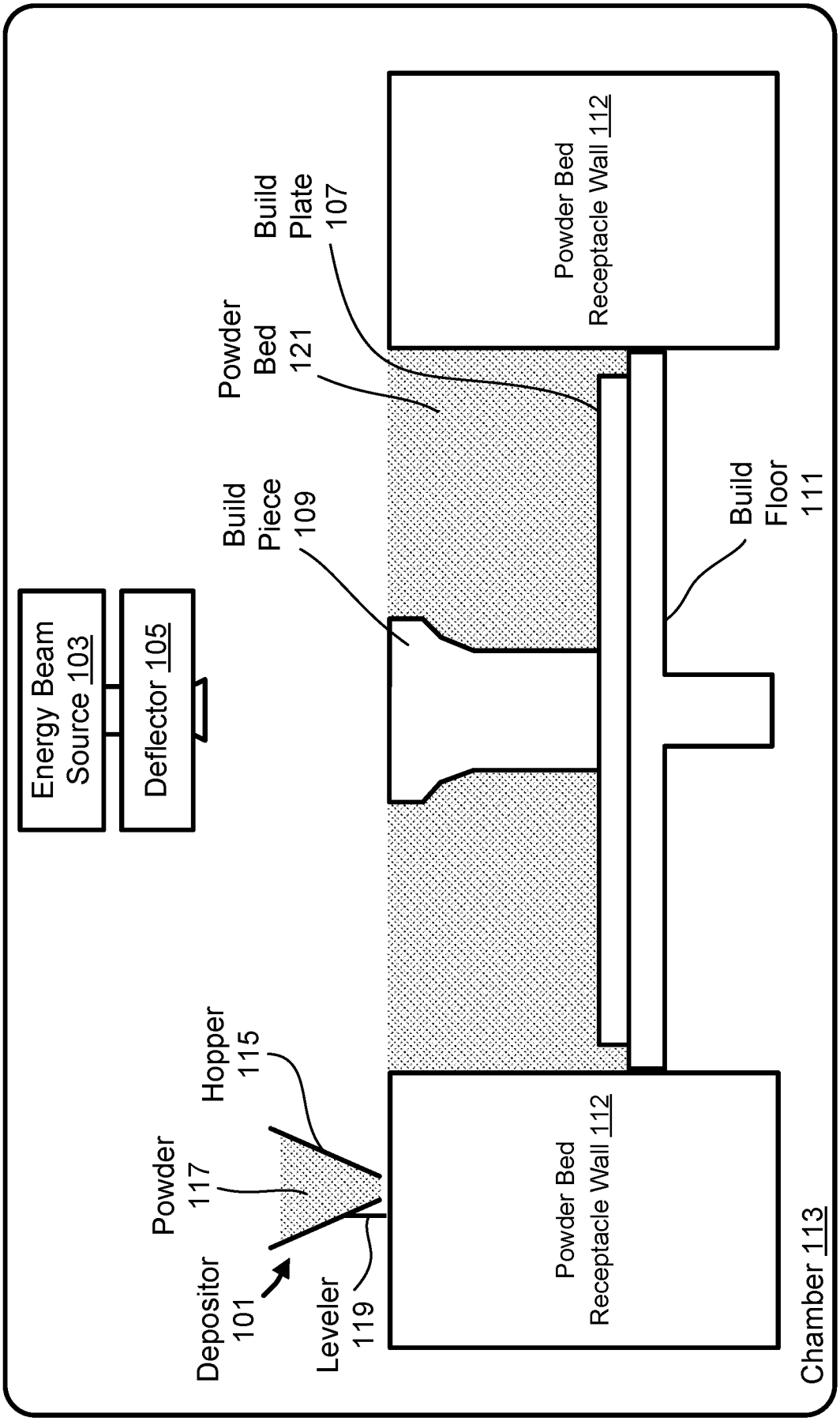

PBF System 100
Powder Bed Receptacle Wall 112
Build Plate 107
Powder Bed 121
Build Piece 109
Build Floor 111
Energy Beam Source 103
Deflector 105
Hopper 115
Powder 117
Depositor 101
Leveler 119
Powder Bed Receptacle Wall 112
Chamber 113

FIG. 1A

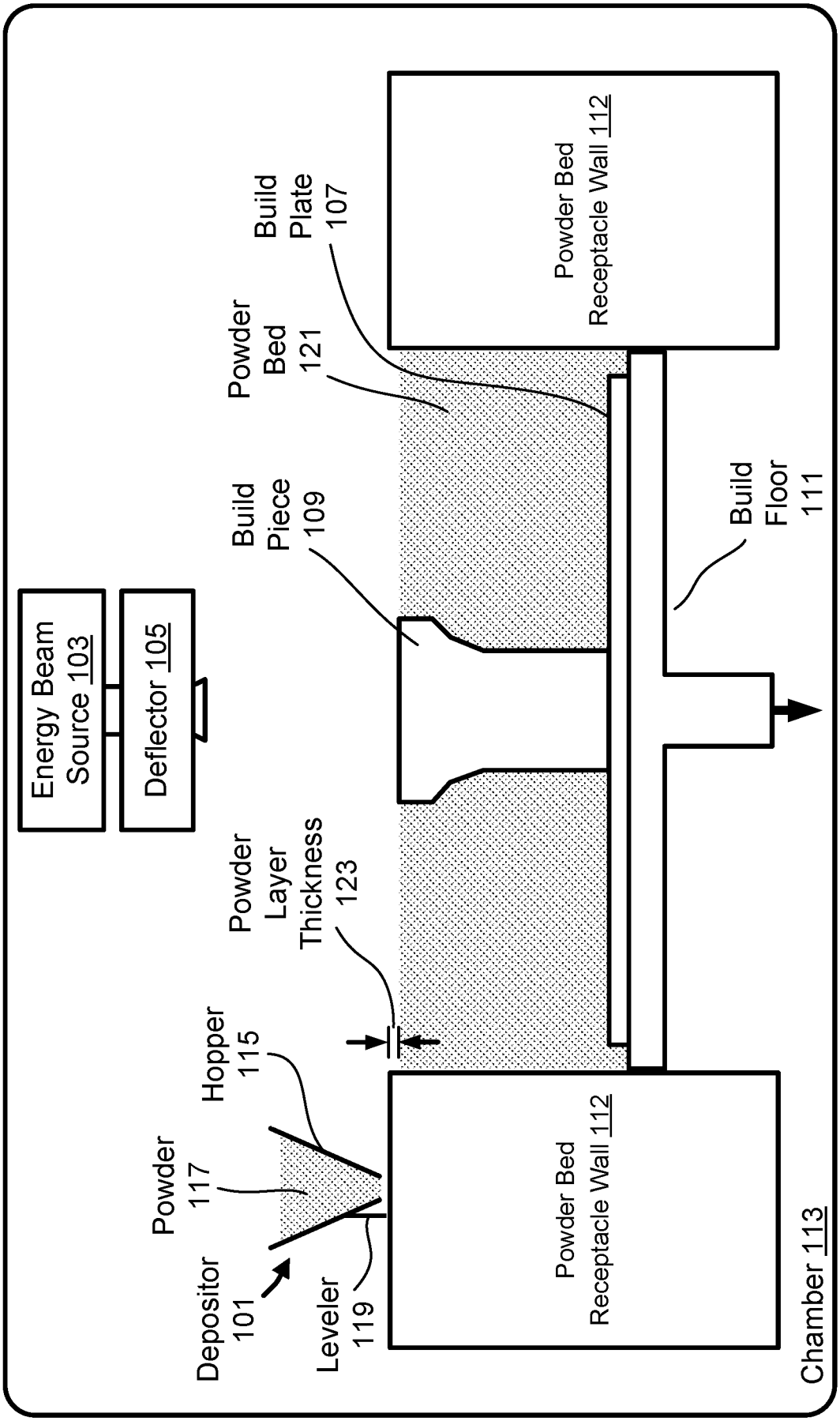

PBF System 100
Energy Beam Source 103
Deflector 105
Build Plate 107
Powder Bed Receptacle Wall 112
Powder Bed 121
Build Piece 109
Build Floor 111
Powder Layer Thickness 123
Hopper 115
Powder 117
Depositor 101
Leveler 119
Powder Bed Receptacle Wall 112
Chamber 113

FIG. 1B

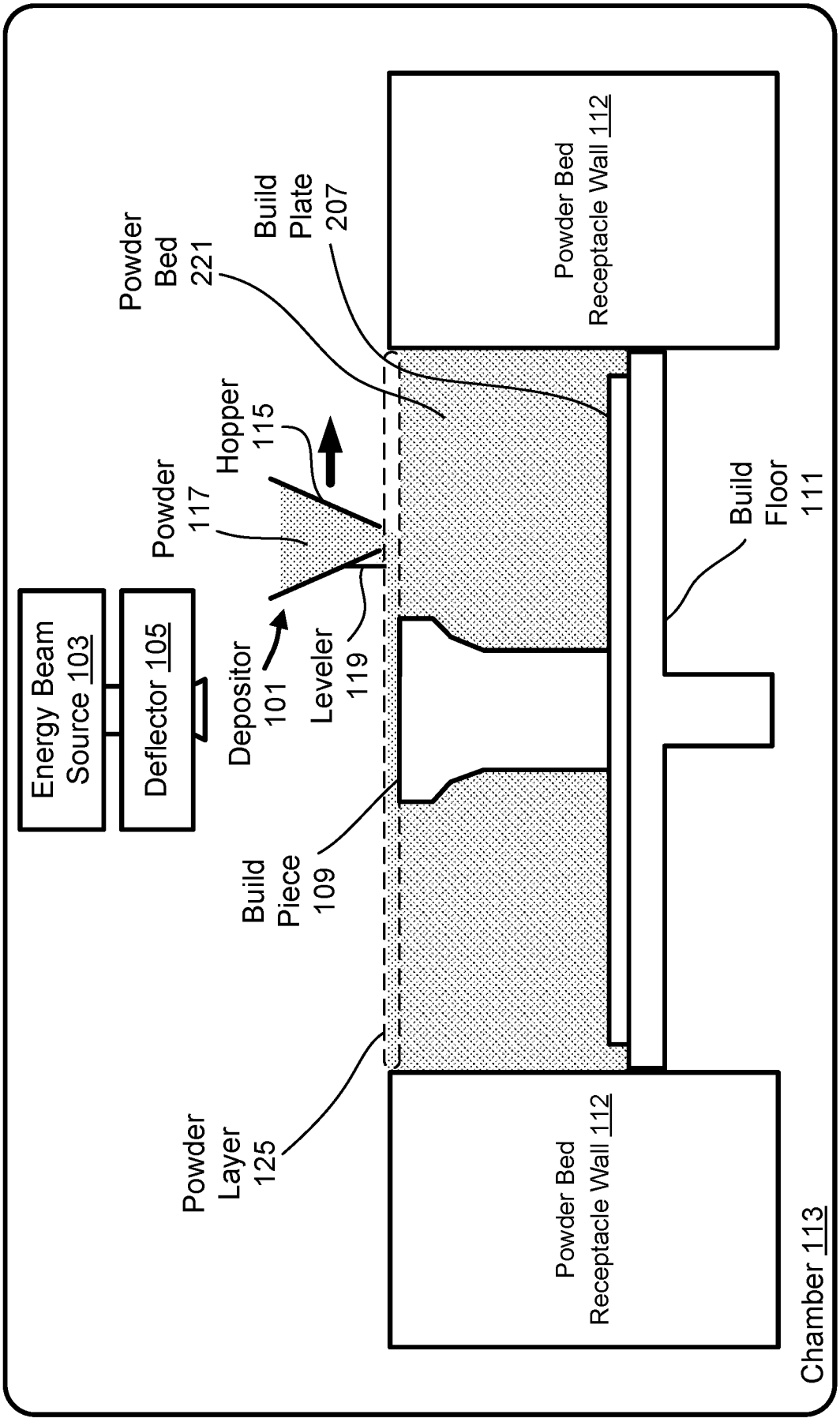

PBF System 100
Chamber 113
Powder Bed Receptacle Wall 112
Powder Bed Receptacle Wall 112
Build Floor 111
Build Plate 207
Powder Bed 221
Hopper 115
Powder 117
Energy Beam Source 103
Deflector 105
Depositor 101
Leveler 119
Build Piece 109
Powder Layer 125

FIG. 1C

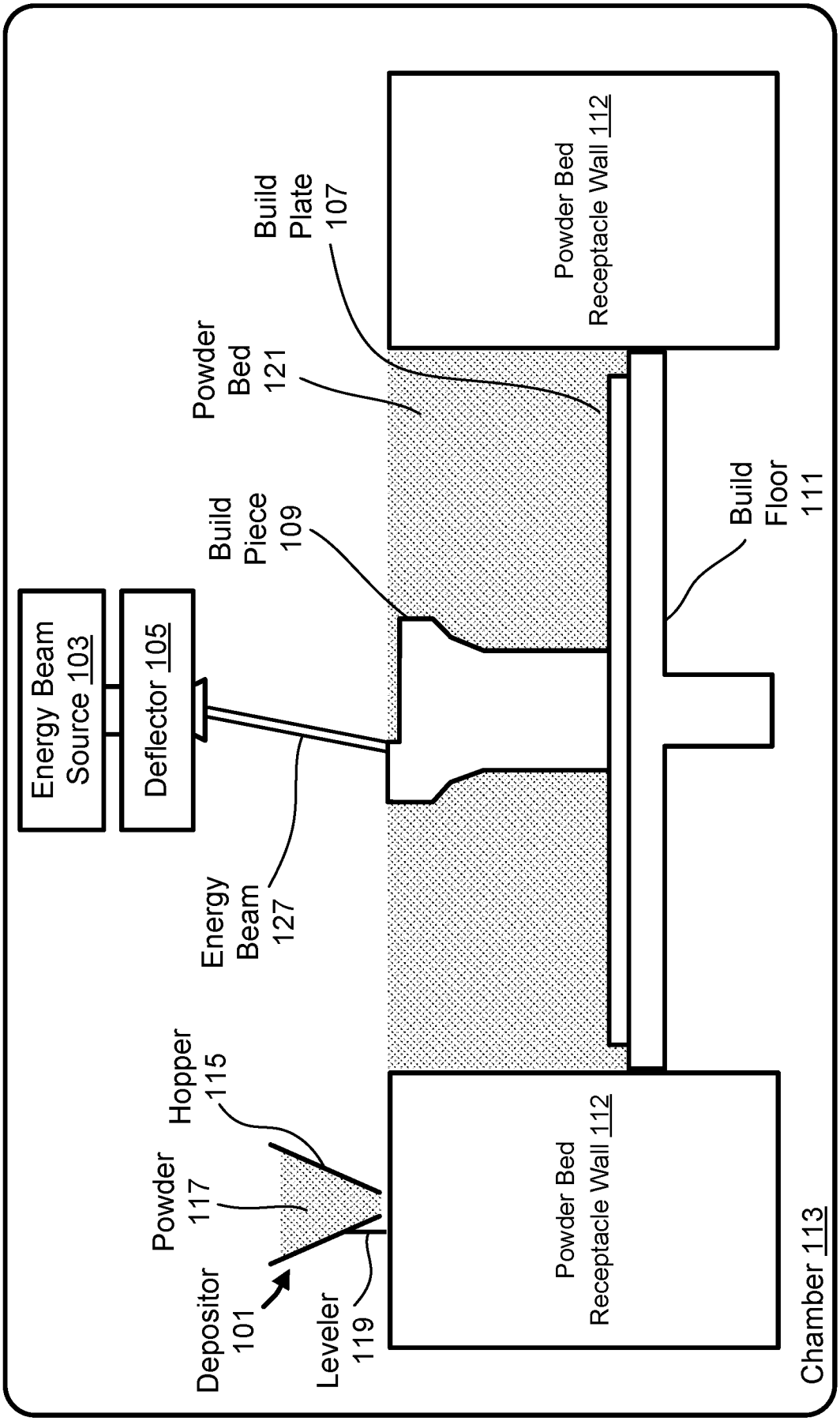

PBF System 100
Chamber 113
Powder Bed Receptacle Wall 112
Powder Bed Receptacle Wall 112
Build Plate 107
Powder Bed 121
Build Piece 109
Build Floor 111
Energy Beam Source 103
Deflector 105
Energy Beam 127
Hopper 115
Powder 117
Depositor 101
Leveler 119

