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(54) **Title**: THREE-DIMENSIONAL PRINTING PROGRESS VERIFICATION METHODS AND APPARATUSES

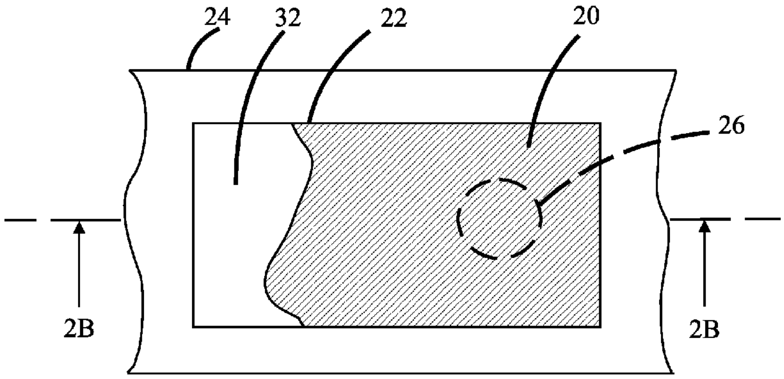

FIG. 2A

(57) **Abstract**: Three-dimensional printing processes are disclosed which include at least one of a step of determining satisfactoriness of a powder layer (22) prior to printing and a step of determining the satisfactoriness of a print bed after the powder layer (22) has been printed upon. If at least one of the powder layer (22) and the print bed are not satisfactory, then the three-dimensional printing process is halted and, optionally, the operator is alerted. Three-dimensional printing apparatuses (120) suitable for carrying out the processes are also disclosed.

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PATENT COOPERATION TREATY PATENT APPLICATION

Title: Three-Dimensional Printing Progress Verification Methods and Apparatuses

Inventors: Andrew Klein and Thomas Lizzi

[0001] Field of the Invention: The present invention relates to methods of and apparatuses for three-dimensional printing processes which utilize a powder spreading step followed by a binder-jet deposition step.

[0002] Background of the Invention: Three dimensional printing was developed in the 1990's at the Massachusetts Institute of Technology and is described in several United States patents, including the following United States patents: 5,490,882 to Sachs et al., 5,490,962 to Cima et al., 5,518,680 to Cima et al., 5,660,621 to Bredt et al., 5,775,402 to Sachs et al., 5,807,437 to Sachs et al., 5,814,161 to Sachs et al., 5,851,465 to Bredt, 5,869,170 to Cima et al., 5,940,674 to Sachs et al., 6,036,777 to Sachs et al., 6,070,973 to Sachs et al., 6,109,332 to Sachs et al., 6,112,804 to Sachs et al., 6,139,574 to Vacanti et al., 6,146,567 to Sachs et al., 6,176,874 to Vacanti et al., 6,197,575 to Griffith et al., 6,280,771 to Monkhouse et al., 6,354,361 to Sachs et al., 6,397,722 to Sachs et al., 6,454,811 to Sherwood et al., 6,471,992 to Yoo et al., 6,508,980 to Sachs et al., 6,514,518 to Monkhouse et al., 6,530,958 to Cima et al., 6,596,224 to Sachs et al., 6,629,559 to Sachs et al., 6,945,638 to Teung et al., 7,077,334 to Sachs et al., 7,250,134 to Sachs et al., 7,276,252 to Payumo et al., 7,300,668 to Pryce et al., 7,815,826 to Serdy et al., 7,820,201 to Pryce et al., 7,875,290 to Payumo et al., 7,931,914 to Pryce et al., 8,088,415 to Wang et al., 8,211,226 to Bredt et al., and 8,465,777 to Wang et al. In essence, three-dimensional printing involves the spreading of a layer of particulate material and then selectively jet-printing a fluid onto that layer to cause selected portions of the particulate layer to bind together. This sequence is repeated for additional layers until the desired article has been constructed. The material making up the particulate layer is often referred as the "build material" and the jetted fluid is often referred to as a "binder", or in some cases, an "activator"; the term "binder" will be used herein to refer to all types of jetted fluids used in three-dimensional printing. Post-processing of the three-dimensionally printed article is often required in order to strengthen and/or densify the article.

[0003] The powder layer thickness determines the resolution of the article in the vertical direction – also known as the "z-direction" or the "build direction" – and so it is desirable to set the powder layer thickness to be as thin as possible. On the other hand, the number of powder layers that need to be deposited and printed upon to make an article determines the number of powder deposition/printing cycles and therefore the amount of time to print the article. Thus, there is also an incentive to make the powder layer thickness as great as possible to minimize the time necessary to make the article. The powder layer thickness is therefore determined by balancing resolution and print time. Typically, the selected print layer thickness is within the range of a few tens of microns to a few hundreds of microns. Thus, hundreds to thousands of powder deposition/print cycles typically are required to make an article or set of articles.

[0004] Three-dimensional printing is an automated process which typically requires little or no operator attention between the start and the finish of the printing of an article or a set of articles. Thus, the three-dimensional printing process may go on for hours without operator supervision. Nonetheless, glitches may occur during the three-dimensional printing process which may compromise the aesthetic and/or structural integrity of the printed article. For example, physical or electrical anomalies during the printing process may occur which cause the powder layer deposition to be unsatisfactory or one or more jets of a printhead to fail to print. Thus, there is a need in the art to be able to immediately detect irregularities in the powder deposition and printing steps of the three-dimensional printing process.

Summary of the Invention

[0005] The present invention satisfies this need by providing methods for detecting irregularities in the powder deposition and/or printing steps of the three-dimensional printing process.

[0006] In some method embodiments of the present invention, an image of an as-deposited powder layer is captured and compared against a standard to determine if the powder layer is sufficiently satisfactory for the production of the article or articles that are being made by the three-dimensional process. If the powder layer is deemed to be unsatisfactory as a result of this comparison, the three-dimensional printing process is halted and, optionally, an alert message is provided to the operator that his or her attention is required.

[0007] In some method embodiments of the present invention, an image of a powder layer is captured and compared against the expected image for the powder layer to determine if the binder jet deposition onto the powder layer, i.e., the printing, is sufficiently satisfactory for the production of the article or articles that are being made by the three-dimensional process. If the binder jet deposition is deemed to be unsatisfactory as a result of this comparison, the three-dimensional printing process is halted and, optionally, an alert message is provided to the operator that his or her attention is required.

[0008] Some method embodiments of the present invention include the aforementioned step of determining the satisfactoriness of the as-deposited powder layer and the aforementioned step of determining the satisfactoriness of the printing. If either of the powder layer or the binder jet deposition is deemed to be unsatisfactory as a result of these comparisons, the three-dimensional printing process is halted and, optionally, an alert message is provided to the operator that his or her attention is required.

[0009] In the aforementioned method embodiments of the present invention, the image capturing and comparison steps may be conducted for each layer of the article or they may done for preselected layers or they may be done for random layers. In the method embodiments which include both types of image capturing, both types of image capturing and comparison steps may be done for the same layer or for different layers, e.g. for alternative layers. In some method embodiments, both types of image capturing may be done simultaneously.

[0010] The present invention also includes apparatuses which are adapted to carry out the method embodiments of the present invention.

Brief Description of the Drawings

[0011] The criticality of the features and merits of the present invention will be better understood by reference to the attached drawings. It is to be understood, however, that the drawings are designed for the purpose of illustration only and not as a definition of the limits of the present invention.

[0012] FIG. 1 is a schematic flow chart which generally outlines the step of determining the satisfactoriness of a powder layer in embodiments of the present invention.

[0013] FIG. 2A is a schematic planar view a powder layer within the build cavity of a three-dimensional printing apparatus (only partly shown) which is used as an aid in the description of a method embodiment of the present invention.

[0014] FIG. 2B is a schematic cross-sectional view taken along cutting plane **2B-2B** of FIG. 2A.

[0015] FIG. 3 is a schematic perspective drawing showing an example of mobile instrument sensing portions attached to a powder spreader carriage in accordance with an embodiment of the present invention.

[0016] FIG. 4 is a schematic flowchart which generally outlines the step of determining the satisfactoriness of the printing in embodiments of the present invention.

[0017] FIG. 5 is a schematic perspective view of a base three-dimensional printing device.

[0018] FIG. 6 is a schematic flow chart which generally outlines a step of determining the satisfactoriness of both the powder layer and the print bed according to an embodiment.

[0019] FIG. 7 is schematic flow chart which generally outlines a step of determining the satisfactoriness of both the powder layer and the print bed simultaneously according to an embodiment.

[0020] FIG. 8 is schematic flow chart which generally outlines another step of determining the satisfactoriness of both the powder layer and the print bed simultaneously according to an embodiment.

Detailed Description of Preferred Embodiments

[0021] In this section, some preferred embodiments of the present invention are described in detail sufficient for one skilled in the art to practice the present invention without undue experimentation. It is to be understood, however, that the fact that a limited number of preferred embodiments are described herein does not in any way limit the scope of the present invention as set forth in the claims. It is to be understood that whenever a range of values is described herein or in the claims that the range includes the end points and every point therebetween as if each and every such point had been expressly described. Unless otherwise stated, the word "about" as used herein and in the claims is to be construed as meaning the normal measuring and/or fabrication limitations related to the value which the word "about" modifies. Unless expressly stated otherwise, the term "embodiment" is used herein to mean an embodiment of the present invention.

[0022] It is to be understood that it is within the scope of the present invention that the embodiments of the methods and apparatuses described herein may be used to make a single article or to make multiple articles at the same time. However, for simplicity sake, the descriptions of the preferred embodiments below reference only the making of a single article.

[0023] It is to be understood that the term "powder" herein is also sometimes referred to in the art as "particulate material" or "particles" and the term "powder" is to be construed herein as meaning any such material, by whatever name, that is used in the three-dimensional printing process as a layer-forming material upon which a binder is deposited for the creation of the desired article. The powder may comprise any type of material capable of taking on the powder form, e.g. metal, plastics, ceramics, composite materials, minerals, etc.

[0024] It is to be understood that the term "base three-dimensional printing device" is to be construed herein as referring to the three-dimensional printing apparatus sans the instrument or other item of auxiliary equipment, which from the context of the discussion, will, after its addition or attachment, become part of the three-dimensional printing apparatus. For example, in a discussion of an instrument being added to the base three-dimensional printing device, it is implied that, when added, the three-dimensional printing apparatus then comprises the instrument.

[0025] The three-dimensional printing process comprises repeating iterations of a cycle of powder layer formation followed by printing upon the powder layer (hereinafter referred to as a "build cycle iteration") until the article has been completely formed.

[0026] It is to be understood that two types of layers are discussed herein. The first type is a "powder layer" and that term is to be construed as referring to a physical layer of powder that is or is to be deposited in a particular build cycle iteration. The second type is referred to simply as "layer" or as a "layer of the article" or as a "two-dimensional layer". This type of layer is to be construed as meaning one of the slices of the stack of slices into which the article to be made has been conceptually divided for use in the three-dimensional printing process.

[0027] Method embodiments comprise conducting the three-dimensional printing process so as to include one or both of a step of determining the powder layer satisfactoriness and a step of determining the printing satisfactoriness. Initially, the descriptions of method embodiments of the step of determining the powder layer satisfactoriness and of the step of determining the printing satisfactoriness are presented in separate subsections below for clarity. An additional subsection below then discusses some of the method embodiments which include steps for determining both kinds of satisfactoriness, including some embodiments wherein both types of satisfactoriness are determined practically at the same time. Subsequently, some apparatus embodiments are described.

Powder Layer Satisfactoriness Determination

[0028] Different methods of forming a powder layer during the three-dimensional printing process are known in the art. For example, the three-dimensional printing apparatus may include twin cavities which are open at their tops at a common horizontal plane and are each bottomed by a vertically indexible support platform. One of the cavities is used as a powder supply reservoir and the other as a build box. At the start of the three-dimensional printing process, the powder supply reservoir cavity is filled with powder and its support platform is adjusted so that the top of the mass of powder it contains is level with the aforementioned common horizontal plane and the support platform of the build box cavity is level with the aforementioned common horizontal plane. Thereafter, for each build cycle iteration, the vertical position of the powder supply reservoir cavity is indexed upward a predetermined amount to expose a predetermined volume of powder above the common horizontal plane and the support platform of the build box cavity is indexed downward a predetermined amount to create a volume which approximately corresponds to the volume of the exposed powder. A mechanism, e.g. a counter-rotating roller, a doctor blade, etc., is used to scalp off the exposed powder from the powder supply reservoir cavity and transfer it and spread it evenly across the top of the build box cavity to form a new powder layer.

[0029] Another example of a method for forming a powder layer utilizes the build box cavity as described above but omits the use of a corresponding powder supply reservoir cavity. Instead, powder is spread across the top of the build box cavity by a powder dispenser that travels across the build box cavity dispensing powder as it goes. A mechanism at the bottom of the powder dispenser may be used to smooth and/or tamp down the powder into a uniform powder layer. A roller may be used in conjunction with the traveling powder dispenser to spread the powder into a uniform powder layer.

[0030] In addition to the foregoing examples, other methods may be used to accomplish the step of powder layer creation in the build cycle iterations. Regardless of the method used for powder layer creation, it is important that each powder layer have a predetermined level of flatness, thickness, and area coverage uniformity. Up until the present invention, the satisfactoriness of the powder layer creation with regard to any or all of these characteristics has been determined only by visual inspection by the operator. Such an inspection is typically done only at the start and finish of the three-dimensional printing process and occasionally during the course of the three-dimensional printing process.

[0031] In some method embodiments, the satisfactoriness of one or more of the predetermined level of flatness, thickness, and area coverage uniformity is conducted automatically for preselected or randomly selected powder layers during the three-dimensional printing process.

[0032] FIG. 1 is a schematic flow chart which generally outlines the step **2** of determining the satisfactoriness of a powder layer in embodiments. After the powder layer is created (substep **4**), an image of the powder layer is captured (substep **6**). The captured image is then compared to a target image for the powder layer (substep **8**) and a decision is made as to whether or not the powder layer is sufficiently satisfactory to continue on with the three-dimensional printing process (substep **10**). If the answer to this decision is yes, then the three-dimensional printing process is continued by going on to the printing step (substep **12**). If the answer is no, then the three-dimensional printing process is halted (substep **14**) and, optionally, the operator is alerted of the situation (substep **16**). The halting is preferably accomplished by placing the three-dimensional printing apparatus into a state of suspension that may be changed to a resumption of three-dimensional printing process or to a complete shutdown of the three-dimensional printing apparatus either by a subsequent decision of the operator or by the predetermined lapse of time following the decision of substep **10**. The halting may also be the immediate and complete shutdown of the three-dimensional printing apparatus.

[0033] The substeps **6, 8, 10** will now be discussed in more detail. These three substeps are intimately interrelated. The type and amount of information available from the capturing of the image of the powder layer (substep **6**) will influence the character and extent of the comparison of that image to the powder layer target image (substep **8**), which in turn, will influence how it is to be determined whether or not the result of the comparison is sufficiently satisfactory to continue on with the three-dimensional printing process (substep **10**). Additionally, the type and amount of information available about the powder layer target image will also influence the type and amount of information that is needed in the capturing of the powder layer image which, in turn, will influence how it is to be determined whether or not the result of the comparison is sufficiently satisfactory to continue on with the three-dimensional printing process. In a sense, the relationship between what is needed for a powder layer target image and what is needed for a captured powder layer image is analogous to the question of the temporal sequence of the chicken and the egg. To circumvent this problem, the discussion will start with the selection of the powder layer target image, though the discussion could just as well start with the selection of the powder layer image.

[0034] The basis for the powder layer target image is the information that is available regarding the characteristics the powder layer is to have and tolerances related thereto. In many embodiments, this will include the two-dimensional geometrical size and/or shape the powder layer, i.e. planar geometrical information, is intended to have and include a requirement that the appearance of the powder layer be satisfactorily uniform within these geometrical confines. The two-dimensional geometrical size and shape of the powder layer, in many instances, will correspond identically with those of the horizontal top plane of the build cavity. In some instances, though, such an identical correspondence is not necessary. For example, in an embodiment wherein the printing is to be done on only a portion of the powder layer and it is known that the entire powder layer is not needed to contribute to the formation of powder bed support for the printed article, the two-dimensional geometrical size and shape of the powder layer may vary significantly from those of the top plane of the build cavity. FIGS. 2A and 2B depict such an embodiment.

[0035] Referring now to FIG. 2A, there is shown a schematic planar view a powder layer **20** within the build cavity **22** of a three-dimensional printing apparatus **24** (only partly shown). The powder layer **20** is indicated by shading and is seen to be non-coextensive with the top plane of the build cavity **22**. An outline of the slice of the article **26** that is to be printed on powder layer **20** is suggested by dashed lines. Referring now to FIG. 2B, which is a schematic cross-sectional view taken along cutting plane **2B-2B** of FIG. 2A, it is seen that the article **26**, which is a vertically oriented cylinder, is sufficiently remote from the free face **28** of the build bed **30** that powder layer deposition in volume **32**, which is free of powder (i.e. it is the unfilled portion of the build cavity **22**), is not necessary for either the printing or the support of the article **26**. Also shown in the drawing is the build platform **34** which forms the bottom of the build cavity **22** and supports the build bed **30**. It must be kept in mind, however, that the presence of an unfilled volume, such as volume **32**, in a build cavity, when the build cavity is contained within a build box that is to be removed from the three-dimensional printing apparatus so that the printed article may be subjected to a strengthening treatment, e.g. a thermal curing cycle, prior to the removal of the article from the powder bed, may make it necessary to handle the build box with particular care after it is removed from the three-dimensional printing apparatus so as not to disturb the powder bed support of the printed article prior to the strengthening treatment.

[0036] In some embodiments, the powder layer target includes the information about the intended thickness of the powder layer.

[0037] In some embodiments, the powder layer target includes information about the intended flatness of the powder layer.

[0038] In some embodiments, the powder layer target image is compiled by selecting from among the available powder layer target information only that information which corresponds to preselected features of the powder layer. These preselected features will be referred to herein as "powder layer key features." In some embodiments, the powder layer key features may be simply a continuous plane having the size and geometry of the top plane of the build cavity. In some embodiments, the powder layer key features may include the boundary of the area that is considered critical for the successful printing and support of the article. In some embodiments, the powder layer key features may include the thickness and/or flatness of the powder layer. Thus, it is the selected information which is representative of the powder layer key features that is referred to herein as the "powder layer target image," whether or not the selected information comprises an "image" in the conventional sense of the word. This information may be saved in a permanent or volatile data file or it may be acquired and delivered in piecemeal fashion, e.g. in real time, to the comparator device which performs the substep **8** comparison of the powder layer captured image to the powder layer target image.

[0039] The term "powder layer image" is to be construed as comprising a body of information about the actual powder layer, again whether or not the selected information comprises an "image" in the conventional sense of the word. The type and amount of information comprising the powder layer image should be selected to correspond to that which comprises the powder layer target image. The powder layer image may be captured, i.e. obtained, by any means suitable for the type and quantity of information that is to make up the powder layer image. As is the case for the powder layer target image, the information comprising the powder layer image may be saved in a permanent or volatile data file or it may be acquired and delivered in piecemeal fashion, e.g. in real time, to the comparator device which performs the substep **8** comparison of the powder layer captured image to the powder layer target image. One or more instruments may be used to capture the body of information that comprises the powder layer image. The sensing portion of each such instrument may be either stationary or move relative to the powder layer, depending on the nature of the instrument and the type and amount of information it is to collect. An individual instrument – whether mobile or stationary – may gather information about all of the powder layer or only a portion of it.