FIG. 1D

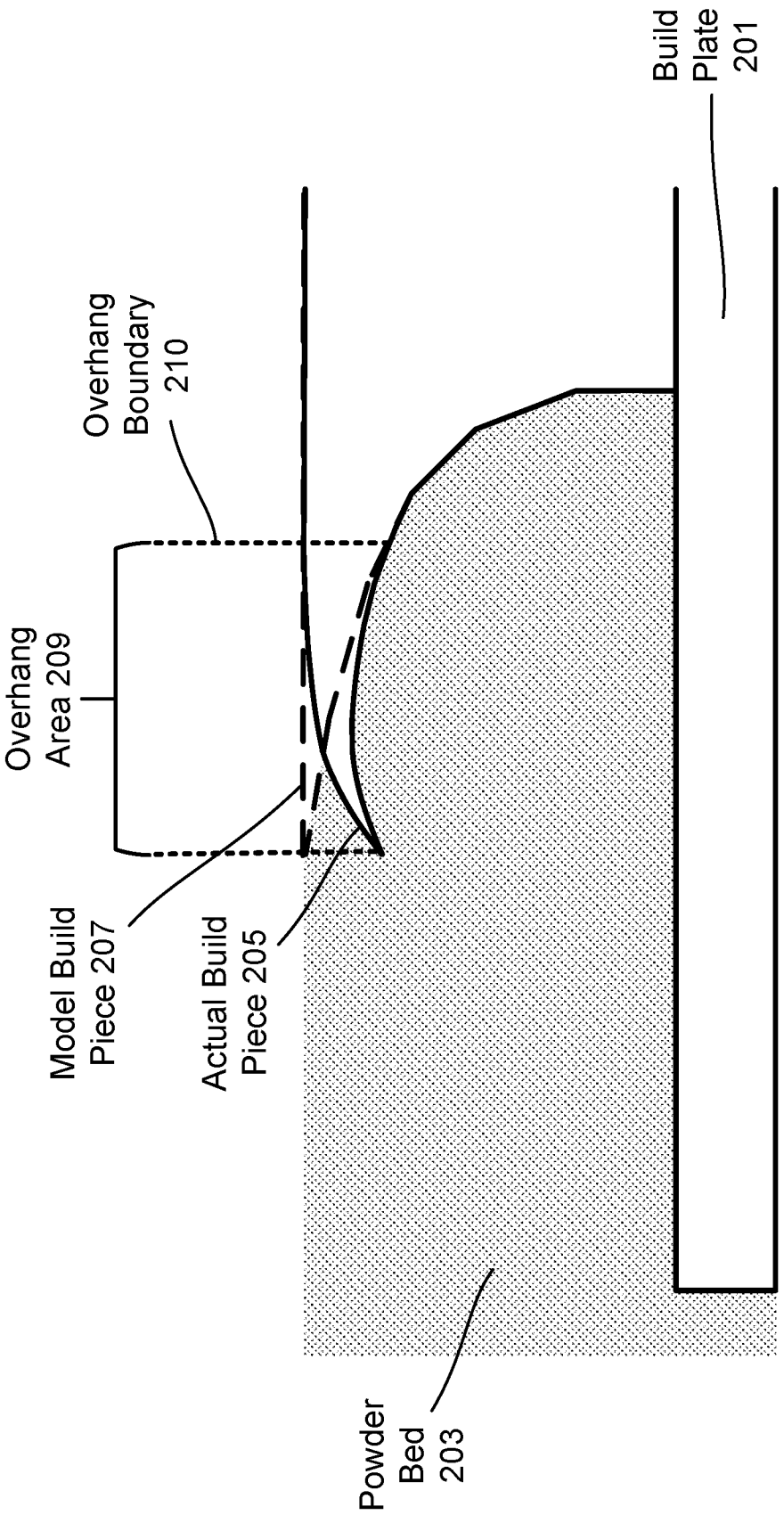

Build Plate 201
Overhang Boundary 210
Overhang Area 209
Model Build Piece 207
Actual Build Piece 205
Powder Bed 203

FIG. 2

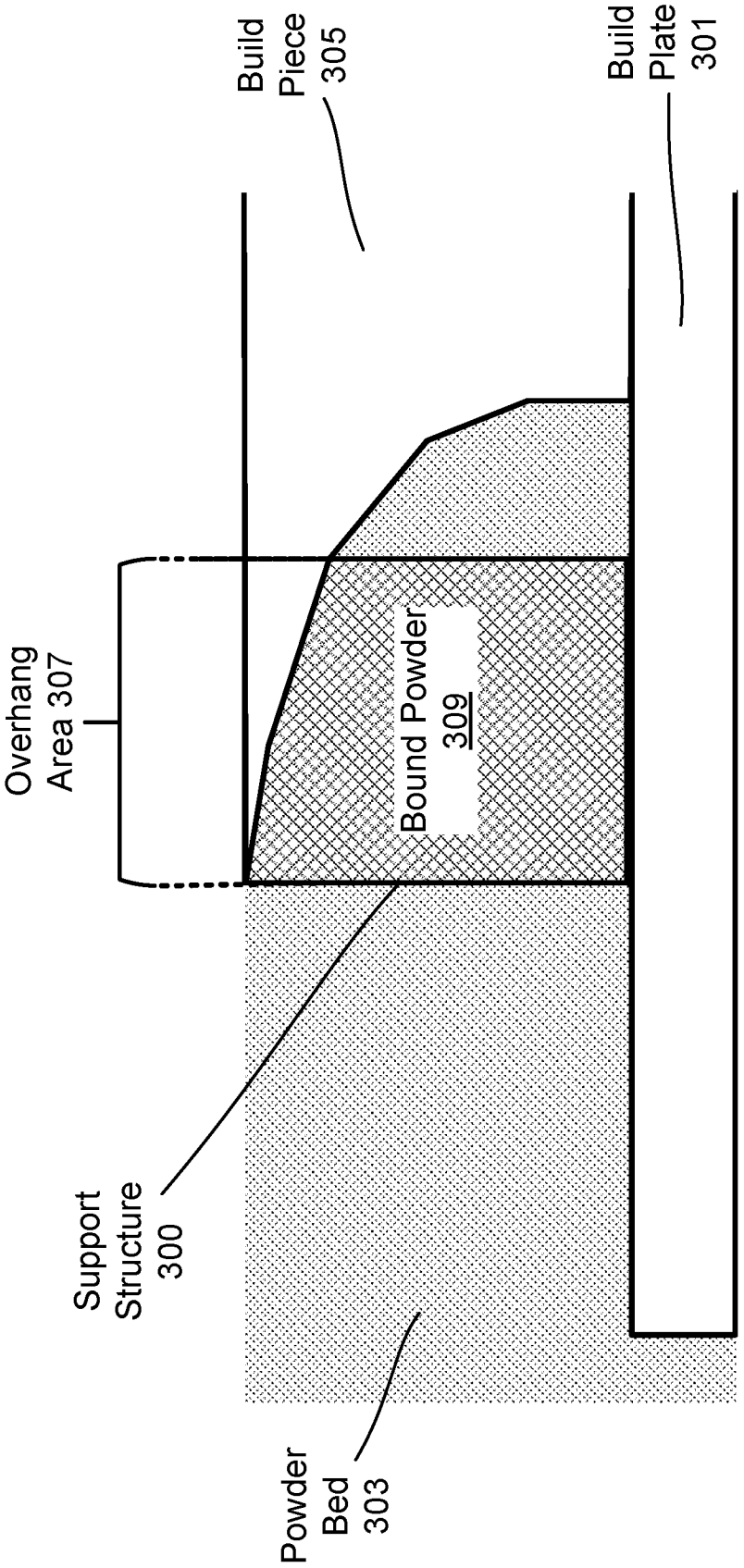

Build Piece 305
Build Plate 301
Overhang Area 307
Bound Powder 309
Support Structure 300
Powder Bed 303

FIG. 3

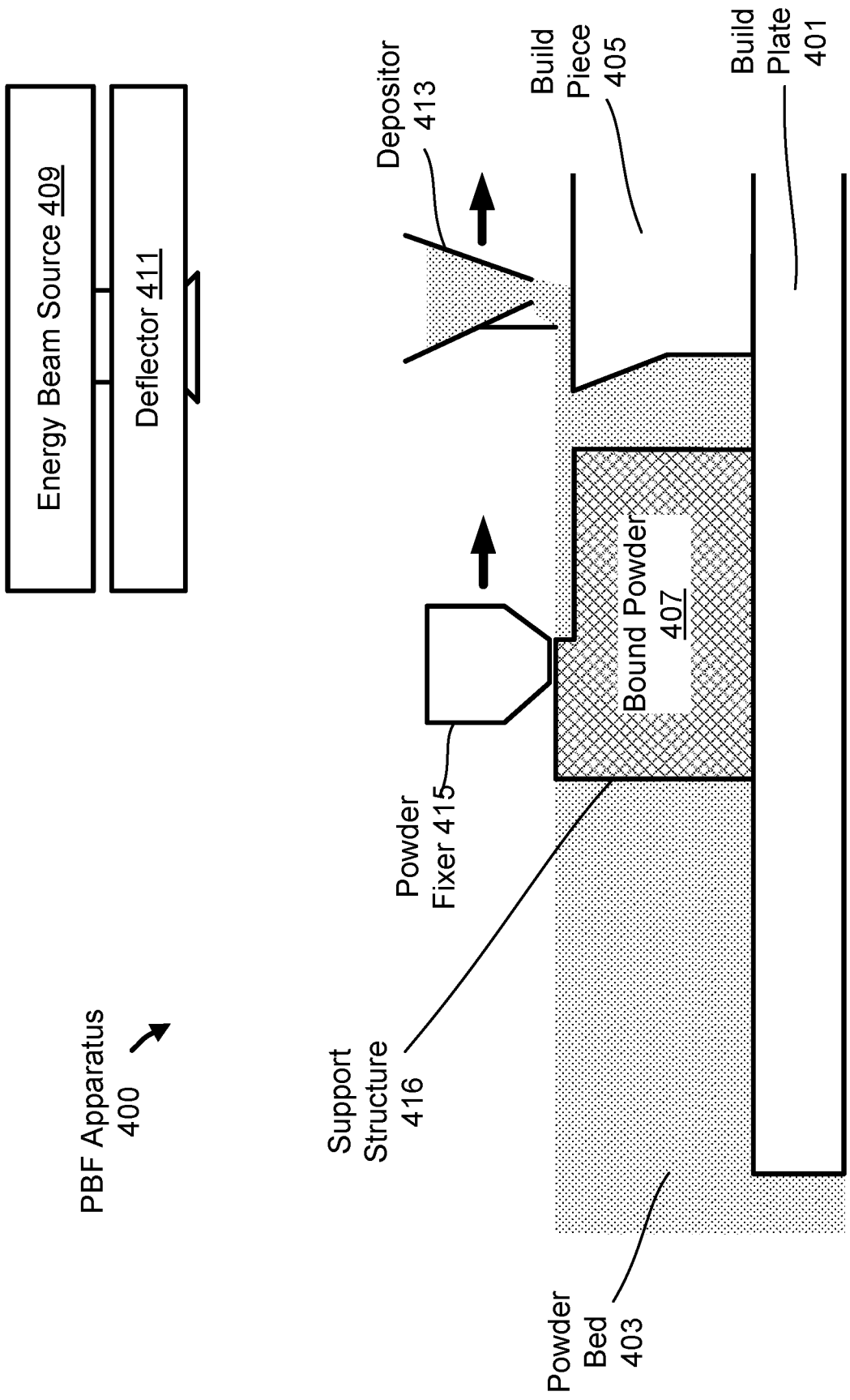

Energy Beam Source 409
Deflector 411
Depositor 413
Build Piece 405
Build Plate 401
Bound Powder 407
Powder Fixer 415
Support Structure 416
Powder Bed 403
PBF Apparatus 400

FIG. 4A

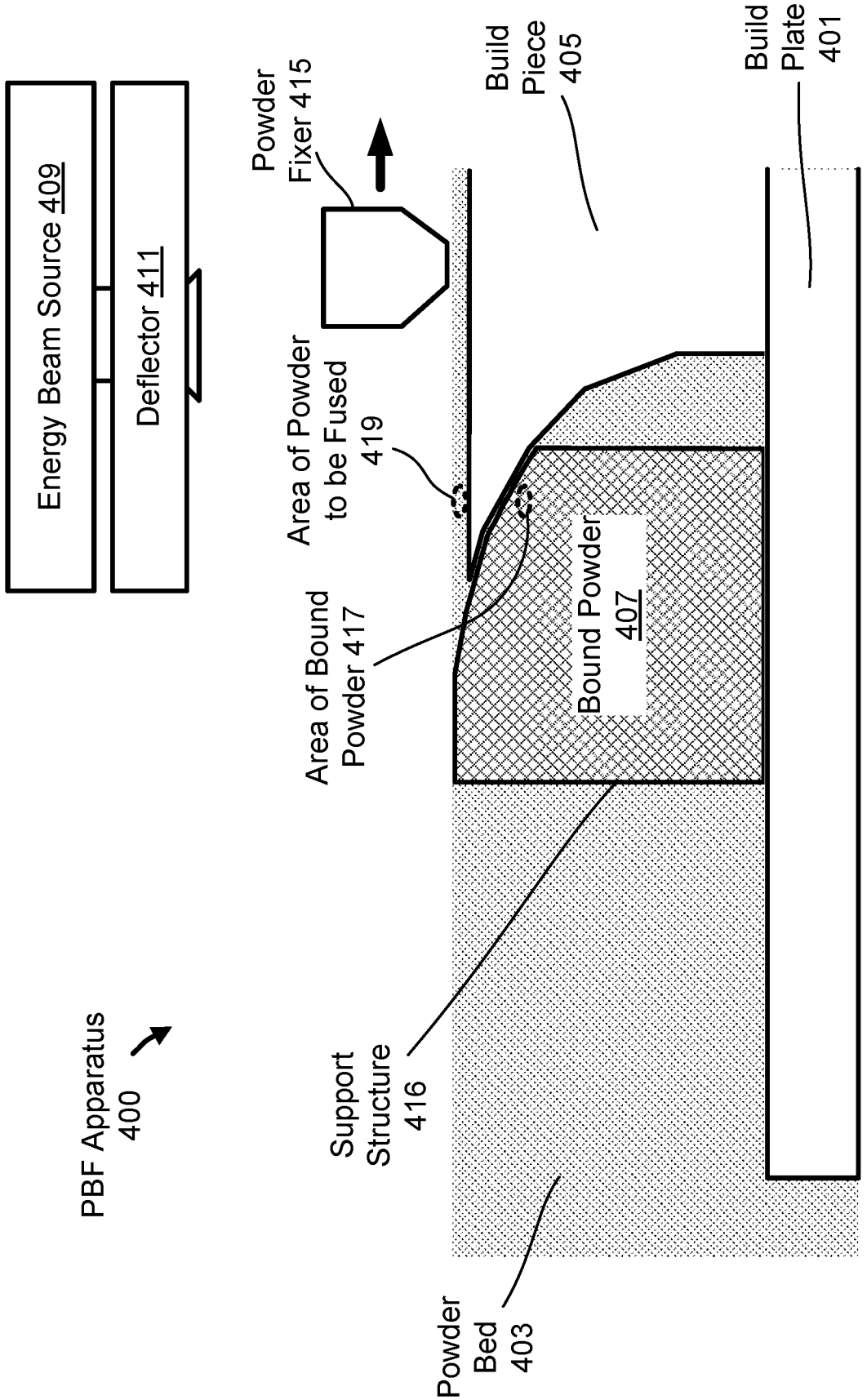

Energy Beam Source 409
Deflector 411
Powder Fixer 415
Build Piece 405
Build Plate 401
Area of Powder to be Fused 419
Area of Bound Powder 417
Bound Powder 407
Support Structure 416
Powder Bed 403
PBF Apparatus 400

FIG. 4B

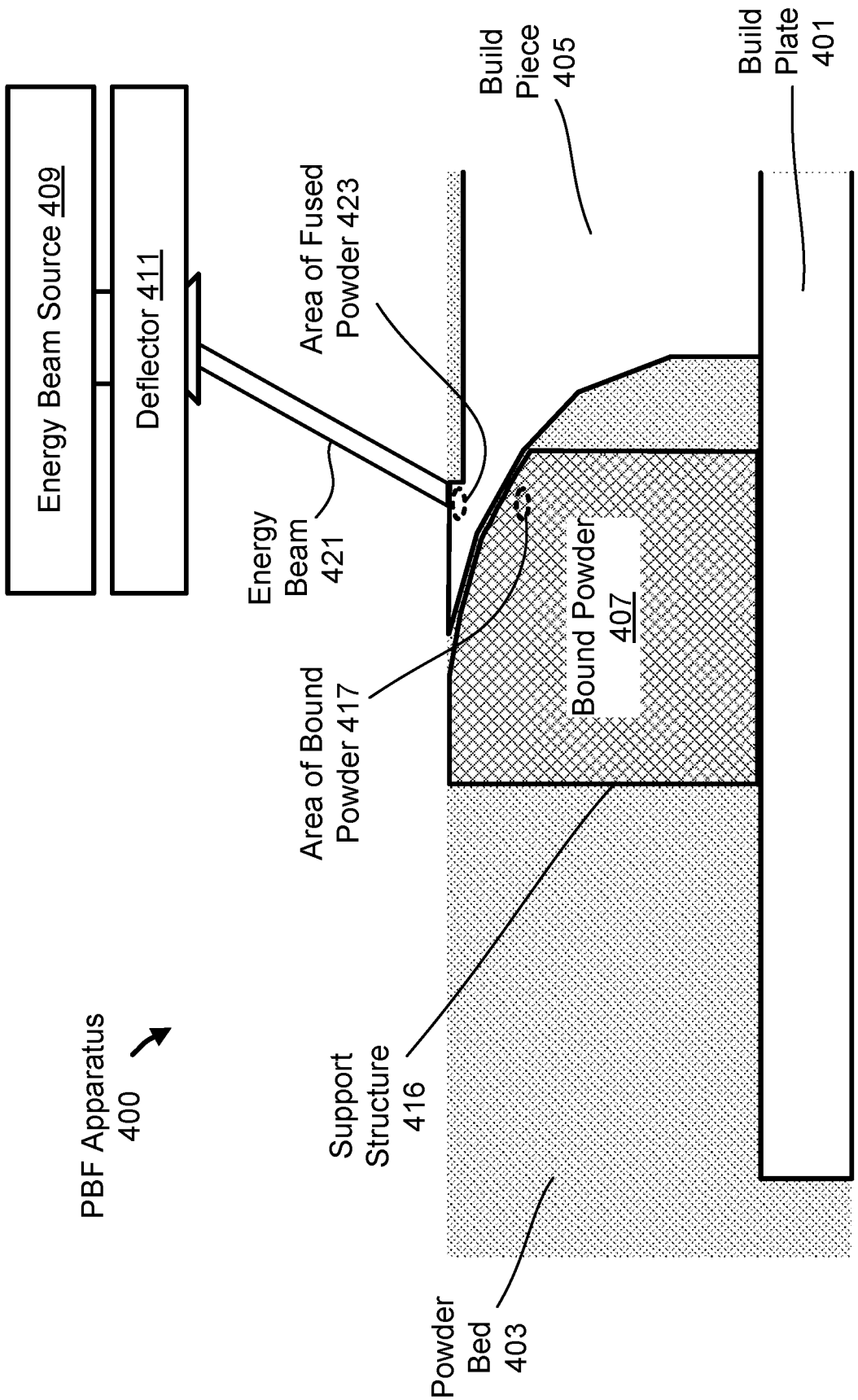

Energy Beam Source 409
Deflector 411
Energy Beam 421
Area of Fused Powder 423
Build Piece 405
Build Plate 401
Area of Bound Powder 417
Bound Powder 407
Support Structure 416
Powder Bed 403
PBF Apparatus 400

FIG. 4C

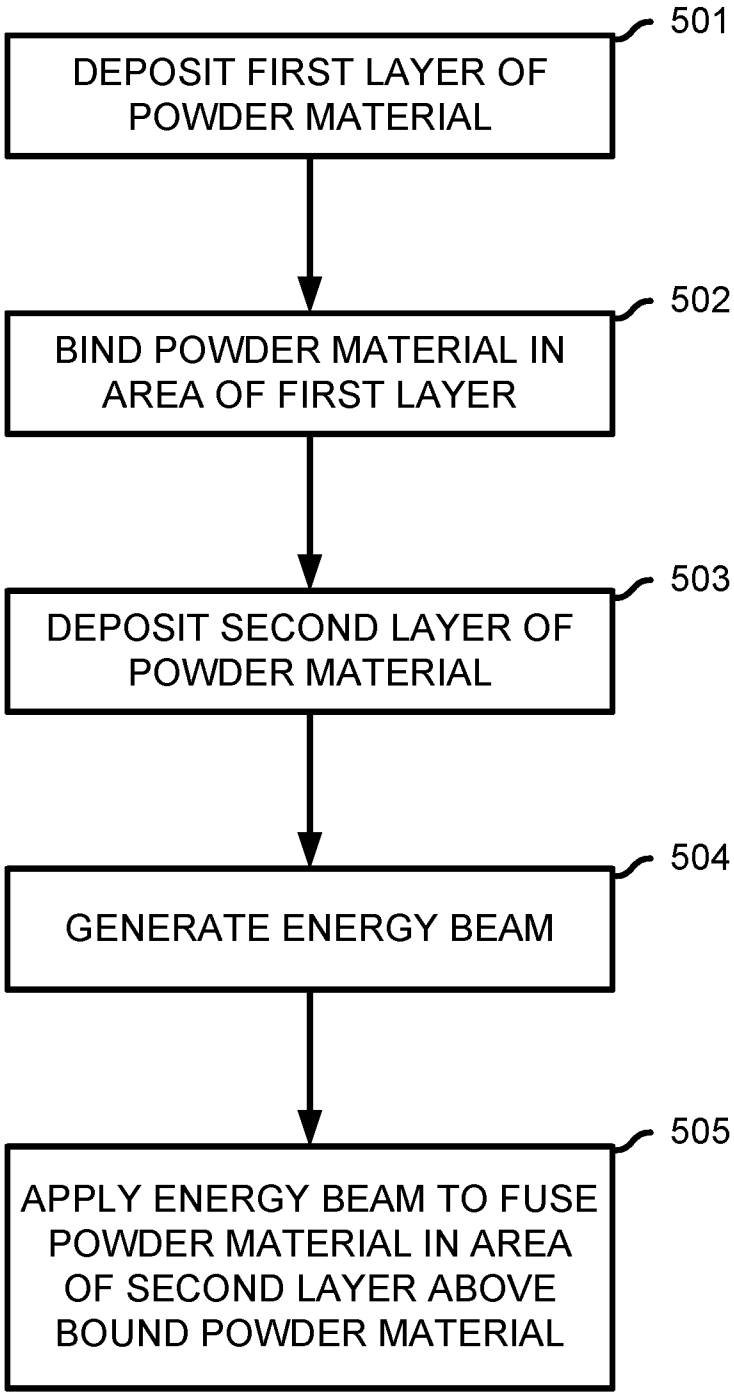

501
DEPOSIT FIRST LAYER OF POWDER MATERIAL
502
BIND POWDER MATERIAL IN AREA OF FIRST LAYER
503
DEPOSIT SECOND LAYER OF POWDER MATERIAL
504
GENERATE ENERGY BEAM
505
APPLY ENERGY BEAM TO FUSE POWDER MATERIAL IN AREA OF SECOND LAYER ABOVE BOUND POWDER MATERIAL

FIG. 5

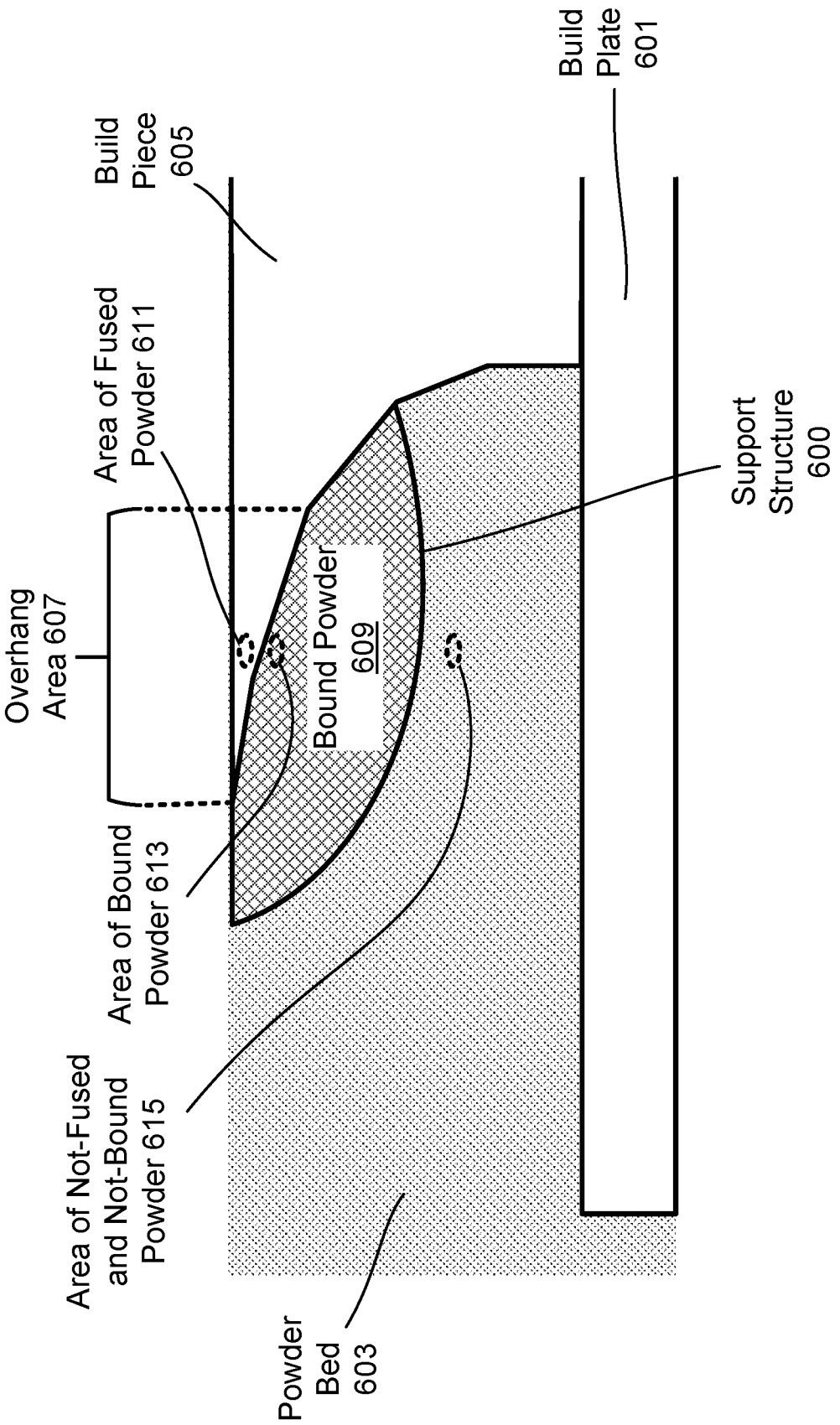

Build Plate 601
Build Piece 605
Area of Fused Powder 611
Support Structure 600
Overhang Area 607
Bound Powder 609
Area of Bound Powder 613
Area of Not-Fused and Not-Bound Powder 615
Powder Bed 603

FIG. 6

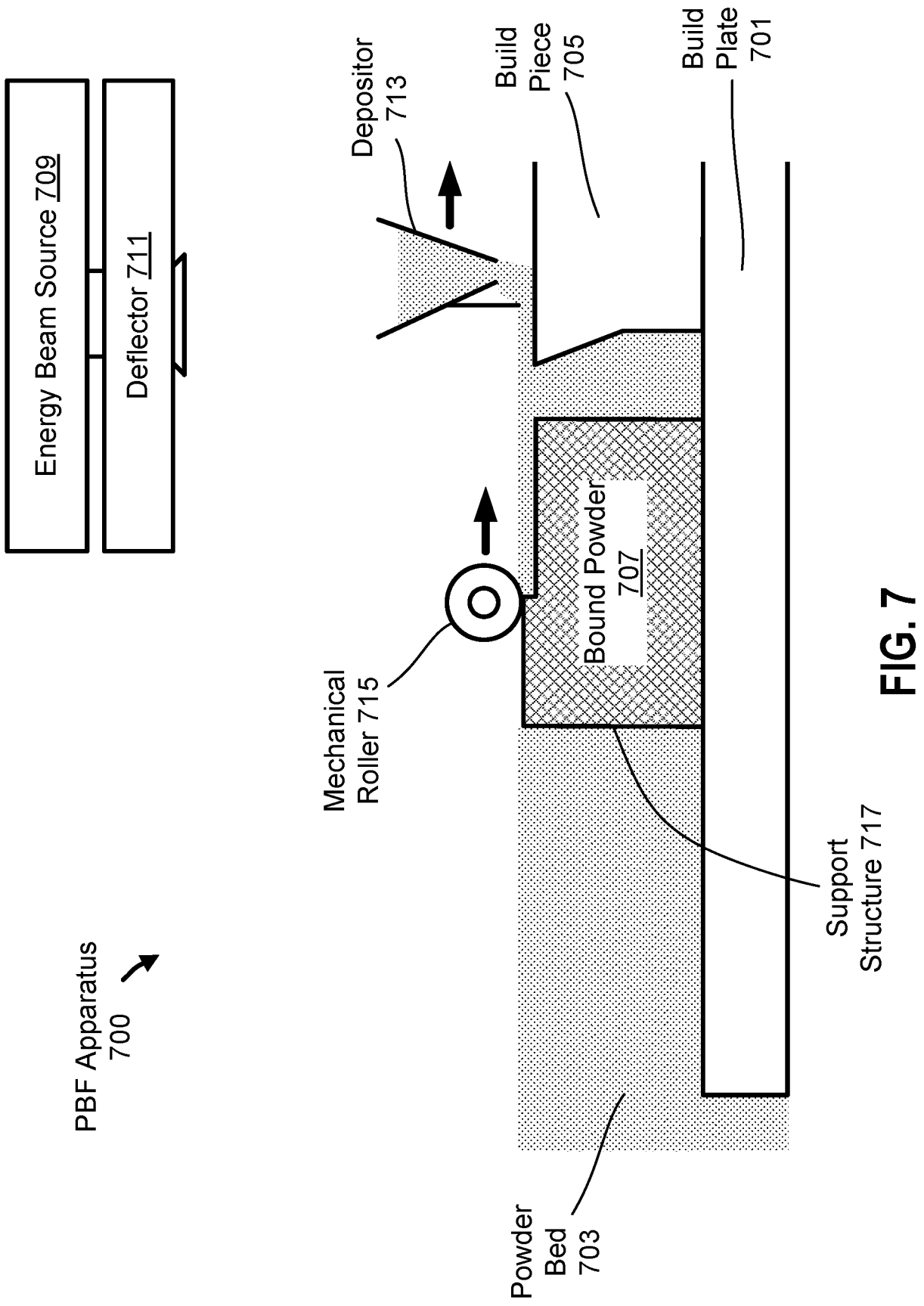

Energy Beam Source 709
Deflector 711
Depositor 713
Build Piece 705
Build Plate 701
Bound Powder 707
Mechanical Roller 715
Support Structure 717
Powder Bed 703
PBF Apparatus 700

FIG. 7

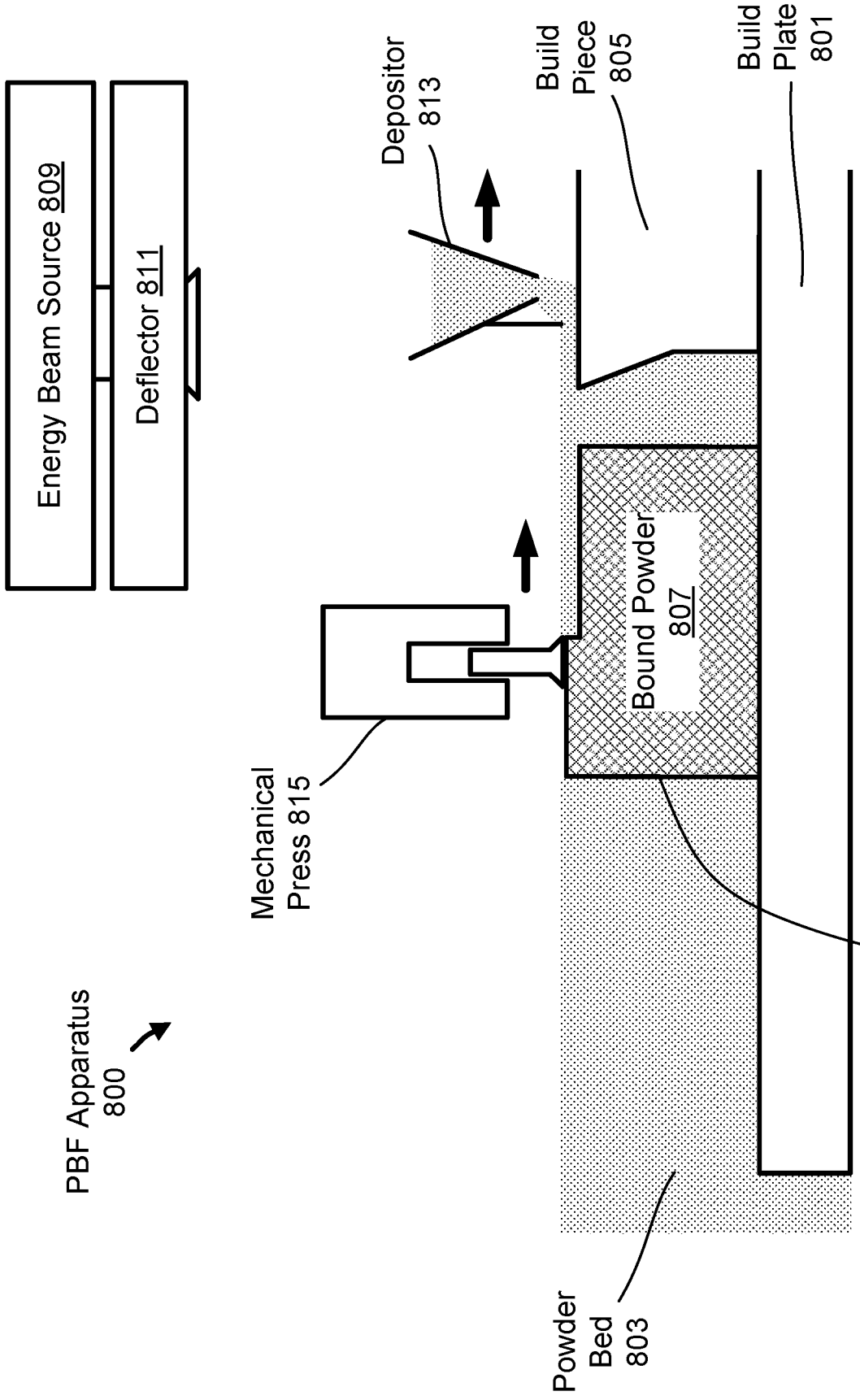

Energy Beam Source 809
Deflector 811
Depositor 813
Build Piece 805
Build Plate 801
Bound Powder 807
Mechanical Press 815
Support Structure 817
Powder Bed 803
PBF Apparatus 800