[0040] The instruments (or sensing portions thereof) which are stationary may be mounted on or otherwise directly or indirectly supported by the base three-dimensional printing device. The instruments (or sensing portions thereof) which are mobile may be attached to a carriage of the base three-dimensional printing device, e.g. a powder layer spreader carriage or a print head carriage, or to an auxiliary carriage. The tracking path of a carriage that carries an instrument sensing portion may be linear or non-linear. Mobile instruments (or sensing portions thereof) may also be pivotably attached to a stationary component of the base three-dimensional printing device or to a carriage. FIG. 3 schematically shows an example of mobile instrument sensing portions **50** that are attached to the powder spreader carriage **52** (shown sans supporting track and drive mechanism) of the base three-dimensional printing device **54** (shown only in part) as the powder spreader carriage **52** is traversing the powder bed **56**.

[0041] For example, in embodiments wherein the powder layer image is to include planar geometrical information, this information may captured using one or more of an electronic camera, a point or line laser scanner, and a white light interferometer. In embodiments wherein the powder layer image is to include powder layer thickness information, this information may be captured using one or more of an electronic camera, a point or line laser scanner, and a white light interferometer. In embodiments wherein the powder layer image is to include powder layer flatness information, this information may be captured using one or more of an electronic camera, a point or line laser scanner, and a chromatic confocal white light interferometer. Some types of instruments may be used to collect information related to more than one of the powder layer's planar geometrical, the powder layer thickness, and the powder layer flatness. Examples of the aforementioned laser scanners which are adaptable for use in embodiments are the model LJ-V7300 ultra-high speed, in-line profilometer, which is available from Keyence Corporation of America, Itasca, Illinois, 60143 US and the SolarScan surface profilometer, which is available from Solarius Development Inc., San Jose, California 95131 US. An example of the aforementioned white light interferometer is the model WLC1 Chromatic Confocal White Light Sensor, which is available from Solarius Development Inc., San Jose, California 95131 US.

[0042] As mentioned above, in substep **10** the determination is made as to whether or not the comparison of the captured powder layer image and the powder layer target image is satisfactory, i.e. whether or not the comparison indicates that the characteristics of the actual powder layer are within the preselected tolerances to permit the three-dimensional printing process to continue. Just what such preselected tolerances are in a particular case is left to the discretion of the user of the three-dimensional printing process and are expected to be dependent on the nature and size of the article and on the value and types of the materials being used in the three-dimensional printing process.

[0043] In the event that the comparison in substep **10** results in the halting of the three-dimensional printing process in substep **12**, it may be desirable in some cases to proceed to substep **16** wherein the operator is alerted of the halting. The desirability of alerting the operator may be influenced by the amount of time remaining before it is expected that the operator otherwise would be checking on the status of the three-dimensional printing process. For example, if the halting occurs with just a few powder deposition/printing cycles left before the expected completion of the three-dimensional printing process and it is known that the operator will check on the three-dimensional printing process at the end of the process, then it may not be desirable to alert the operator, whereas if the halting occurs with many powder deposition/printing cycles remaining it may be desirable to alert the operator. To aid in the determination of whether or not the operator should be alerted, in some embodiments, the inventive process includes inputting information about when the operator last checked on the status of the three-dimensional printing process and/or making a determination of when the operator can next be expected to check on the status of the three-dimensional printing process. In any case, if it is decided that the operator is to be alerted, any practicable means of alerting the operator may be used, e.g., through the use of flashing lights, audible signals, and/or cell phone, pagers, or other types electronic communications, etc.

[0044] In some embodiments, the determination of powder layer satisfactoriness step is conducted for each powder layer of the three-dimensional printing process, while in some other embodiments the step is conducted only for preselected powder layers, and in some other embodiments the step is performed only for randomly selected powder layers, and in still other embodiments the step is performed for some preselected powder layers, e.g. every tenth powder layer, and also for some random powder layers.

[0045] In following the descriptions of embodiments, there are descriptions of various kinds of captured images and various kinds of target images. There are also descriptions of comparisons of captured images and target images and of decisions based upon those comparisons. It is to be understood that it is within the scope of the present invention that such captured and target images, comparisons, and results of the comparisons be volatile, i.e. that they cease to exist after a single use in the embodiment, or that one or more of any of them be saved for later use, e.g. for forensic purposes, historical purposes, etc.

Printing Satisfactoriness Determination

[0046] Prior to the start of the three-dimensional printing process, a digital three-dimensional model is made of the article that is to be made by the three-dimensional printing process. The digital model comprises, or is further processed into the form of, a series of virtual cross-sectional slices of the article, each slice representing a layer of the article which, when stacked up together, essentially represent the entire article. During the three-dimensional printing process, likenesses of the slices are consecutively binder jet deposited onto consecutive powder layers until the entire article has been three-dimensionally printed.

[0047] Typically, the three-dimensional model is stored in the format of a stereolithographic file or .stl file. Files in this format are referred to herein as "STL files." An STL file typically comprises of a collection of triangles which sketch out the exterior and interior surfaces of the physical article. Features such as surface normals, i.e., a short ray pointing perpendicularly out from a face of the triangle, are associated with the triangles to indicate which surface of the triangle is facing outward from the physical article. The outward facing surface is sometimes referred to as an "exterior" or "front" face and the inward facing surface is sometimes referred to as an "interior" or "back" face.

[0048] Often, the individual slices are obtained as the result of an STL file being operated upon by a program that is referred to herein as a "slicing program." A slicing program slices the model that is in STL file format along one of three mutually orthogonal axes, e.g., the Z-axis of a set of X-Y-Z axes, to create a stack of two-dimensional layers of a specified layer thickness, i.e., slices. Within each slice, the relevant portion of the model is represented by a set of two-dimensional closed polygons. The slicing program is typically a separate program, e.g., the Magics RP program which is available from the Materialise NV, Leuven, Belgium. However, a slicing program may also be a subset of a larger program that processes the STL file or a functionally similar file into instructions for a solid free-form fabrication machine to construct the physical article. In either case, application of the slicing program results in a binary file which comprises a stack of two-dimensional slices wherein each two-dimensional layer is represented by a set of two-dimensional closed polygons. Such binary files are referred to herein as "slice stack files."

[0049] The individual slices may also be created without the use of a slicing program. For example, U.S. Patent Application Publication US 2010/0168890 A1 discloses methods utilizing ray casting for converting STL files without the use of a slicing program into instructions to the printing mechanism of the three-dimensional printing apparatus for the layer-by-layer construction of the physical article.

[0050] Another way of creating the individual slices without a slicing program is by utilizing an application program interface ("API") to generate a bitmap corresponding to each particular layer of the article that is to be printed directly from the article's STL file. Preferably, this conversion is done essentially in real time immediately before the particular layer is to be printed, although it is also possible to store the results of the conversion of one or more – or even all – of the layers for later use. Once generated, the bitmap may then be used in configuring the printing instructions for the printing mechanism to print that particular layer. In three-dimensional printing processes that use a rasterizing printing mechanism, the bitmap may be used to directly indicate the pixel locations that are to be printed. In three-dimensional printing processes which rely on vectorized instructions for printing, the bitmap may be used in the creation of the vectors utilized in printing.

[0051] Regardless of the manner in which the slice of the article for printing on each layer is obtained, in embodiments, electronic data corresponding to the slice to be printed is utilized for more than just the printing of the slice onto its respective powder layer. For convenience, this electronic data for a given layer is hereinafter referred to as the “slice likeness file”. In some embodiments, the slice likeness file is also used in determining whether or not the slice has been satisfactorily printed onto its respective powder layer. As described in more detail below, the slice likeness file may be used directly or indirectly in the printing satisfactoriness determination.

[0052] FIG. 4 is a schematic flowchart which generally outlines the step **100** of determining the satisfactoriness of the printing in embodiments. In this discussion, the printed upon powder layer which makes up the substrate for the printing iteration that is the subject of the determination analysis is referred to as the “print bed”. At the start of the step **100**, the printing portion of a build cycle iteration is conducted for the print bed (substep **102**) and subsequently an image is captured of the print bed (substep **104**). The captured print bed image is compared against a target image for the print bed (substep **106**). The print bed target image comprises and/or is derived from information contained in the slice likeness file which corresponds to that printing iteration. A decision is then made as to whether or not the print bed is sufficiently satisfactory to continue on with the three-dimensional printing process (substep **108**). If the answer is no, then the three-dimensional printing process is halted (substep **110**) and, optionally, the operator is alerted of the situation (substep **112**). The halting is preferably accomplished by placing the three-dimensional printing apparatus into a state of suspension that may be changed to a resumption of three-dimensional printing process or to a complete shutdown of the three-dimensional printing apparatus either by a subsequent decision of the operator or by the predetermined lapse of time following the decision of substep **108**. The halting may also be the immediate and complete shutdown of the dimensional printing apparatus. If the answer is yes in substep **108**, a determination is made as to whether or not there are any more build cycle iterations left in the three-dimensional printing process (substep **114**). If the answer is yes, then the three-dimensional printing process is continued on to the next build cycle iteration (substep **116**); if the answer is no, then the three-dimensional printing process may be terminated or other desired action may be taken (substep **118**).

[0053] The substeps **104, 106, 108** will now be discussed in more detail. These substeps are related to one another in the same way as are substeps **6, 8, 10** as described above. Thus, the discussion will arbitrarily begin with a discussion of the print bed target image.