FIG. 8

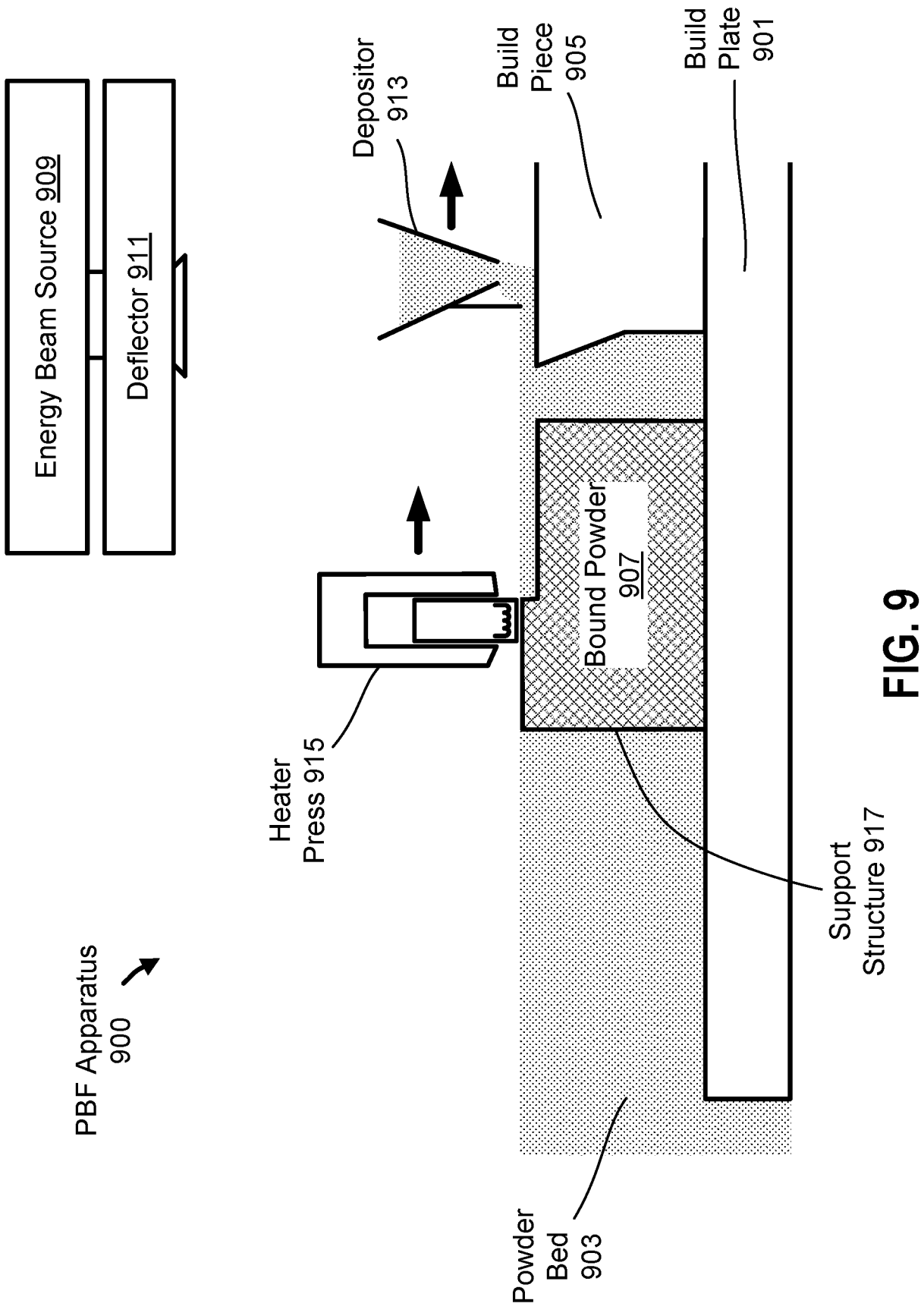

Energy Beam Source 909
Deflector 911
Depositor 913
Build Piece 905
Build Plate 901
Bound Powder 907
Heater Press 915
Support Structure 917
Powder Bed 903
PBF Apparatus 900

FIG. 9

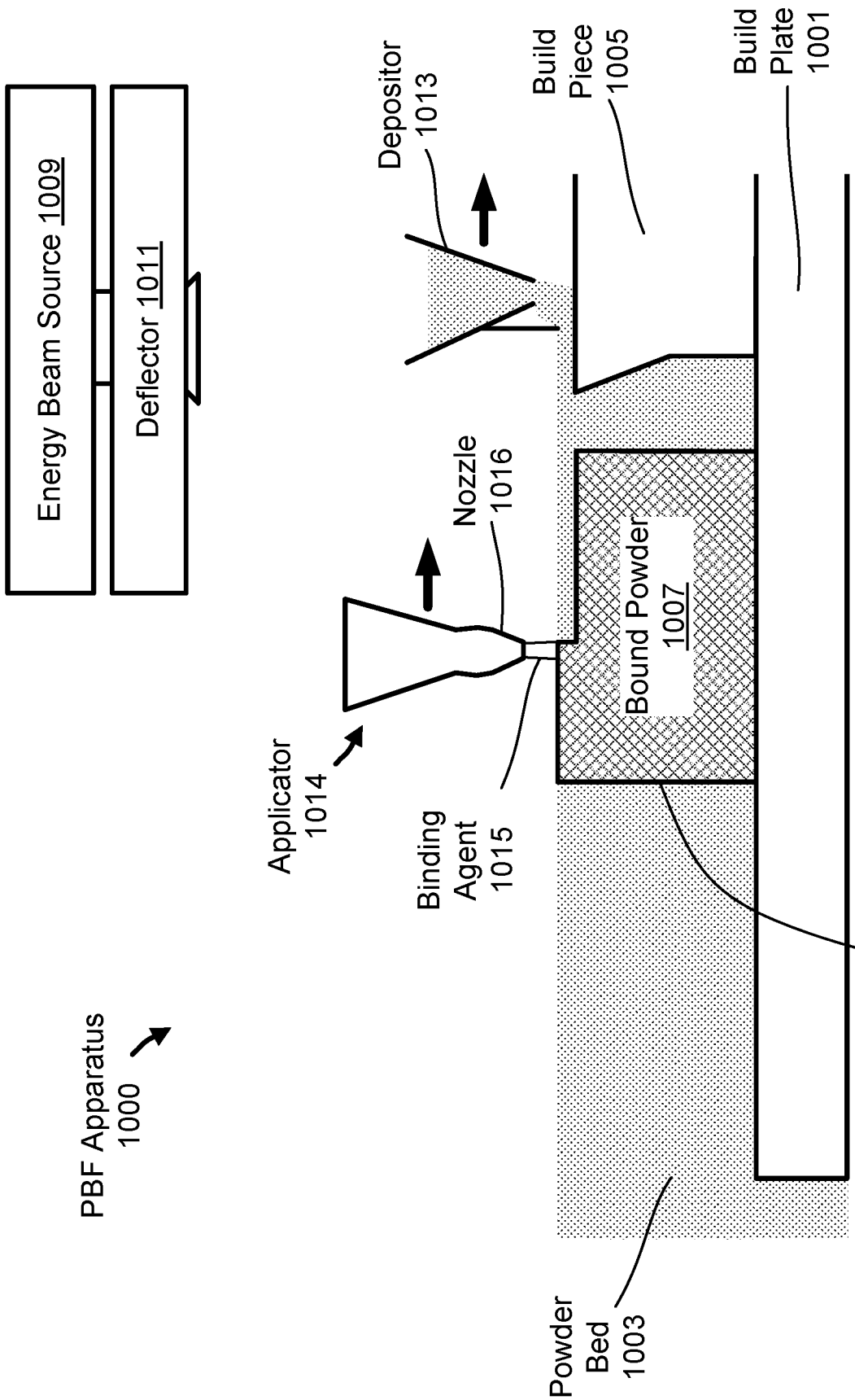

Energy Beam Source 1009
Deflector 1011
Depositor 1013
Build Piece 1005
Build Plate 1001
Nozzle 1016
Bound Powder 1007
Applicator 1014
Binding Agent 1015
Support Structure 1017
Powder Bed 1003
PBF Apparatus 1000

FIG. 10

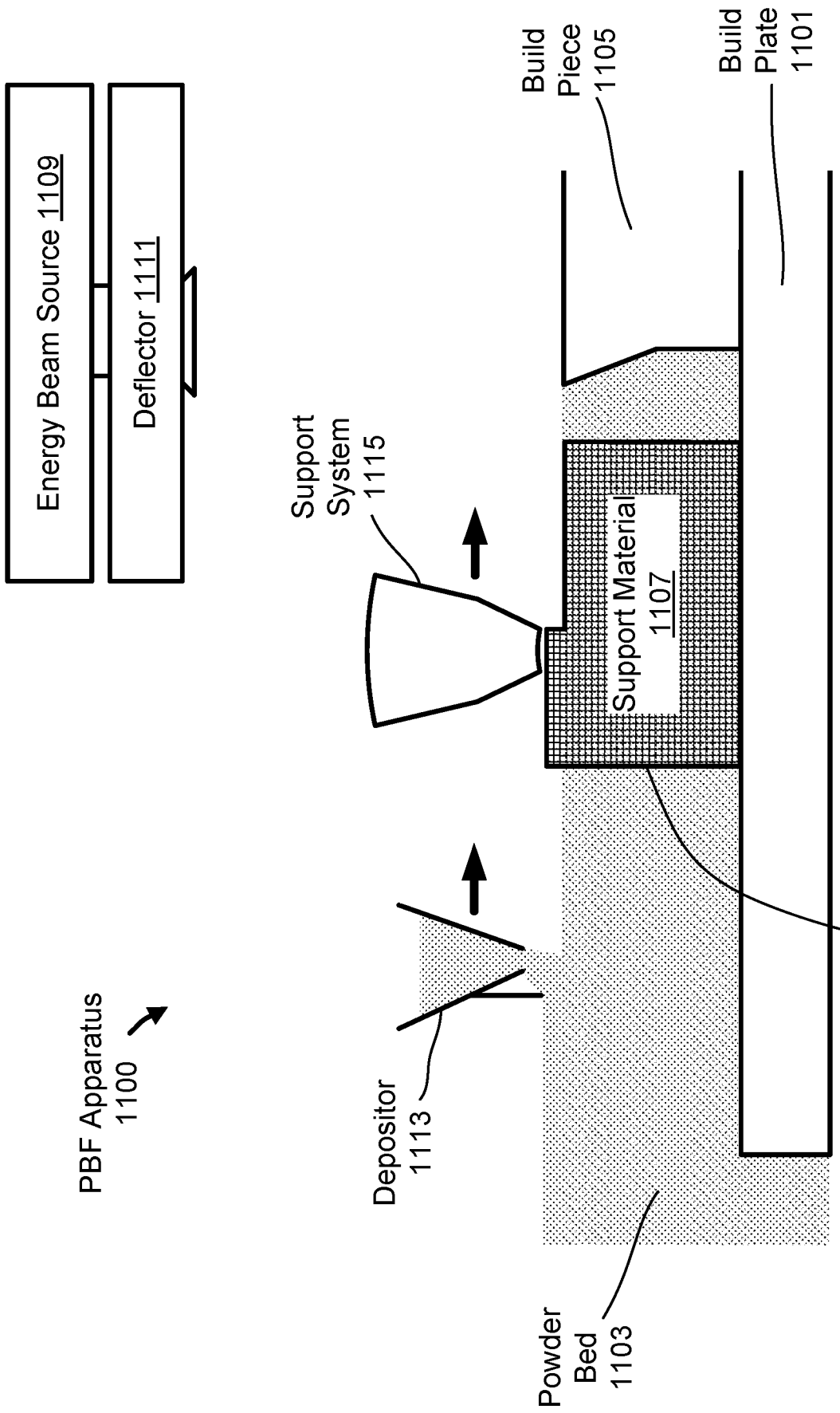

Energy Beam Source 1109
Deflector 1111
Build Piece 1105
Build Plate 1101
Support System 1115
Support Material 1107
Support Structure 1117
Depositor 1113
Powder Bed 1103
PBF Apparatus 1100

FIG. 11A

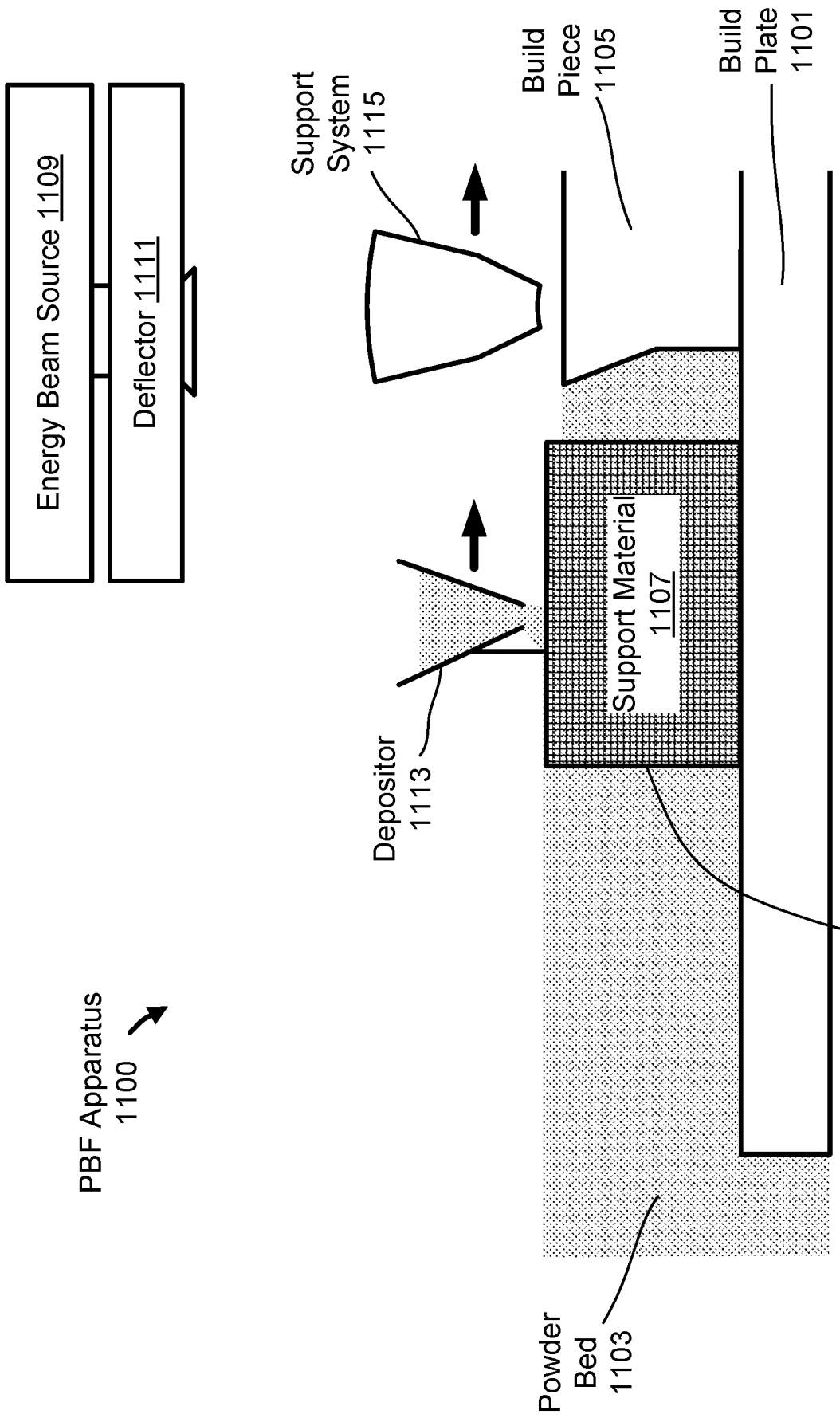

Energy Beam Source 1109
Deflector 1111
Support System 1115
Build Piece 1105
Build Plate 1101
Support Material 1107
Depositor 1113
Support Structure 1117
Powder Bed 1103
PBF Apparatus 1100

FIG. 11B

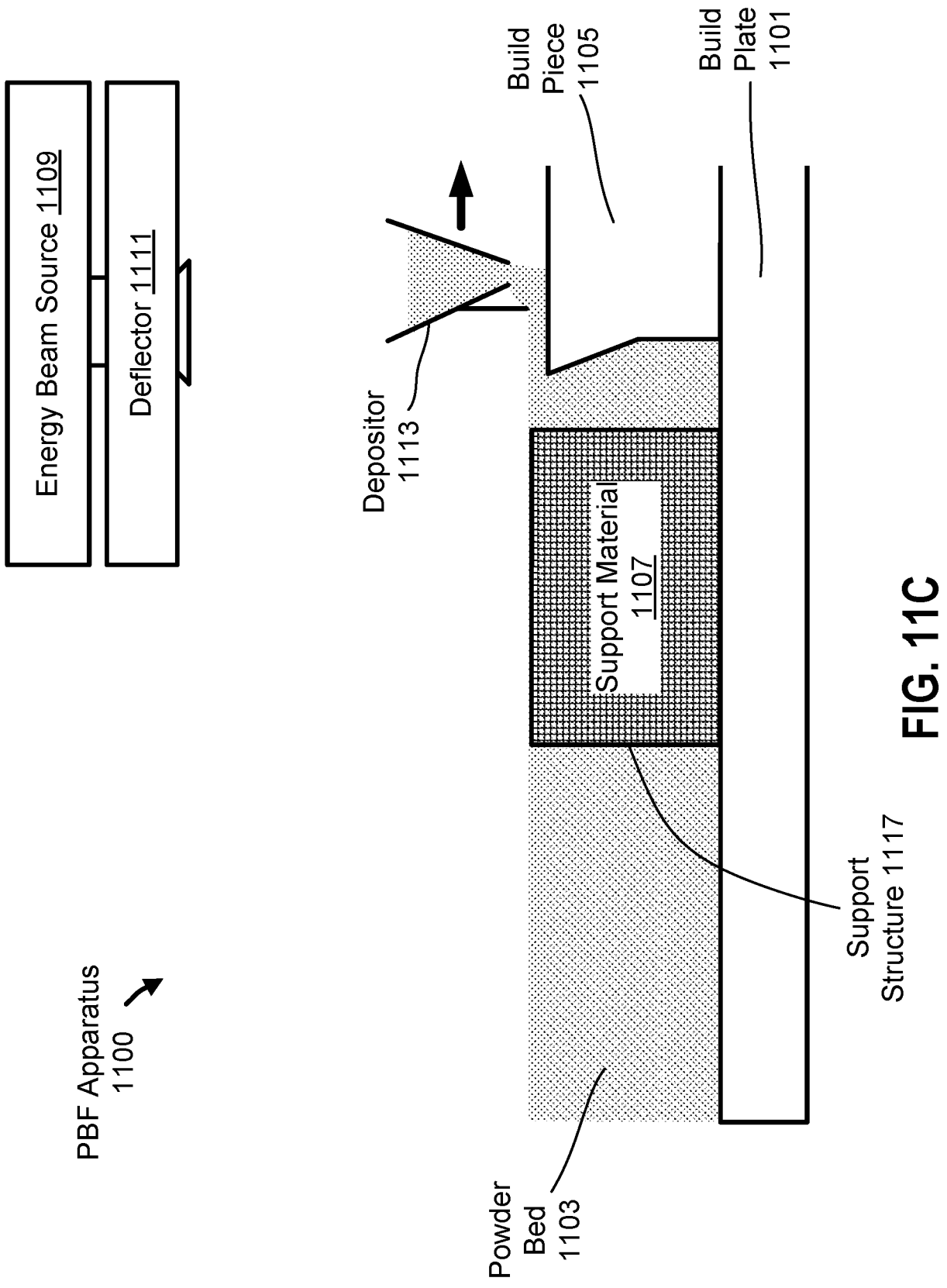

Energy Beam Source 1109
Deflector 1111
PBF Apparatus 1100
Build Piece 1105
Build Plate 1101
Depositor 1113
Support Material 1107
Support Structure 1117
Powder Bed 1103

FIG. 11C

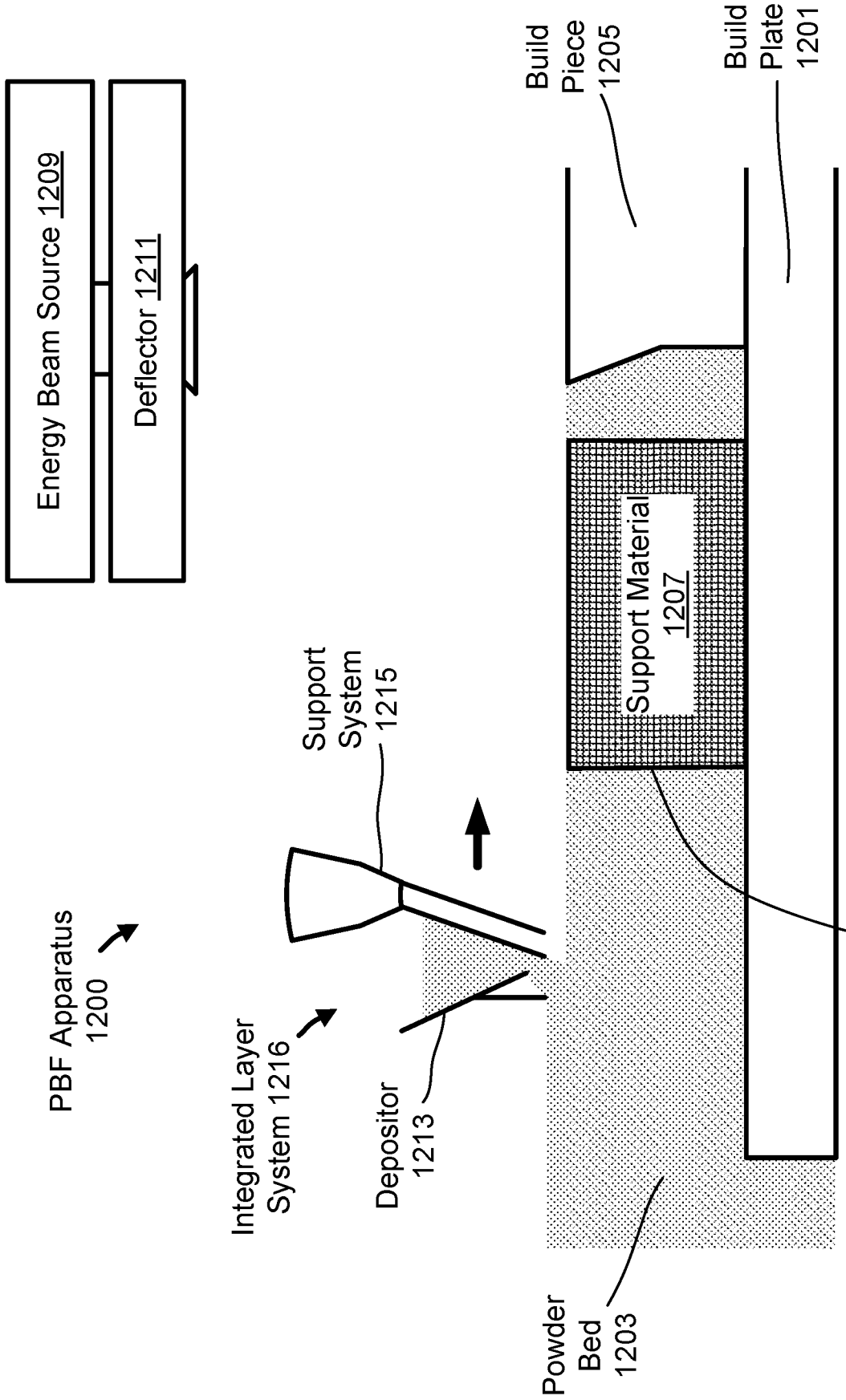

Energy Beam Source 1209
Deflector 1211
Build Piece 1205
Build Plate 1201
Support Material 1207
Support System 1215
PBF Apparatus 1200
Integrated Layer System 1216
Depositor 1213
Support Structure 1217
Powder Bed 1203

FIG. 12A

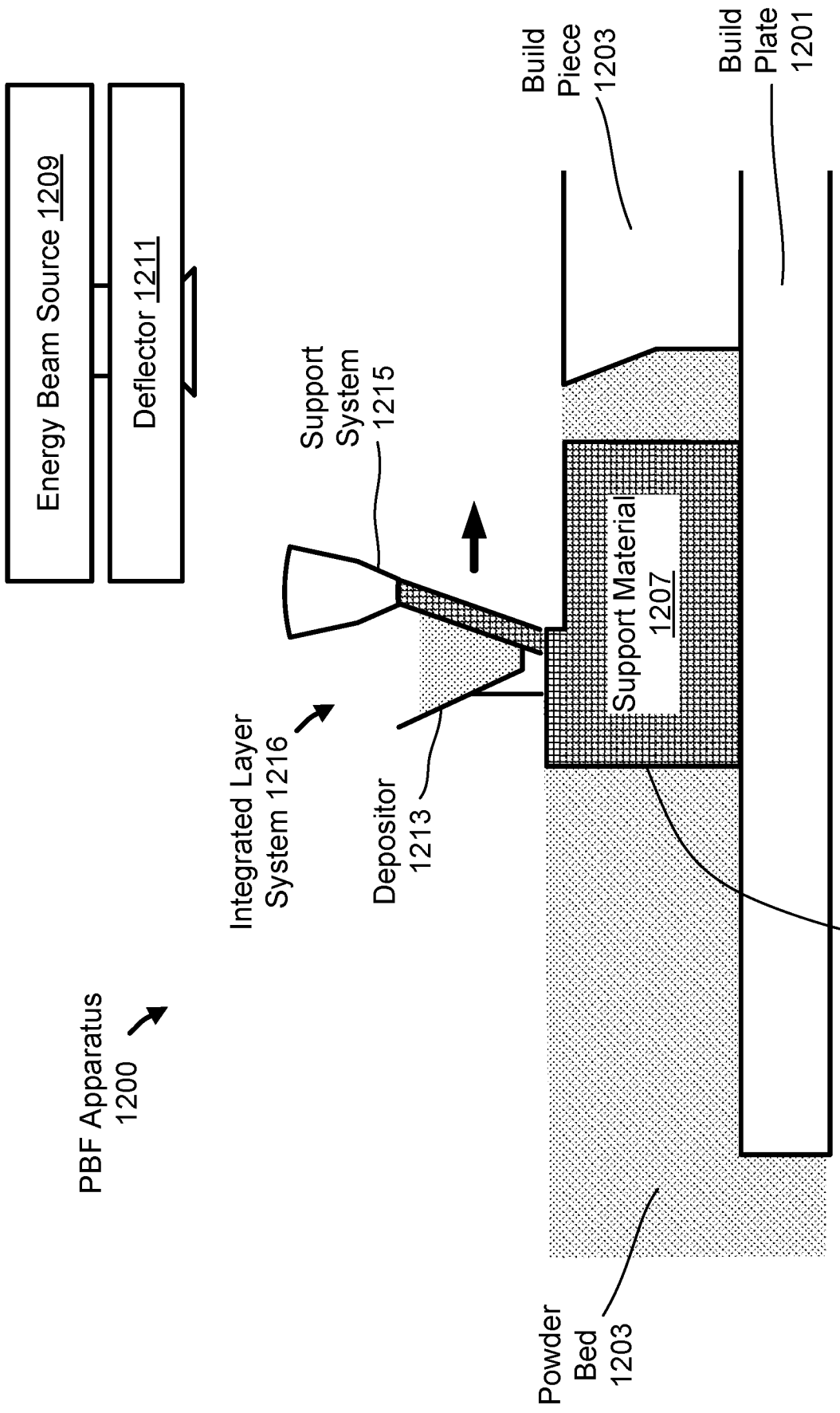

Energy Beam Source 1209
Deflector 1211
Build Piece 1203
Build Plate 1201
Support System 1215
Support Material 1207
Integrated Layer System 1216
Depositor 1213
Support Structure 1217
Powder Bed 1203
PBF Apparatus 1200

FIG. 12B

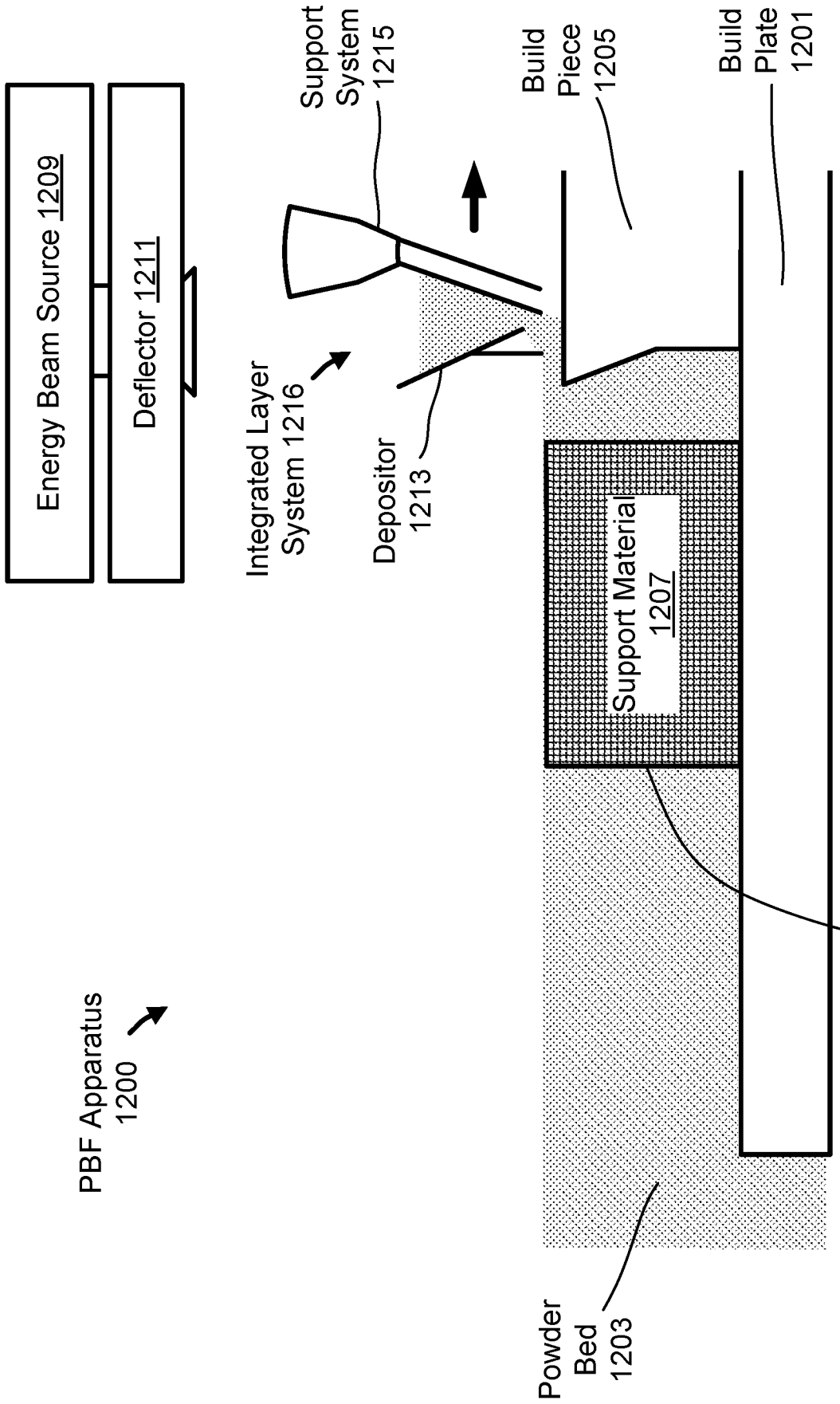

Energy Beam Source 1209
Deflector 1211
Support System 1215
Build Piece 1205
Build Plate 1201
Integrated Layer System 1216
Depositor 1213
Support Material 1207
PBF Apparatus 1200
Support Structure 1217
Powder Bed 1203

FIG. 12C

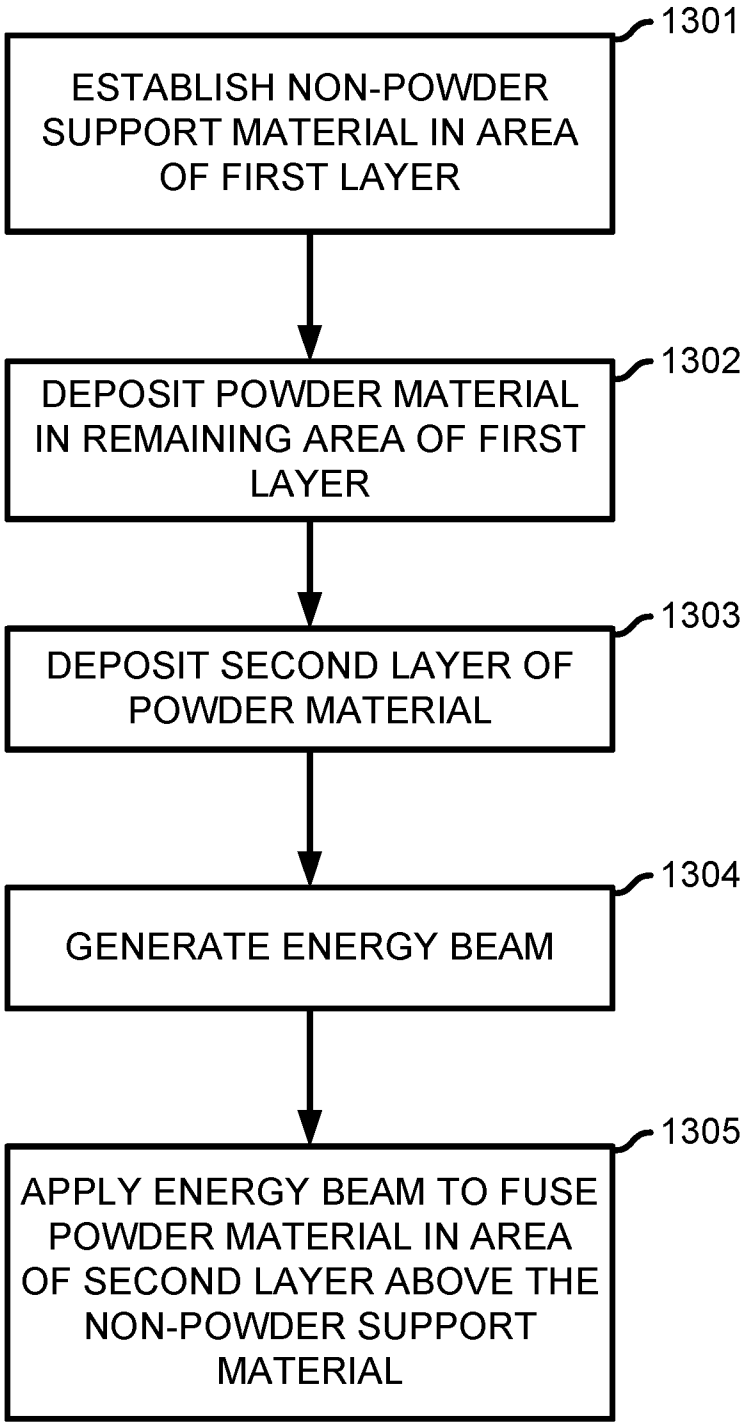

1301
ESTABLISH NON-POWDER SUPPORT MATERIAL IN AREA OF FIRST LAYER
1302
DEPOSIT POWDER MATERIAL IN REMAINING AREA OF FIRST LAYER
1303
DEPOSIT SECOND LAYER OF POWDER MATERIAL
1304
GENERATE ENERGY BEAM
1305
APPLY ENERGY BEAM TO FUSE POWDER MATERIAL IN AREA OF SECOND LAYER ABOVE THE NON-POWDER SUPPORT MATERIAL