[0054] The basis for the print bed target image is the information contained within the slice likeness file in conjunction with information that is available about the intended physical location of the article within the build box and information about the relevant powder layer and tolerances related to any of the foregoing. From these sets of information, the locations of the print bed at which printing is to have occurred is determined. This location data can be stored in a file for later comparison in substep **106** or streamed essentially in real time as it is generated, e.g. to be used in a just-in-time fashion for the substep **106** comparison. The print bed target information image also includes information about how one or more characteristics of the powder layer are to be after printing has occurred as opposed to how the characteristic or characteristics are to be if no printing has occurred, i.e. "print validation information." For example, the print validation information may include information about the color or reflectivity of a location on the print bed, the difference in its brightness compared with surrounding locations, the absolute or relative temperature of the location, and/or the chemical composition signature of the location.

[0055] Additionally, in some embodiments, the print bed target image includes information about the print head array of jets. The print head information may include the number of jets, the location of a jet on the print head, the intended path of a jet, etc. This information may be used in conjunction with the results of the comparison of the captured print bed image to the print bed target image to identify which jets in the array are malfunctioning. For example, when the comparison identifies locations of the print bed that have not been printed and those areas correspond to areas where jet X is to have printed, then jet X may be identified as malfunctioning. Another example is that where areas where both jet X and jet Y were to have printed appear to be only partially printed and other areas where both jet X and jet Z were to have printed appear to be only partially printed and yet other areas where both jet Y and jet Z were to have printed appear to be fully printed, then jet X can be identified as malfunctioning.

[0056] While in some embodiments, the print bed target image includes information identifying all locations which were to have been printed and print validation information, in some embodiments, the print bed target image includes a lesser amount of information. For example, in some embodiments the print bed target image is compiled by selecting from the available print bed target information only that information which corresponds to preselected features of the print bed, i.e. the "print bed key features," plus print validation information. In some embodiments, a print bed key feature may be the identity of one or more locations of the print bed at which printing is to have occurred. In some embodiments, a print bed key feature is the border between locations which are to have been printed and those which are not to have been printed. Thus, it is the selected information, whether it be the set of information which identifies all locations which were to have been printed and print validation information for those locations or a set of information that identifies a lesser number of print bed key features, that is referred to herein as the "print bed target image," whether or not the selected information comprises an "image" in the conventional sense of the word. This selected information may be saved in a permanent or volatile data file or it may be acquired and delivered piecemeal to the comparator device which performs the substep **106** comparison of the captured print bed image to the print bed target image.

[0057] The print bed image comprises information about the actual print bed, again whether or not the selected information comprises an "image" in the conventional sense of the word. The type and amount of information comprising the print bed image should be selected to correspond to that which comprises the print bed target image. The print bed image may be captured by any means suitable for the type and quantity of information that is to make up the print bed image. The information comprising the print bed image may be saved in a permanent or volatile data file or it may be acquired and delivered in piecemeal fashion, e.g. in real time, to the comparator device which performs the substep **106** comparison of the captured print bed image and the print bed target image. One or more instruments may be used to capture the body of information that comprises the print bed image. The sensing portion of each such instrument may be either stationary or move relative to the print bed, depending on the nature of the instrument and the type and amount of information it is to collect. An individual instrument – whether mobile or stationary – may gather information about all of the print bed or only a portion of it. The mounting of the stationary and mobile portions of the instruments may be the same as is described above with regard to the instrumentation for the determination of the powder layer satisfactoriness.

[0058] Examples of instrumentation for capturing the print bed image include electronic cameras, point or line laser scanners, white light interferometers, infrared sensors, and remote chemical sensors, e.g. laser or infrared spectrometers. Some examples of laser scanners and white light interferometers which are suitable to be adapted for use in embodiments are identified above with regard to capturing the powder layer image. A single instrument or any combination of instruments may be used to capture the print bed image.

[0059] As was the case for the determination of the satisfactoriness of the powder layer, the determination in substep **114** of the satisfactoriness of the print bed involves determining whether or not the comparison indicates that the characteristics of the actual print bed layer are within the preselected tolerances to permit the three-dimensional printing process to continue. Just what such preselected tolerances are in a particular case is left to the discretion of the user of the three-dimensional printing process and are expected to be dependent on the nature and size of the article and on the value and types of the materials being used in the three-dimensional printing process. Also as was the case for the determination of the satisfactoriness of the powder layer, the desirability of alerting the operator in substep **112** of the halting of the three-dimensional printing process due to the unsatisfactoriness of the captured print bed image in comparison to the print bed target image is dependent on the particular factors of the three-dimensional printing process and the decision as to employ that step and the means by which to make the alert are left to the discretion of the user of the three-dimensional printing process. The means by which the operator may be alerted are the same as described above with regard to the step of determining the satisfactoriness of the powder layer.

[0060] In some embodiments, the determination of print bed satisfactoriness step is conducted for each layer of the three-dimensional printing process, while in some other embodiments the step is conducted only for preselected layers, and in some other embodiments the step is performed only for randomly selected layers, and in still other embodiments the step is performed for some preselected layers, e.g. every tenth layer, and also for some random layers.

Preferred Embodiments Using Determinations of Both Types of Satisfactoriness

[0061] Some embodiments include the step of determining the satisfactoriness of the powder layer and the step of determining the satisfactoriness of the print bed. In some of these embodiments, both of these steps are done for each layer. In some other embodiments, one or other of the steps is done for all layers and the remaining step is done for only preselected and/or random layers. In yet some other embodiments, both of the steps are done for only preselected and/or random layers.

[0062] In some embodiments, one or more of the same instruments are used in the capture of both the powder layer image and the print bed image while in some other embodiments different instruments are used to capture the powder layer image and the print bed image. For example, in some embodiments a high resolution electronic camera may be used for capturing the powder layer image and for capturing the print bed image while in some embodiments a low resolution electronic camera may be used for capturing the powder layer image and an infrared detector is used for capturing the print bed image. It is within the scope of the present invention for any combination of the instruments described above to be used in embodiments which include both the step of determining the satisfactoriness of the powder layer and the step of determining the satisfactoriness of the print bed.

[0063] Examples will now be discussed of some embodiments which include both the step of determining the satisfactoriness of the powder layer and the step of determining the satisfactoriness of the print bed. Referring now to FIG. 6, there is shown a schematic flow chart which generally outlines the step **200** of determining the satisfactoriness of both the powder layer and the print bed according to an embodiment. After a powder layer is created (substep **202**), an image of the powder layer is captured (substep **204**) and the captured powder layer image is compared to the powder layer target image for that powder layer (substep **206**) and a decision is made as to whether or not the powder layer is sufficiently satisfactory to continue on with the three-dimensional printing process (substep **208**). If the answer to this decision is no, then the process is halted (substep **210**), and, optionally, the operator is alerted of the situation (substep **212**). If the answer is yes, then printing is done on the powder layer (substep **214**), which, according to the terminology adopted herein, renders the powder layer into a print bed. An image of the print bed is captured (substep **216**) and compared to a print bed target image for this print bed (substep **218**). A decision is made as to whether or not the print bed is sufficiently satisfactory to continue with the three-dimensional printing process (substep **220**). If the answer to this decision is no, then the process is halted (substep **210**), and, optionally, the operator is alerted of the situation (substep **212**). If the answer in substep **220** is yes, then a determination is made as to whether or not there are any more build cycle iterations left in the three-dimensional printing process (substep **222**). If the answer to this decision is yes, then the three-dimensional printing process is continued onto the next build cycle iteration (substep **224**). If the answer is no, then the three-dimensional printing process may be terminated or another desired action may be taken (substep **226**).

[0064] In some embodiments, the satisfactoriness of both the powder layer and the print bed are determined simultaneously. Examples of these embodiments are presented in FIGS. 7 and 8. Referring now to FIG. 7, there is shown another schematic flow chart which generally outlines the step **230** of determining the satisfactoriness of both the powder layer and the print bed according to an embodiment. After a powder layer is created (substep **232**), the printing is done (substep **234**) transforming the powder layer to a print bed under the terminology adopted herein. An image of the print bed is captured (substep **236**). The captured print bed image is compared to both a target image for the powder layer and a target image for the print bed (substep **238**). Decisions are made as to whether or not the captured print bed image is sufficiently satisfactory with regard to both target images to continue on with the three-dimensional printing process (substep **240**). If the answer to this decision is no, then the process is halted (substep **242**), and, optionally, the operator is alerted of the situation (substep **244**). If the answer in substep **240** is yes, then a determination is made as to whether or not there are any more build cycle iterations left in the three-dimensional printing process (substep

246). If the answer to this decision is yes, then the three-dimensional printing process is continued onto the next build cycle iteration (substep **248**). If the answer is no, then the three-dimensional printing process may be terminated or another desired action may be taken (substep **250**).

[0065] Referring now to FIG. 8, there is yet another schematic flow chart which generally outlines the step **260** of determining the satisfactoriness of both the powder layer and the print bed according to an embodiment. The substeps of this embodiment are the same as those for the embodiment described in relation to FIG. 7, except instead of using two separate target images, i.e. a powder layer target image and a print bed target image, this embodiment uses a single target image which is referred to herein as a "composite target image." The composite target image includes information about one or more powder layer key features and about one or more print bed key features, again whether or not the selected information comprises an "image" in the conventional sense of the word. Accordingly, after a powder layer is created (substep **262**), the printing is done (substep **264**) transforming the powder layer to a print bed under the terminology adopted herein. An image of the print bed is captured (substep **266**). The captured print bed image is compared to the composite target image for the print bed (substep **268**). A decisions is made as to whether or not the captured print bed image is sufficiently satisfactory with regard to the composite target image to continue on with the three-dimensional printing process (substep **270**). If the answer to this decision is no, then the process is halted (substep **272**), and, optionally, the operator is alerted of the situation (substep **274**). If the answer in substep **270** is yes, then a determination is made as to whether or not there are any more build cycle iterations left in the three-dimensional printing process (substep **276**). If the answer to this decision is yes, then the three-dimensional printing process is continued onto the next build cycle iteration (substep **278**). If the answer is no, then the three-dimensional printing process may be terminated or another desired action may be taken (substep **280**).