FIG. 13

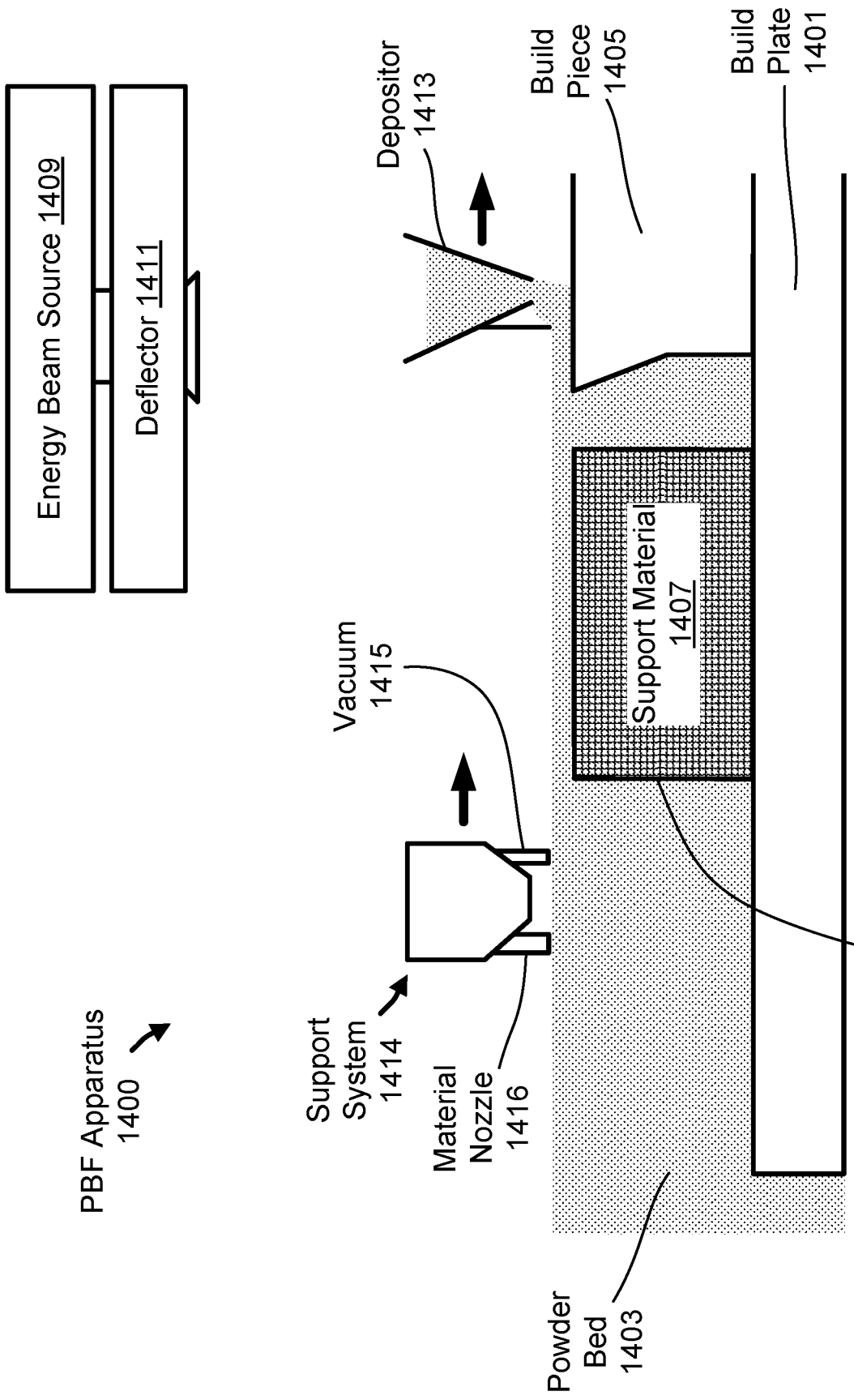

Energy Beam Source 1409
Deflector 1411
Depositor 1413
Build Piece 1405
Build Plate 1401
Support Material 1407
Vacuum 1415
Support System 1414
Material Nozzle 1416
Support Structure 1417
Powder Bed 1403
PBF Apparatus 1400

FIG. 14A

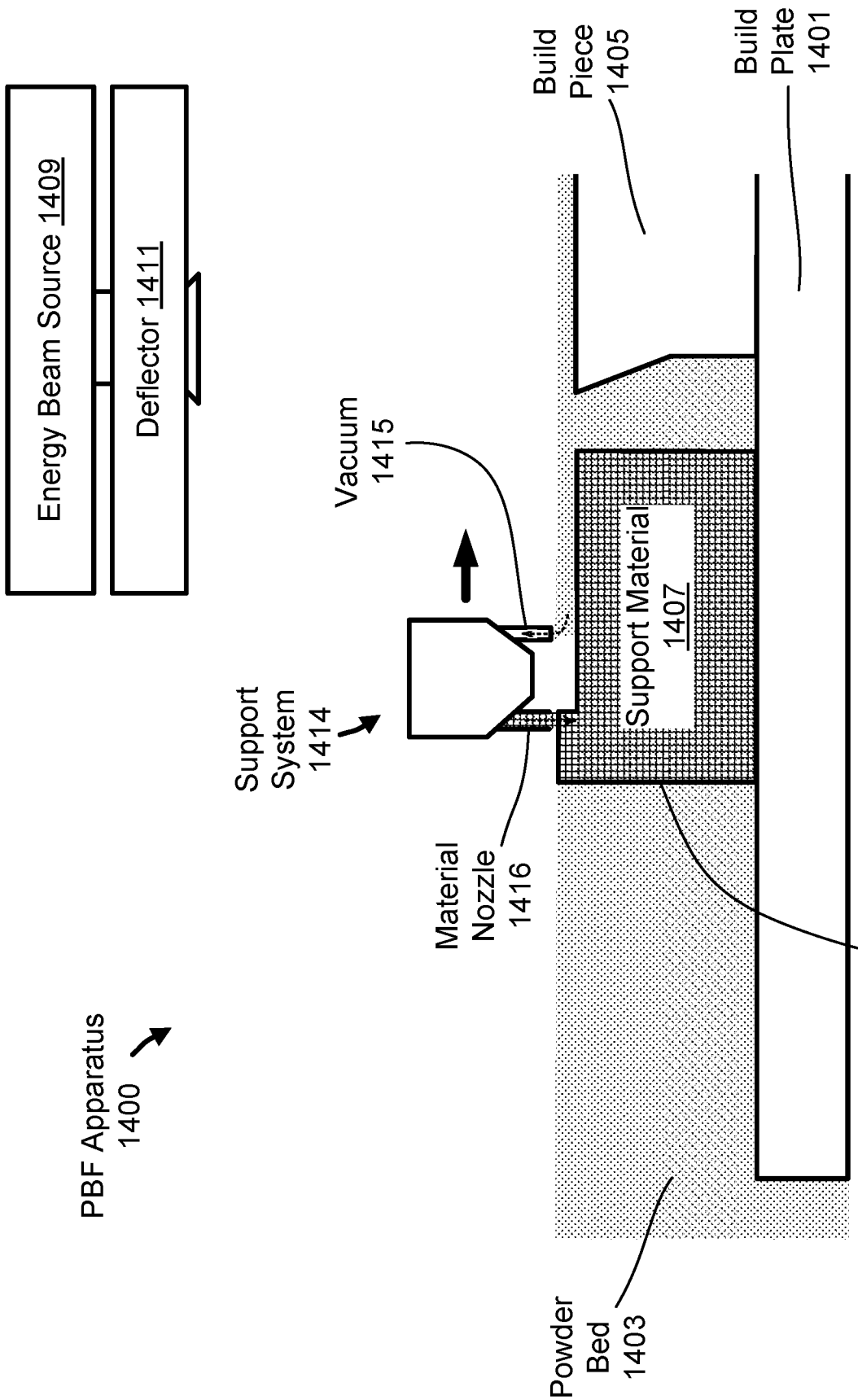

Energy Beam Source 1409
Deflector 1411
Build Piece 1405
Build Plate 1401
Vacuum 1415
Support System 1414
Support Material 1407
Material Nozzle 1416
Support Structure 1417
Powder Bed 1403
PBF Apparatus 1400

FIG. 14B

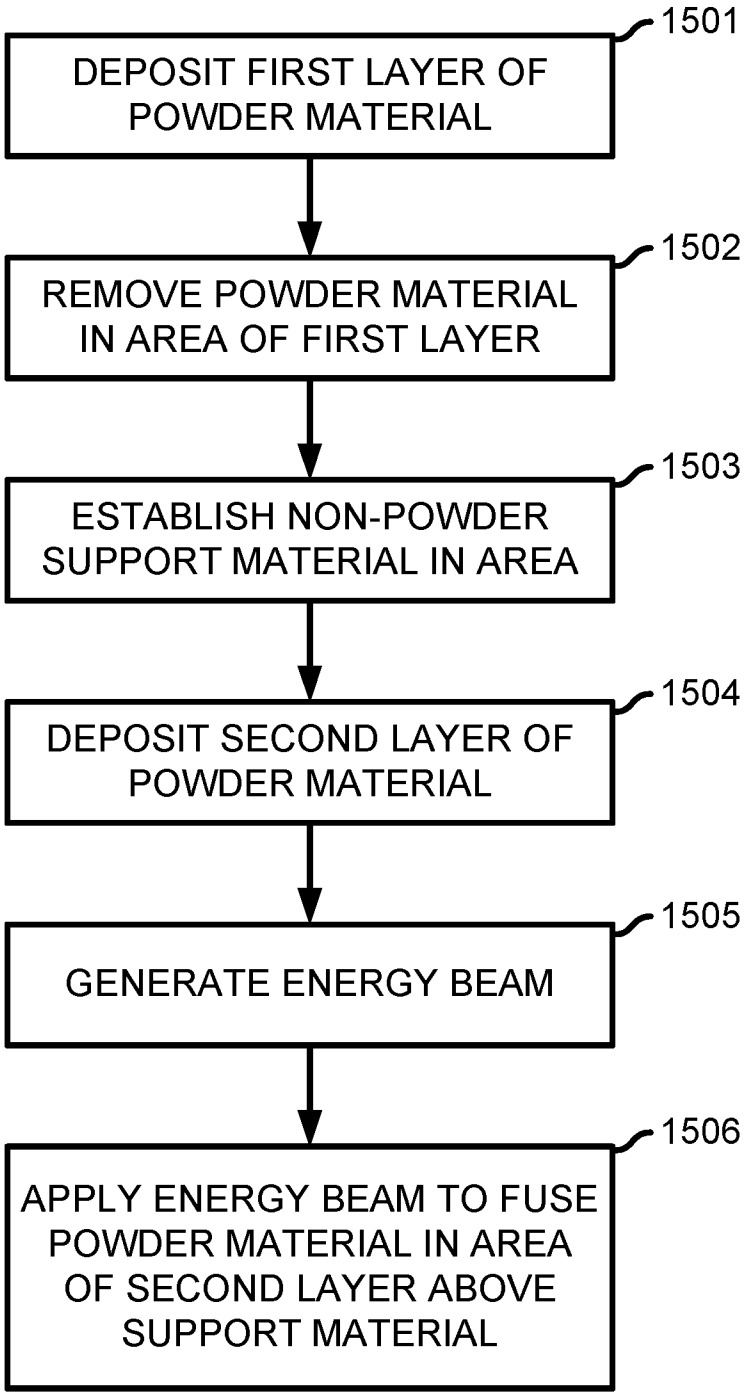

1501
DEPOSIT FIRST LAYER OF POWDER MATERIAL
1502
REMOVE POWDER MATERIAL IN AREA OF FIRST LAYER
1503
ESTABLISH NON-POWDER SUPPORT MATERIAL IN AREA
1504
DEPOSIT SECOND LAYER OF POWDER MATERIAL
1505
GENERATE ENERGY BEAM
1506
APPLY ENERGY BEAM TO FUSE POWDER MATERIAL IN AREA OF SECOND LAYER ABOVE SUPPORT MATERIAL

FIG. 15

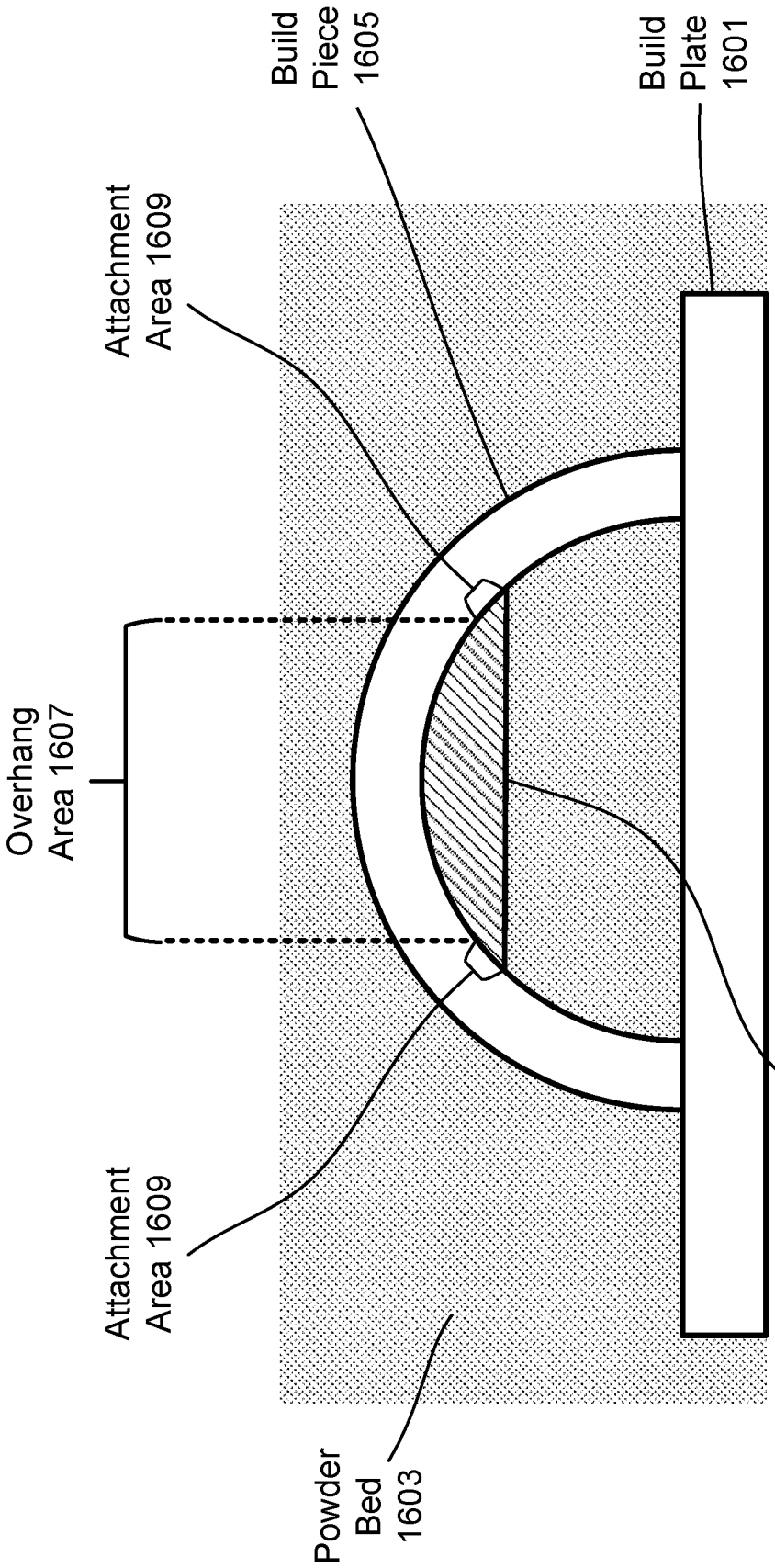

Build Piece 1605
Build Plate 1601
Attachment Area 1609
Overhang Area 1607
Attachment Area 1609
Support Structure 1600
Powder Bed 1603

FIG. 16

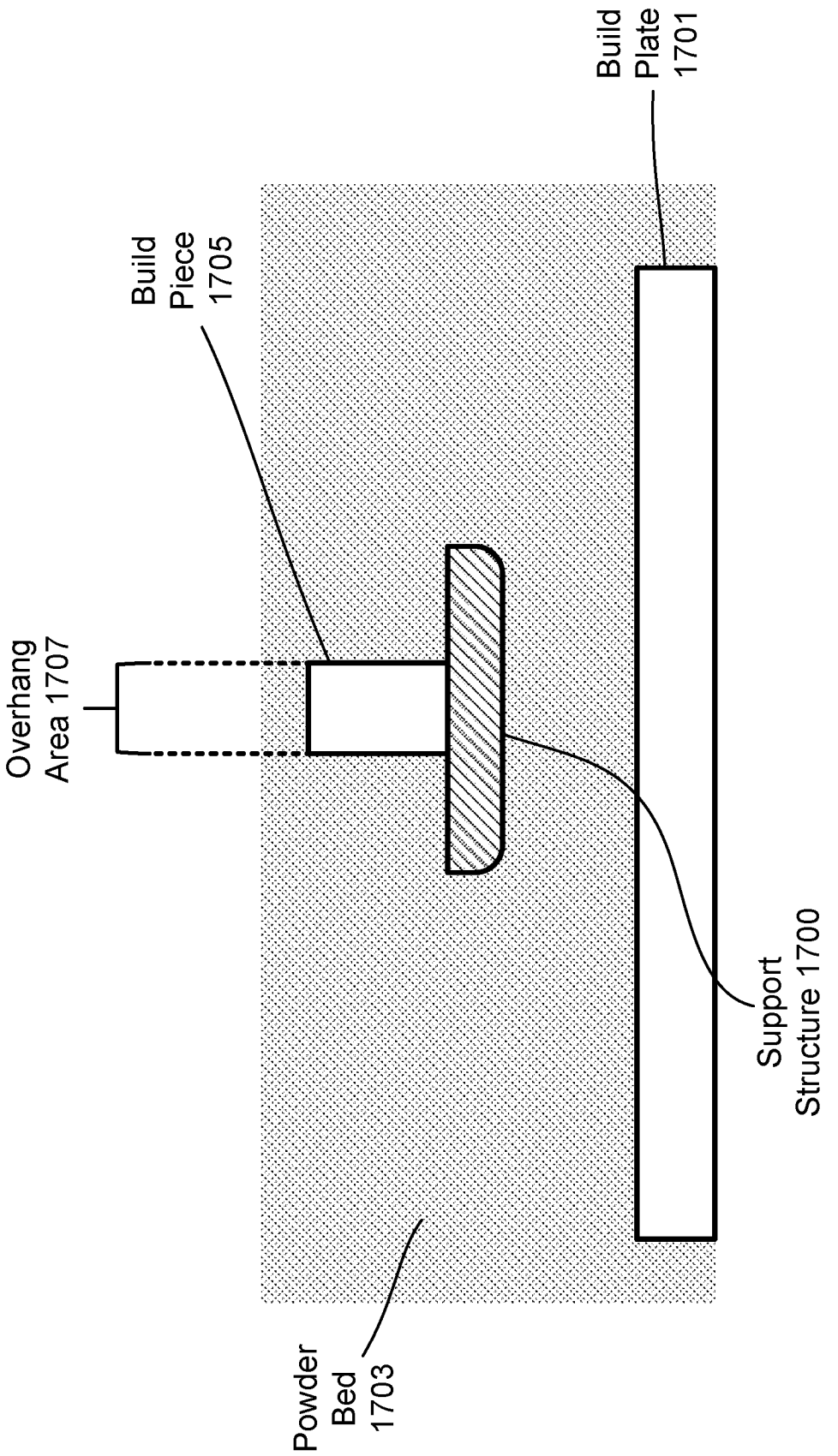

Build Plate 1701
Build Piece 1705
Overhang Area 1707
Support Structure 1700
Powder Bed 1703