<u>Preferred Apparatus Embodiments</u>

[0066] The present invention also includes apparatus embodiments. In these embodiments, a base three-dimensional printing device is adapted to perform one or both of the step of determining the satisfactoriness of the powder layer and the step of determining the satisfactoriness of the print bed. The adaptation is accomplished by providing the base three-dimensional printing device with the instrumentation, the respective target image or images, and the computer programming to accomplish the respective comparisons and halting and, optionally, the alerting required for performing one or both of those steps. Examples of such instrumentation are described above as part of the description of those steps.

[0067] For example, FIG. 5 shows a schematic perspective view of a base three-dimensional printing device **120**. The base three-dimensional printing device **120** includes a removable build box **122** (only the top surfaces of which are visible) having a vertically indexable floor, a powder layer depositing device **124**, a selectively positionable printing device **126** and a housing **128**. The base three-dimensional printing device **120** also includes a computer (not shown) with a human interface (e.g. touch screen **130**) and data storage units (not shown). The computer, human interfaces, and data storage units may be attached to or contained within the housing **128** or located remotely from the housing **128**.

[0068] During the operation of the base three-dimensional printing device **120**, after the powder layer depositing device **124** has deposited one or more powder layers, the printing device **126** imparts the pattern of a slice of the article which is to be printed by selectively inkjet printing (also known as binder jetting) a binder onto the uppermost deposited powder layer. The floor of the build box **122** is indexed downward to receive each next powder layer deposited by the powder layer depositing device **124**. The process of powder layer deposition and printing is continued until all of the desired article has been printed.

[0069] A particular instance of instrumentation used in the capturing the powder layer image and/or the print layer image may comprise a single unit or it may comprise of a base unit, which contains a portion of the instrument, and one or more detachable and/or remote sensor units. In some embodiments, the single unit or the base unit is mounted so as to be stationary or mobile on or within the base three-dimensional printing device **120**. As described above, the sensing portions of the instrumentation may be mounted on or otherwise directly or indirectly supported by the base three-dimensional printing device **120** so as to be stationary or mobile. Refer to FIG. 3 and the discussion related thereto for further information about location and support of the sensing units.

[0070] The programming to accomplish the comparisons and the halting and, optionally, the alerting required by one or both of the step of determining the satisfactoriness of the powder layer and the step of determining the satisfactoriness of the print bed may be done in any computer language that is compatible with the computer resources that are associated with the base three-dimensional printer and/or with an auxiliary general purpose computer. The programming includes the steps of comparing one or more aspects of the captured image or images to corresponding aspects of the corresponding target image or images and of determining if the respective powder layer and/or print bed are sufficiently satisfactory for the three-dimensional printing process to continue. The computer resource and/or auxiliary general purpose computer which utilizes such programming is referred to herein as a "comparator". The programming also comprises steps for controlling the base three-dimensional printing device to be halted if the comparator determines the powder layer and/or the print bed are not sufficiently satisfactory for the three-dimensional printing process to continue. The programming also may comprise steps for alerting an operator if the comparator determines the powder layer and/or the print bed are not sufficiently satisfactory for the three-dimensional printing process to continue using one or more of the various means described above.

[0071] While only a few embodiments of the present invention have been shown and described, it will be obvious to those skilled in the art that many changes and modifications may be made thereunto without departing from the spirit and scope of the invention as described in the claims. All United States patents and patent applications, all foreign patents and patent applications, and all other documents identified herein are incorporated herein by reference as if set forth in full herein to the full extent permitted under the law.

Claims

What is claimed is:

1. A method for producing an article by a three-dimensional printing process comprising a step of performing one or more build cycle iterations and a step of making a powder layer satisfactoriness determination, the step of making a powder layer satisfactoriness determination comprising the substeps of:

creating a powder layer;

capturing a powder layer image containing information about the powder layer;

comparing the powder layer image to a powder layer target image;

determining from the comparison if the powder layer is sufficiently satisfactory to permit the three-dimensional printing process to continue; and

halting the three-dimensional printing process if the powder layer is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue.

2. The method of claim 1, further comprising alerting an operator if the powder layer is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue.

3. The method of claim 1, wherein the step of making a powder layer satisfactoriness determination further comprises including in the powder layer target image at least one selected from information about intended thickness of the powder layer, information about intended flatness of the powder layer, and intended planar geometrical information of the powder layer.

4. The method of claim 1, wherein the substep of creating the powder layer includes creating the powder layer in a build cavity having a top plane such that the powder layer is not co-extensive with the top plane of the build cavity.

5. The method of claim 1, wherein the substep of capturing a powder layer image includes using at least one of the following to obtain information about the powder layer: an electronic camera, a laser scanner, and a white light interferometer.

6. The method of claim 1, wherein the substep of capturing a powder layer image includes using at least one mobile sensor to obtain information about the powder layer.

7. The method of claim 1, wherein the step of making a powder layer satisfactoriness determination is performed for one or more predetermined instances of the build cycle iterations.

8. The method of claim 1, wherein the step of making a powder layer satisfactoriness determination is performed for one or more randomly selected instances of the build cycle iterations.

9. A method for producing an article by a three-dimensional printing process comprising a step of performing one or more build cycle iterations and a step of making a print bed satisfactoriness determination, the step of making a print bed satisfactoriness determination comprising the substeps of:

printing on a powder layer to form a print bed;

capturing a print bed image containing information about the print bed;

comparing the print bed image to a print bed target image;

determining from the comparison if the print bed is sufficiently satisfactory to permit the three-dimensional printing process to continue; and

halting the three-dimensional printing process if the print bed is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue.

10. The method of claim 9, further comprising alerting an operator if the print bed is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue.

11. The method of claim 9, wherein the step of performing one or more build cycle iterations includes printing with a print head having an array of jets and the step of making a print bed satisfactoriness determination further comprises including in the print bed target image at least one selected from print validation information, information about a slice likeness file, and information about the print head array of jets.

12. The method of claim 11, wherein the substep of comparing the print bed image to a print bed target image further comprises determining if a jet of the print head array of jets is malfunctioning.

13. The method of claim 9, wherein the substep of capturing a print bed image includes using at least one of the following to obtain information about the powder layer: an electronic camera, a laser scanner, and a white light interferometer.

14. The method of claim 9, wherein the substep of capturing a print bed image includes using at least one mobile sensor to obtain information about the print bed.

15. The method of claim 9, wherein the step of making a print bed satisfactoriness determination is performed for one or more predetermined instances of the build cycle iterations.

16. The method of claim 9, wherein the step of making a print bed satisfactoriness determination is performed for one or more randomly selected instances of the build cycle iterations.

17. A method for producing an article by a three-dimensional printing process comprising a step of performing one or more build cycle iterations and at least one of a step of making a powder layer satisfactoriness determination and a step of making a print bed satisfactoriness determination, wherein the step of making a powder layer satisfactoriness determination comprises the substeps of:

creating a powder layer;

capturing at least one of a powder layer image containing information about the powder layer and a print bed image containing information about the powder layer; and

comparing at least one of the powder layer image and the print bed image to a powder layer target image; and

determining from the comparison if the powder layer is sufficiently satisfactory to permit the three-dimensional printing process to continue; and

halting the three-dimensional printing process if the powder layer is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue;

and wherein the step of making a print bed satisfactoriness determination comprising the substeps of:

printing on a powder layer to form a print bed;

capturing a print bed image containing information about the print bed;

comparing the print bed image to a print bed target image;

determining from the comparison if the print bed is sufficiently satisfactory to permit the three-dimensional printing process to continue; and

halting the three-dimensional printing process if the print bed is determined to be not sufficiently satisfactory to permit the three-dimensional printing process to continue.

18. The method of claim 17, wherein the comparison substeps of the step of making a powder bed satisfactoriness determination and of the step of making a print bed satisfactoriness determination are performed simultaneously.

19. The method of claim 17, wherein at least one of the step of making a powder layer satisfactoriness determination and the step of making a print bed satisfactoriness determination is performed for one or more predetermined instances of the build cycle iterations.

20. The method of claim 17, wherein at least one of the step of making a powder layer satisfactoriness determination and the step of making a print bed satisfactoriness determination is performed for one or more randomly selected instances of the build cycle iterations.

21. An apparatus for three-dimensional printing an article comprising:

a base three-dimensional printing device adapted to perform a three-dimensional printing process;

a sensor adapted to capture at least one of a powder bed image and a print bed image;

at least one of a powder layer target image and a print layer target image; and

computer programming adapted to compare at least one of the powder layer image and the print bed image to at least one of the powder layer target image and the print bed target image and to halt the three-dimensional printing process if at least one of the powder layer and the print bed are not determined to be sufficiently satisfactory for the three-dimensional printing process to continue.

22. The apparatus of claim 21, wherein the programming is adapted to alert an operator if at least one of the powder layer and the print bed are not determined to be sufficiently satisfactory for the three-dimensional printing process to continue.

23. The apparatus of claim 21, wherein the sensor is adapted to be mobile.

24. The apparatus of claim 21, wherein the sensor is selected from the group consisting of an electronic camera, a laser scanner, and a white light interferometer.