FIG. 17

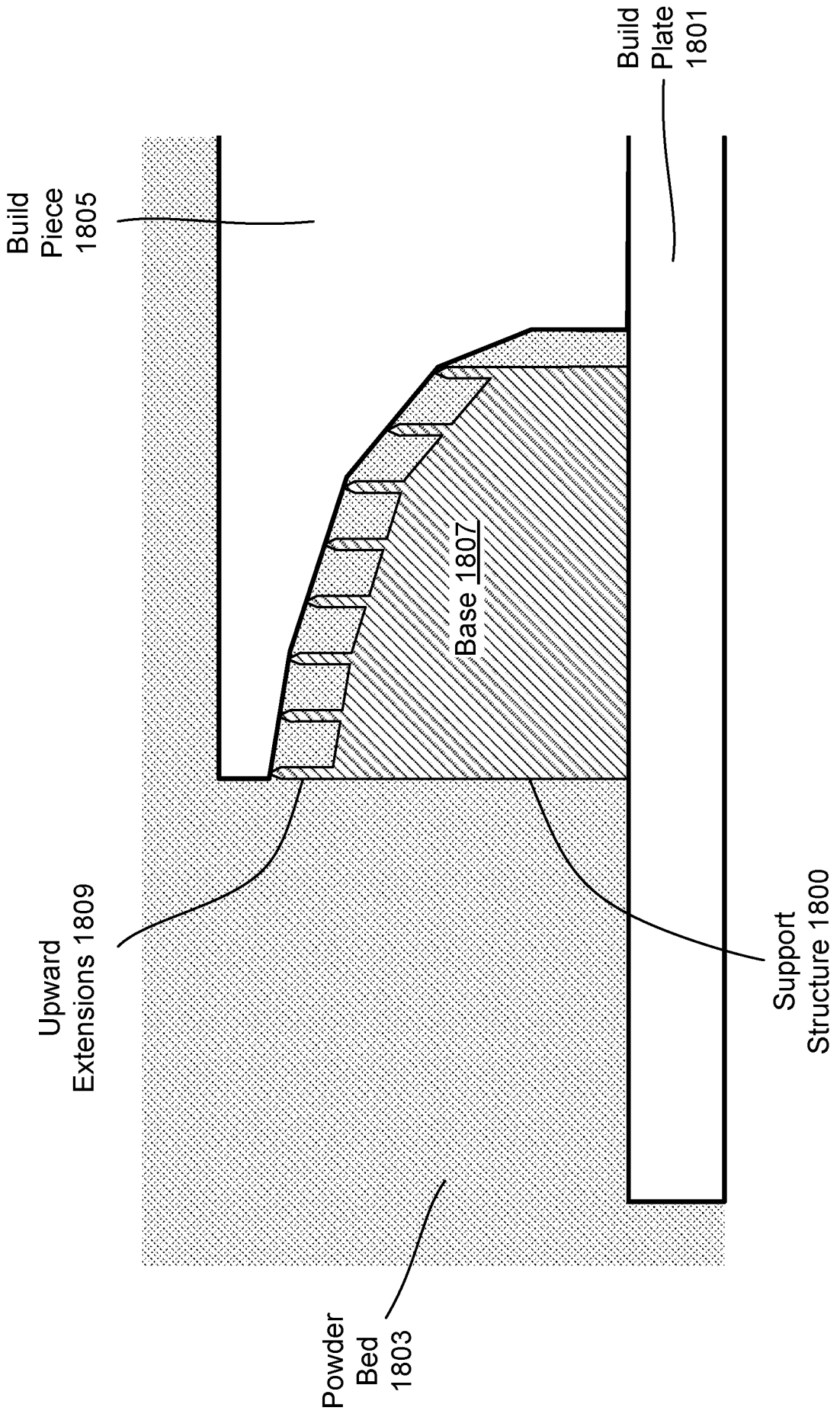

Build Plate 1801
Build Piece 1805
Base 1807
Upward Extensions 1809
Support Structure 1800
Powder Bed 1803

FIG. 18

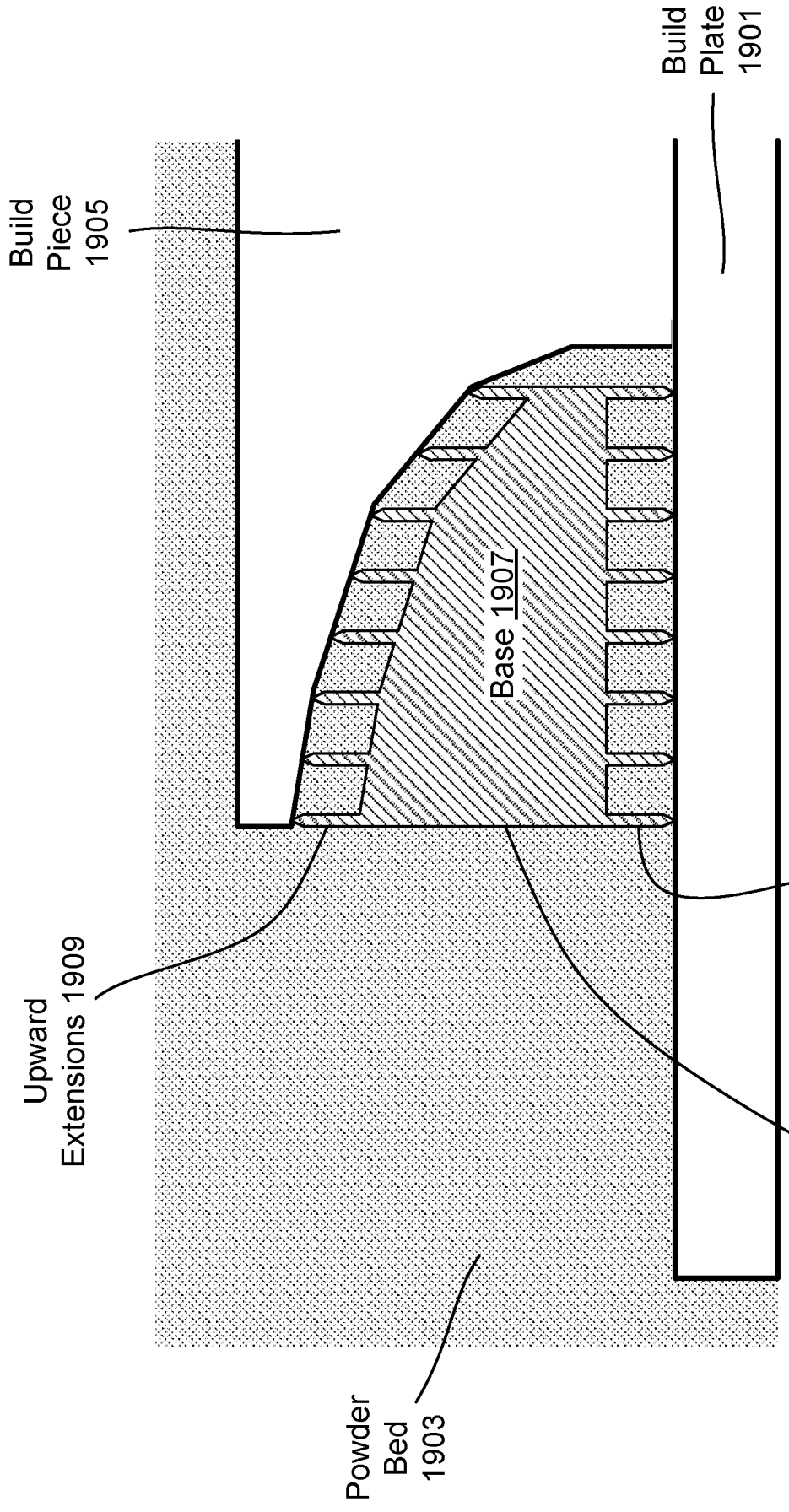

Build Plate 1901
Build Piece 1905
Base 1907
Upward Extensions 1909
Downward Extensions 1911
Support Structure 2400
Powder Bed 1903

FIG. 19

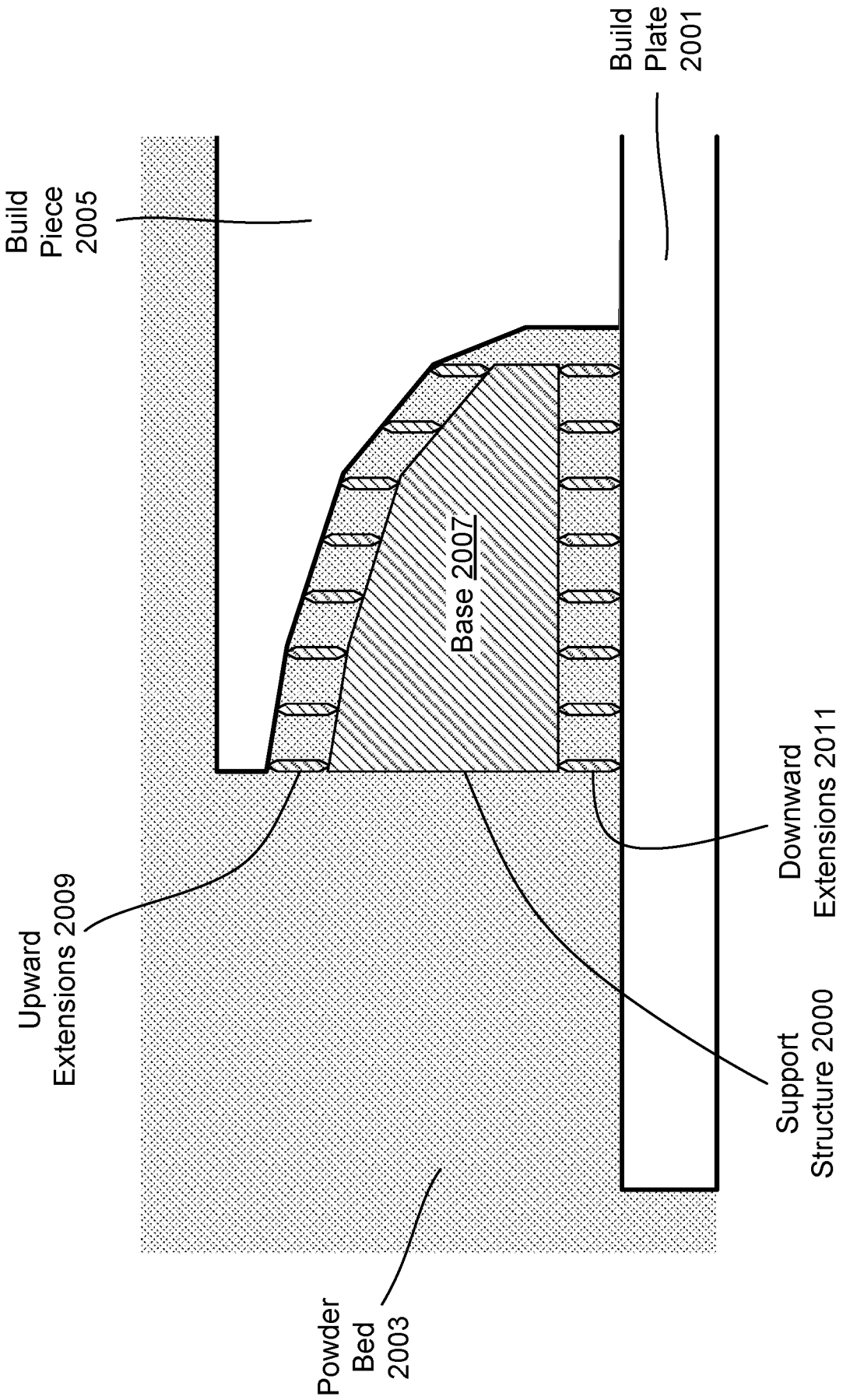

Build Plate 2001
Build Piece 2005
Base 2007
Upward Extensions 2009
Downward Extensions 2011
Support Structure 2000
Powder Bed 2003

FIG. 20

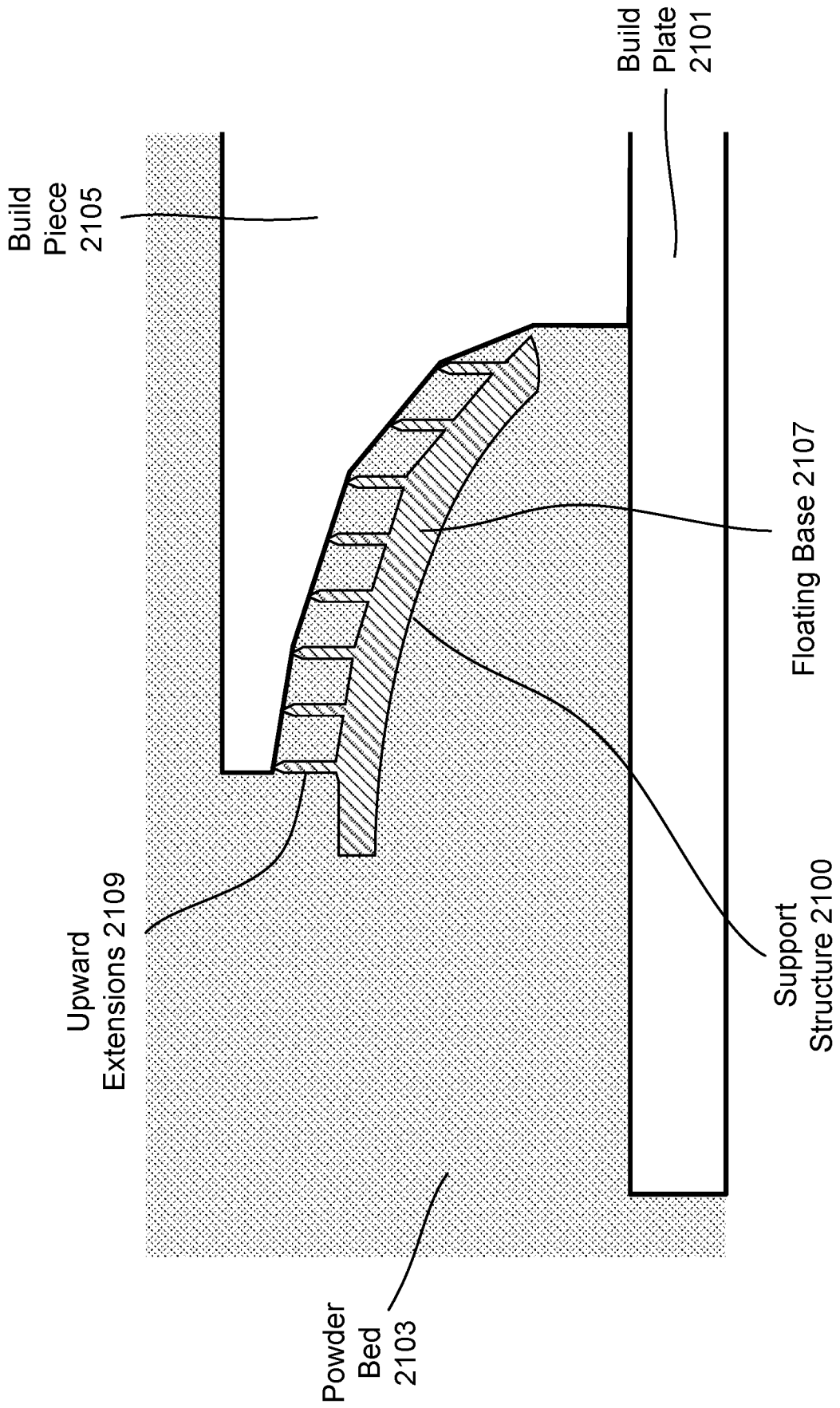

Build Plate 2101
Build Piece 2105
Floating Base 2107
Support Structure 2100
Upward Extensions 2109
Powder Bed 2103