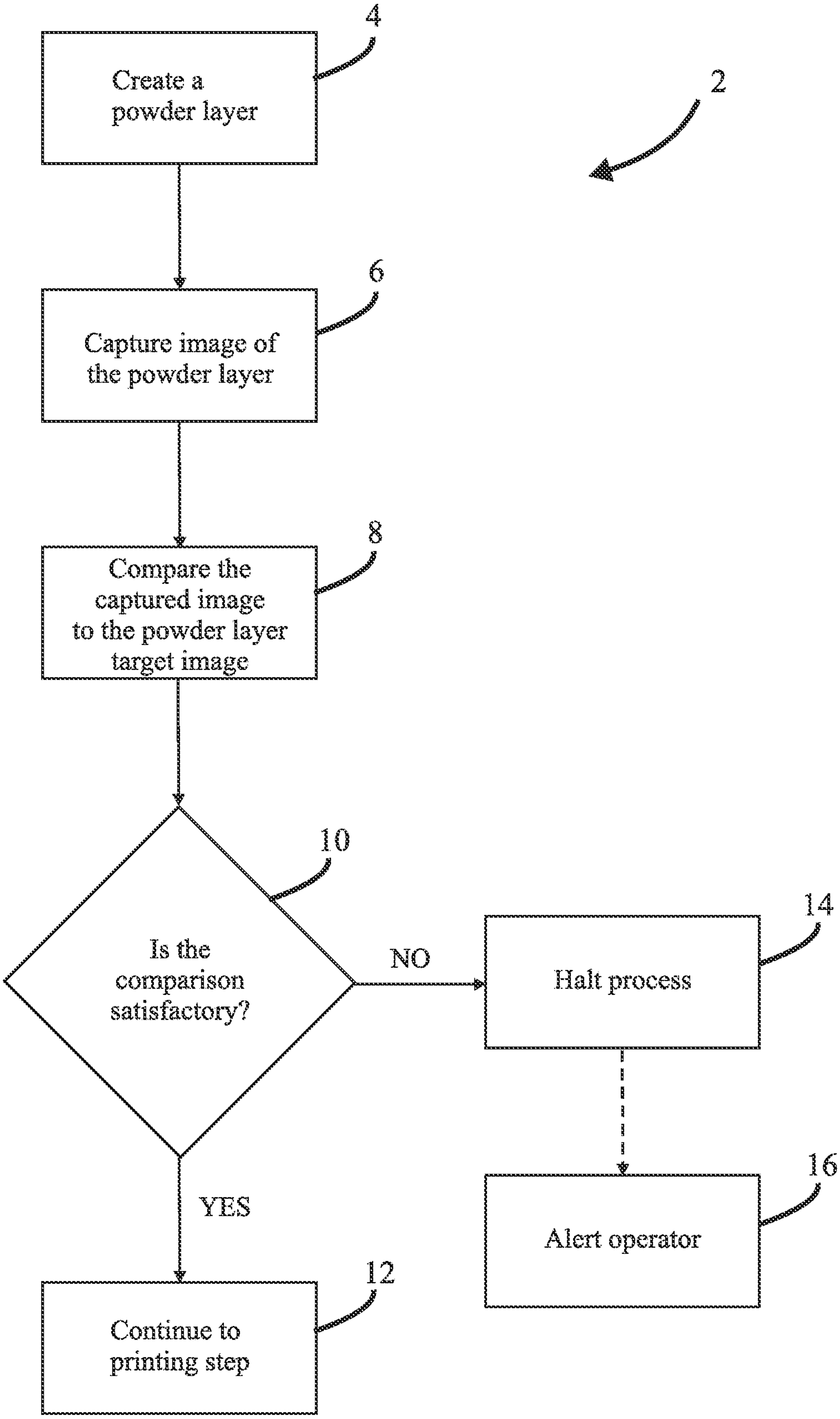

Create a powder layer
4
2
Capture image of the powder layer
6
Compare the captured image to the powder layer target image
8
Is the comparison satisfactory?
10
NO
Halt process
14
Alert operator
16
YES
Continue to printing step
12

FIG. 1

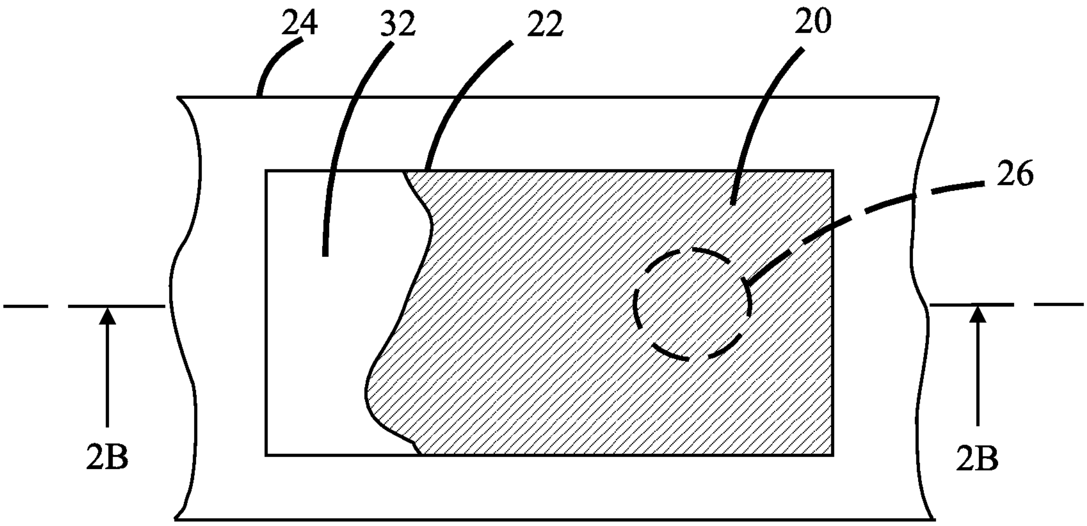


FIG. 2A

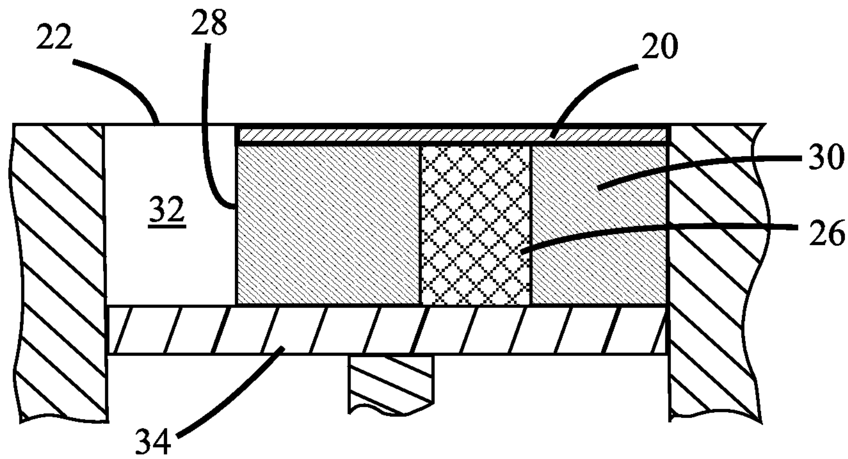


FIG. 2B

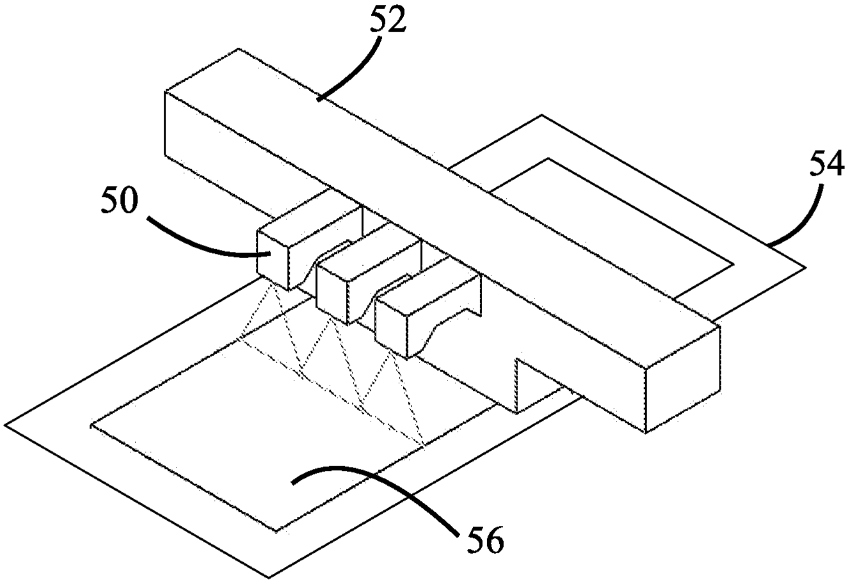


FIG. 3

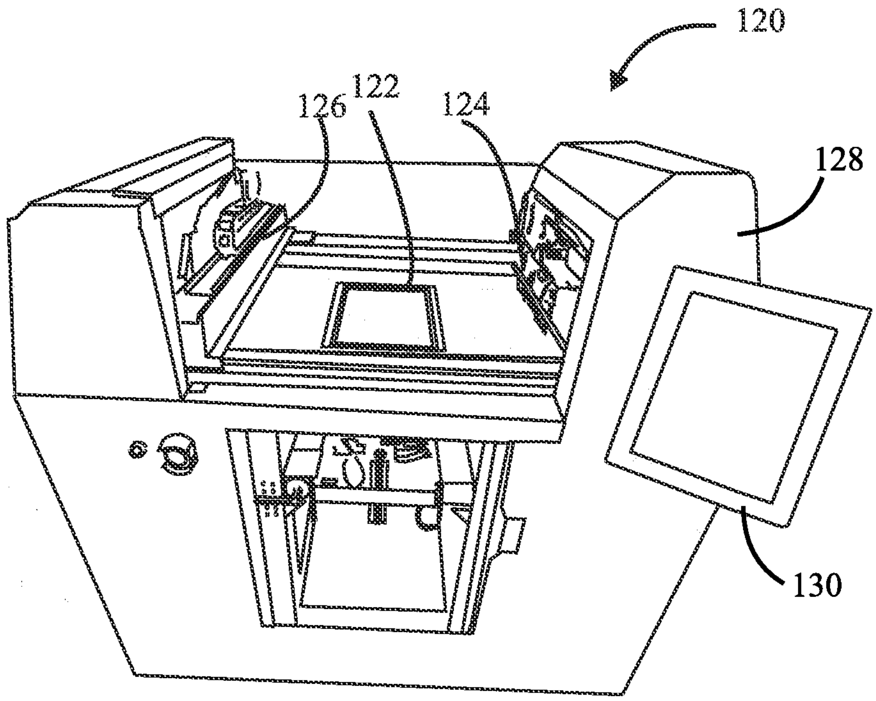


FIG. 5

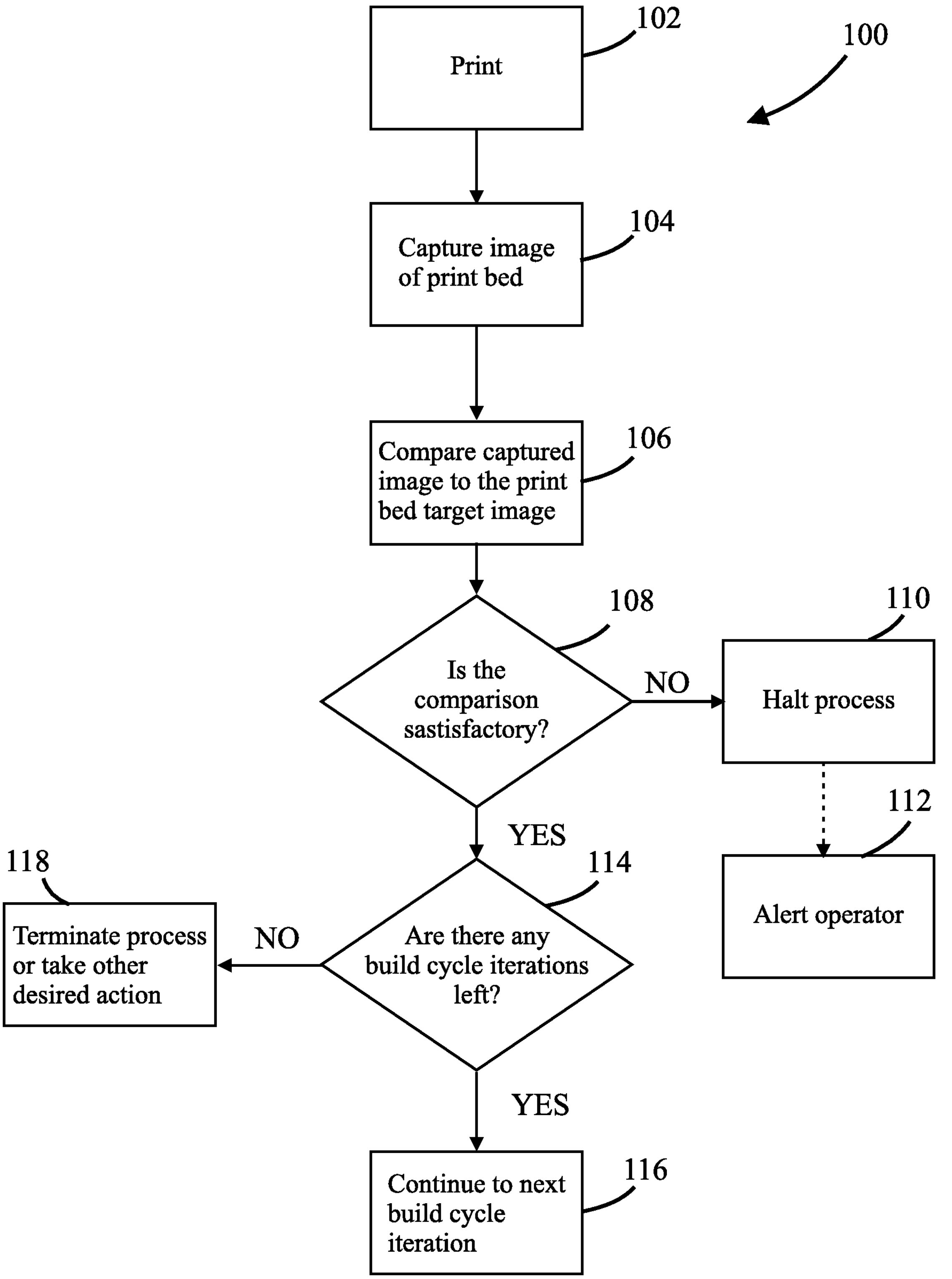
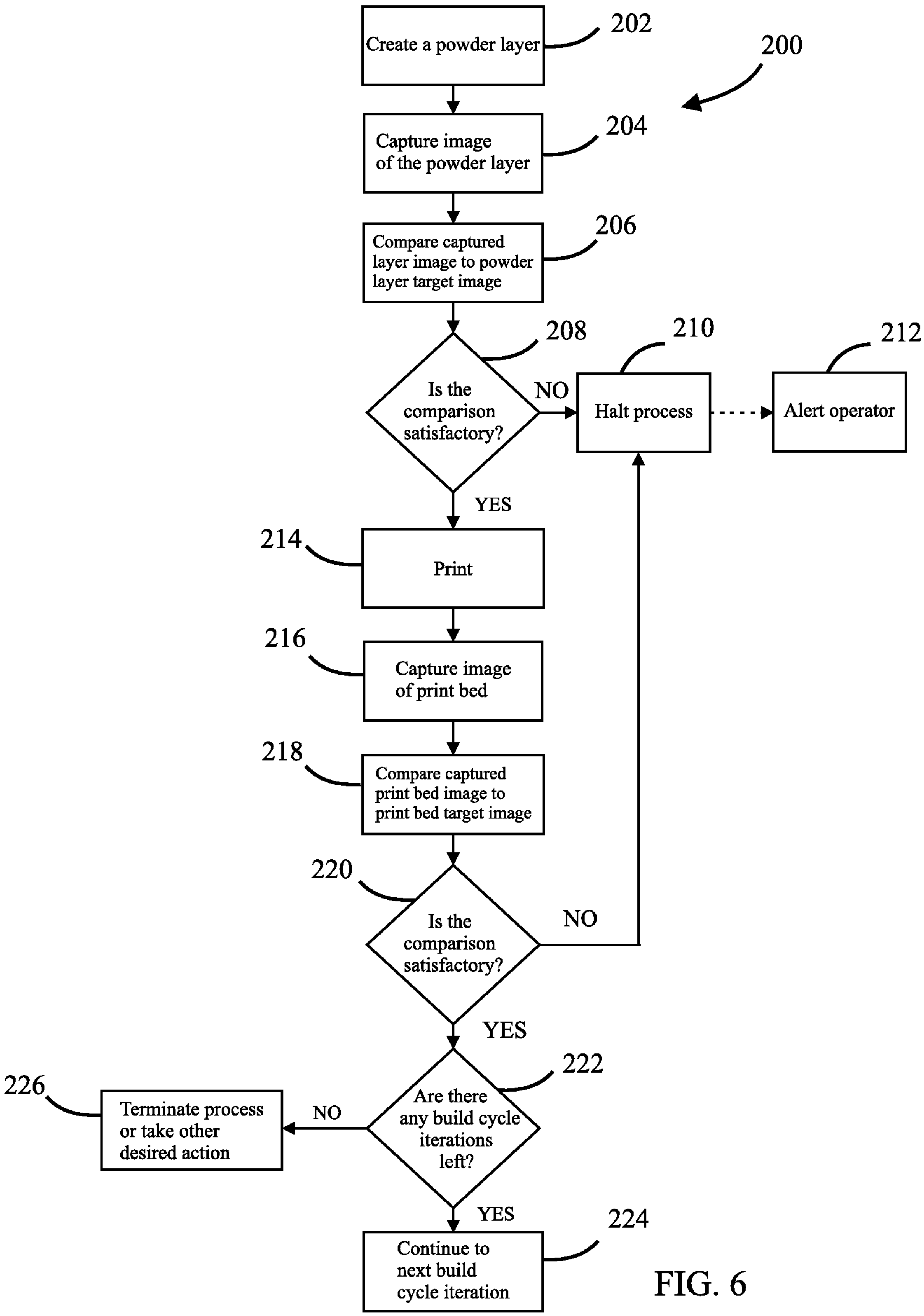

100
Print
102
Capture image of print bed
104
Compare captured image to the print bed target image
106
Is the comparison sastisfactory?
108
NO
Halt process
110
Alert operator
112
YES
Are there any build cycle iterations left?
114
NO
Terminate process or take other desired action
118
YES
Continue to next build cycle iteration
116

FIG. 4



200
Create a powder layer
202
Capture image of the powder layer
204
Compare captured layer image to powder layer target image
206
Is the comparison satisfactory?
208
NO
Halt process
210
Alert operator
212
YES
Print
214
Capture image of print bed
216
Compare captured print bed image to print bed target image
218
Is the comparison satisfactory?
220
NO
YES
Are there any build cycle iterations left?
222
NO
Terminate process or take other desired action
226
YES
Continue to next build cycle iteration
224