FIG. 21

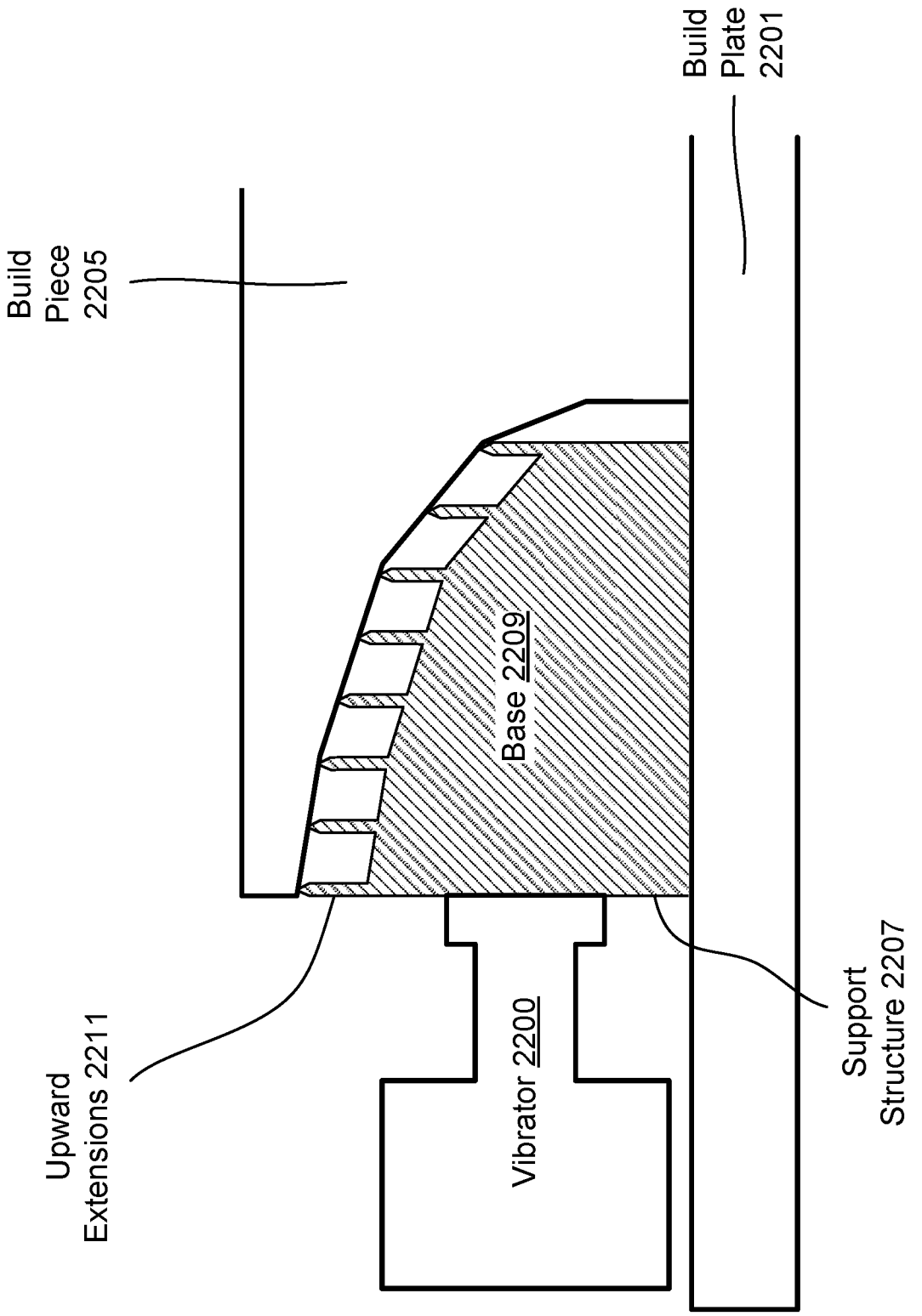

Build Plate 2201
Build Piece 2205
Base 2209
Upward Extensions 2211
Vibrator 2200
Support Structure 2207

FIG. 22

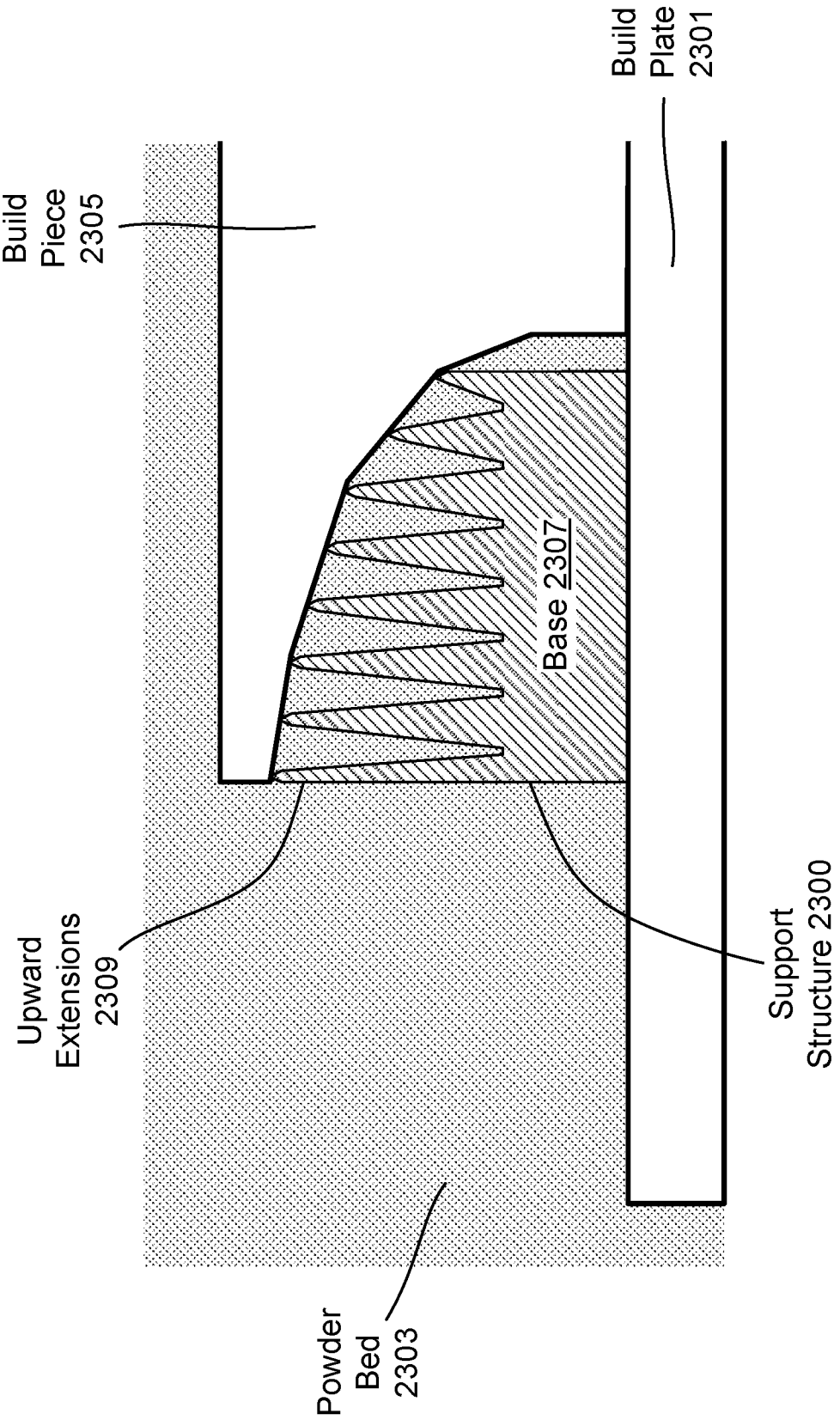

Build Plate 2301
Build Piece 2305
Base 2307
Upward Extensions 2309
Support Structure 2300
Powder Bed 2303

FIG. 23

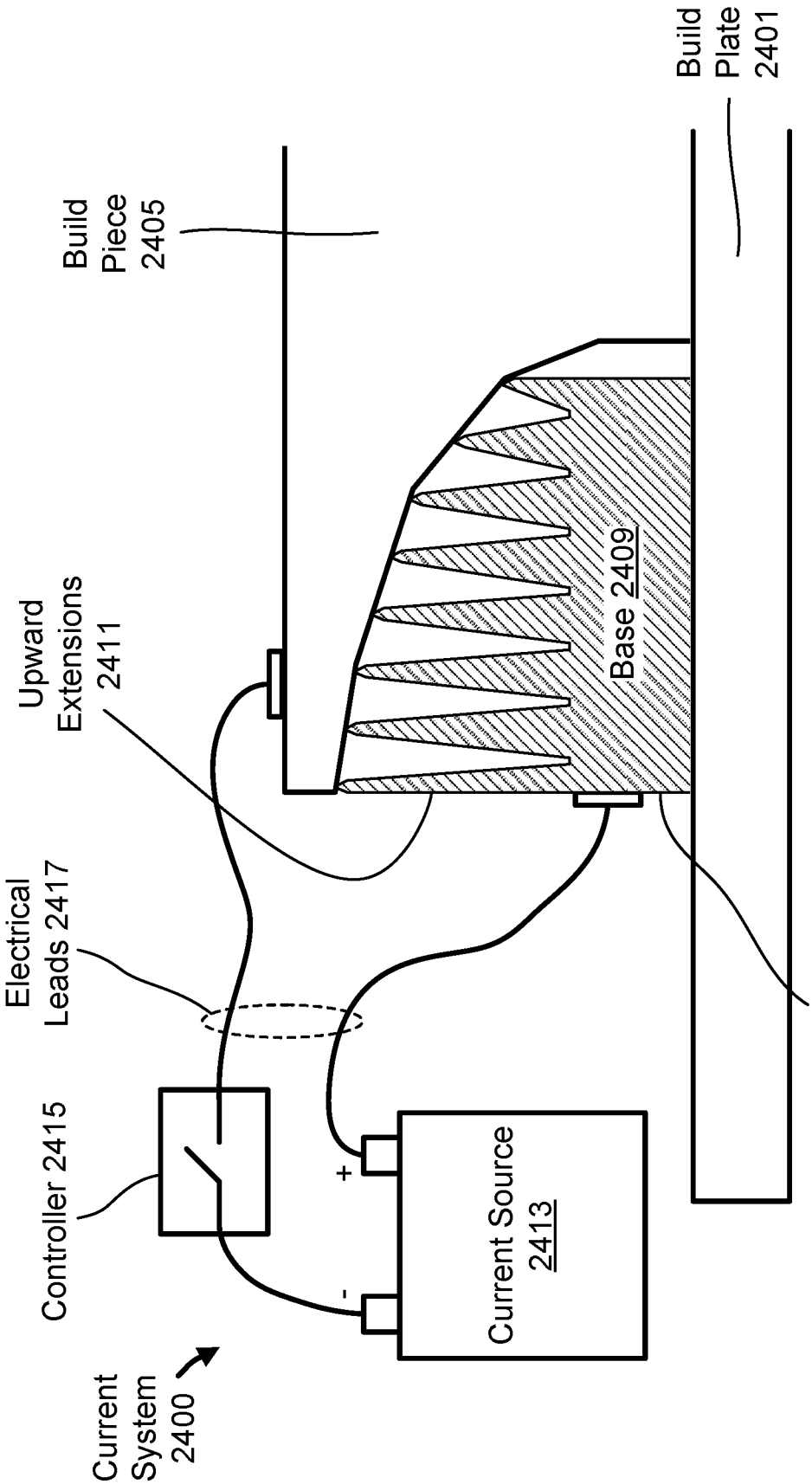

Build Plate 2401
Build Piece 2405
Upward Extensions 2411
Base 2409
Electrical Leads 2417
Controller 2415
Current Source 2413
+
-
Support Structure 2407
Current System 2400

FIG. 24

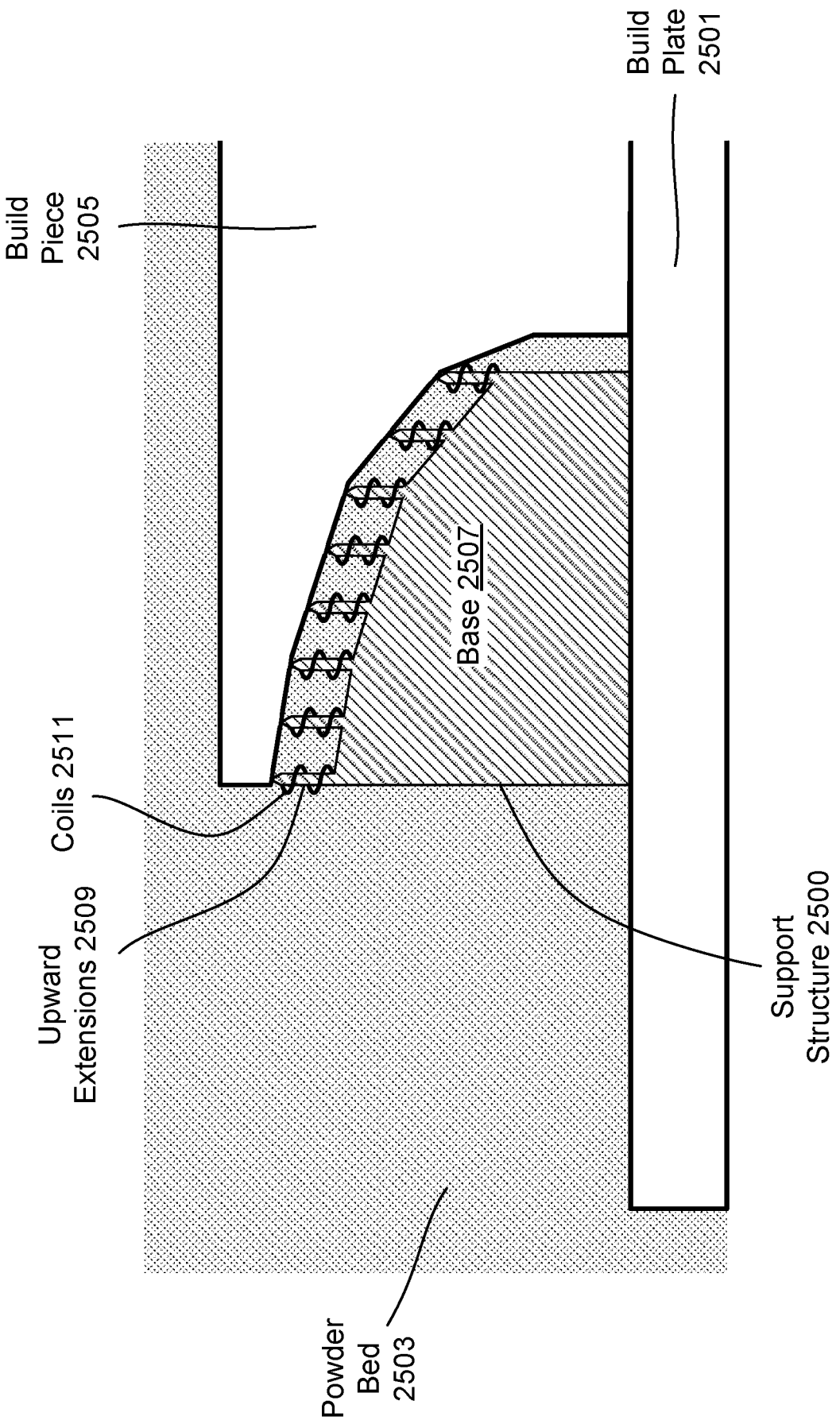

Build Plate 2501
Build Piece 2505
Base 2507
Coils 2511
Upward Extensions 2509
Support Structure 2500
Powder Bed 2503

FIG. 25

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/026944

A. CLASSIFICATION OF SUBJECT MATTER

B29C 64/218(2017.01)i, B29C 64/264(2017.01)i, B29C 64/141(2017.01)i, B29C 64/295(2017.01)i, B33Y 40/00(2015.01)i, B33Y 30/00(2015.01)i, B33Y 70/00(2015.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B29C 64/218; B33Y 30/00; B29C 31/04; B22F 3/105; B28B 11/24; B29C 64/264; B29C 64/141; B29C 64/295; B33Y 40/00; B33Y 70/00

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: support structure, additive manufacturing, powder-bed fusion, powder fixer, electrical current source, vibrator

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BOBBIO, LOURDES D. et al., "Characterization of the strength of support structures used in powder bed fusion additive manufacturing of Ti-6Al-4V", Additive Manufacturing, 2017 (Online published date: 19 January 2017), Vol. 14, pages 60-68 See abstract; pages 61-67; table 1; and figure 1.	1-51
X	US 2017-0072467 A1 (APPLIED MATERIALS, INC.) 16 March 2017 See paragraphs [0036]-[0140]; claim 1; and figures 1A, 4A-4D.	1-51
X	LEFKY, CHRISTOPHER S. et al., "Dissolvable supports in powder bed fusion-printed stainless steel", 3D Printing and Additive Manufacturing, 2017 (Online published date: 01 March 2017), Vol. 4, No. 1, pages 3-11 See abstract; pages 4-6; and figures 1, 3.	1-51
A	US 2004-0084814 A1 (BOYD, MELISSA D. et al.) 06 May 2004 See paragraphs [0016]-[0038]; claims 1, 5; and figure 2B.	1-51
A	CALIGNANO, F., "Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting", Materials & Design, 2014, Vol. 64, pages 203-213 See abstract; and pages 204-213.	1-51

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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

Date of the actual completion of the international search	Date of mailing of the international search report
16 August 2018 (16.08.2018)	**20 August 2018 (20.08.2018)**

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

Authorized officer
KWON, Yong Kyong
Telephone No. +82-42-481-3371

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/026944

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		CN 108025499 A	11/05/2018
		CN 108025500 A	11/05/2018
		CN 108025501 A	11/05/2018
		CN 108025502 A	11/05/2018
		KR 10-2018-0042305 A	25/04/2018
		KR 10-2018-0042306 A	25/04/2018
		KR 10-2018-0043295 A	27/04/2018
		KR 10-2018-0043303 A	27/04/2018
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		WO 2017-048926 A1	23/03/2017
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		WO 2017-049156 A1	23/03/2017
US 2004-0084814 A1	06/05/2004	None	