FIG. 6

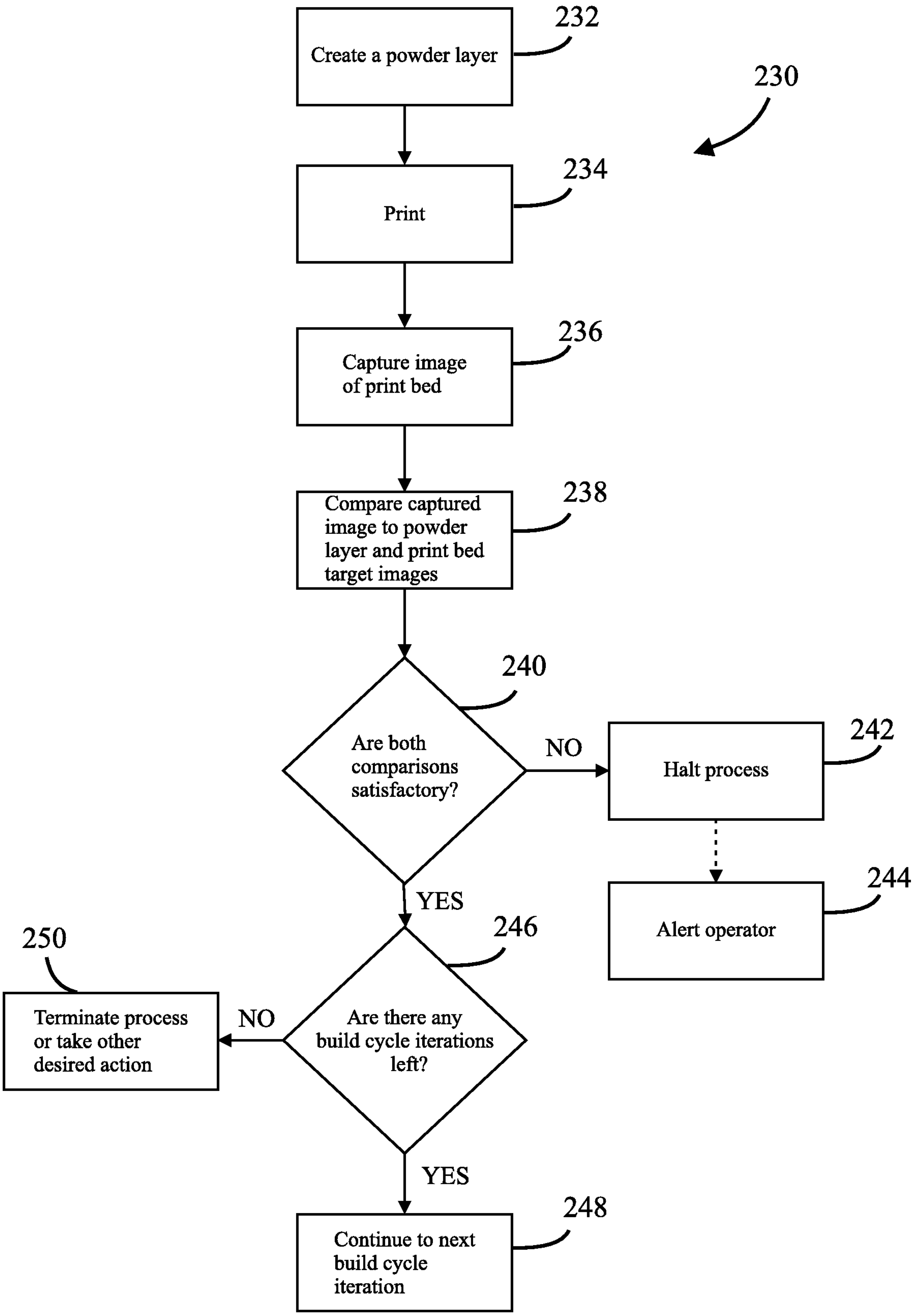

230
Create a powder layer
232
Print
234
Capture image of print bed
236
Compare captured image to powder layer and print bed target images
238
Are both comparisons satisfactory?
240
NO
Halt process
242
Alert operator
244
YES
Are there any build cycle iterations left?
246
NO
Terminate process or take other desired action
250
YES
Continue to next build cycle iteration
248

FIG. 7

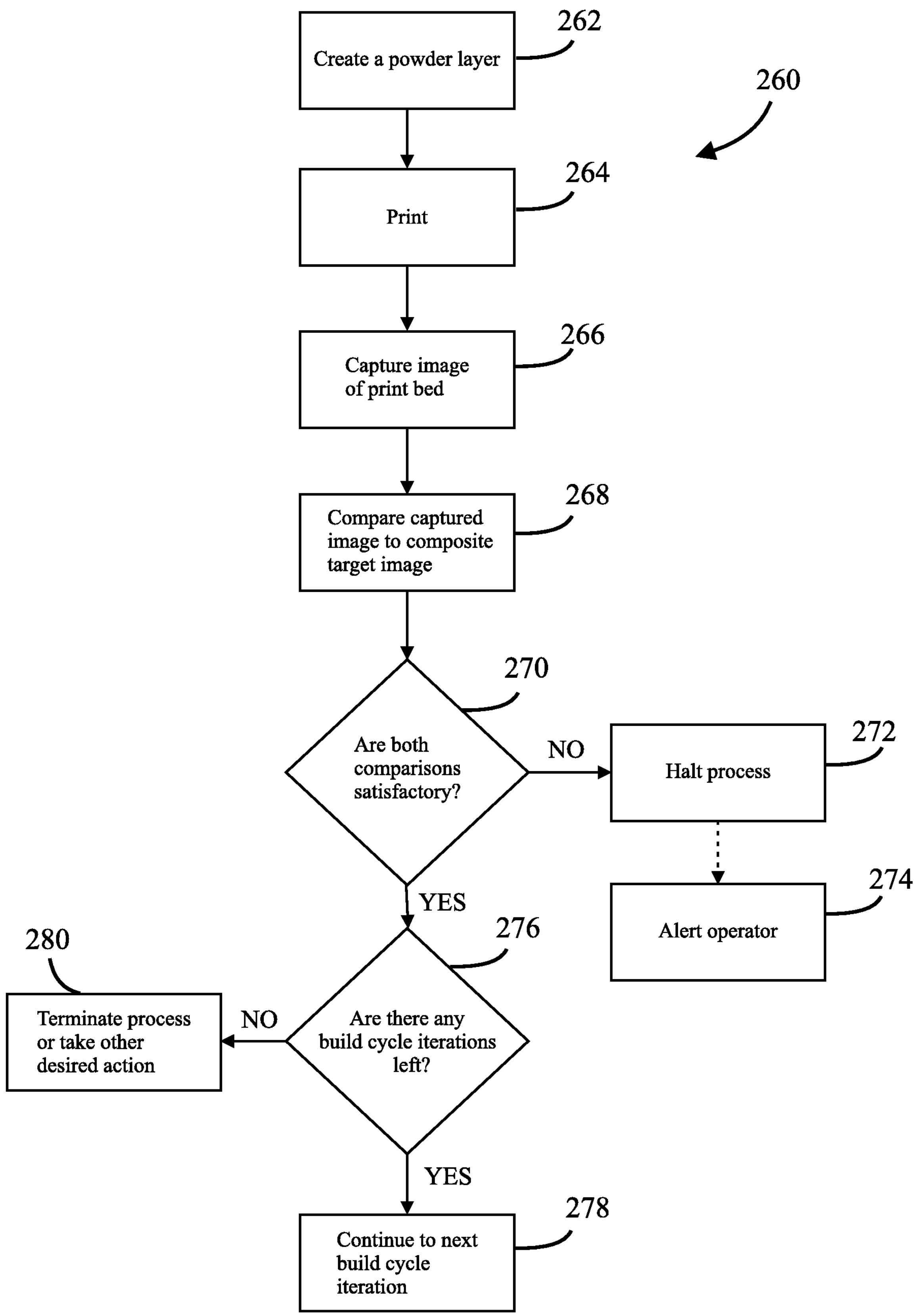

262
Create a powder layer
260
264
Print
266
Capture image of print bed
268
Compare captured image to composite target image
270
Are both comparisons satisfactory?
NO
272
Halt process
274
Alert operator
YES
276
Are there any build cycle iterations left?
280
Terminate process or take other desired action
NO
YES
278
Continue to next build cycle iteration

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/049145

A. CLASSIFICATION OF SUBJECT MATTER
INV. B29C67/00 B33Y10/00 B33Y30/00 B33Y50/02 B33Y40/00
ADD.

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 B33Y

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/173946 A1 (PFEIFER ROLF [DE] ET AL) 9 September 2004 (2004-09-09)	1-3, 5-10, 13-24
Y	figure 1 page 1, paragraphs [0002], [0014], [0017], [0019], [0020] page 2, paragraphs [0025], [0030] page 4, paragraph [0071] page 5, paragraph [0079] -----	4
X	WO 2014/095200 A1 (ARCAM AB [SE]) 26 June 2014 (2014-06-26) figure 2 page 2, paragraphs [0007], [0008] -----	1-3,5, 21,22,24
X	EP 2 363 270 A2 (SONY CORP [JP]) 7 September 2011 (2011-09-07)	9-16, 21-24
Y	figures 2, 5A-D, 10 page 9, paragraphs [0093], [0094], [0095] -----	4

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

☒ See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 November 2015	01/12/2015

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2015/049145

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004173946 A1	09-09-2004	DE 10310385 A1 US 2004173946 A1	23-09-2004 09-09-2004
WO 2014095200 A1	26-06-2014	CN 104853901 A DE 112013006045 T5 GB 2522388 A US 2015283610 A1 WO 2014095200 A1	19-08-2015 17-09-2015 22-07-2015 08-10-2015 26-06-2014
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