

TOOLING ASSEMBLY AND METHOD FOR ALIGNING COMPONENTS FOR A POWDER BED ADDITIVE MANUFACTURING REPAIR PROCESS

FIELD

[0001] The present subject matter relates generally to additive manufacturing machines and processes, and more particularly to tooling assemblies for aligning multiple components for a powder bed additive manufacturing repair process.

BACKGROUND

[0002] Machine or device components frequently experience damage, wear, and/or degradation throughout their service life. For example, serviced compressor blades of a gas turbine engine show erosion, defects, and/or cracks after long term use. Specifically, for example, such blades are subject to significant stresses which inevitably cause blades to wear over time, particularly near the tip of the blade. For example, blade tips are susceptible to wear or damage from friction or rubbing between the blade tips and shrouds, from chemical degradation or oxidation from hot gasses, from fatigue caused by cyclic loading and unloading, from diffusion creep of crystalline lattices, etc.

[0003] Notably, worn or damaged blades may result in machine failure or performance degradation if not corrected. Specifically, such blades may cause a turbomachine to exhibit reduced operating efficiency as gaps between blade tips and turbine shrouds may allow gasses to leak through the turbine stages without being converted to mechanical energy. When efficiency drops below specified levels, the turbomachine is typically removed from service for overhaul and refurbishment. Moreover, weakened blades may result in complete fractures and catastrophic failure of the engine.

[0004] As a result, compressor blades for a gas turbine engine are typically the target of frequent inspections, repairs, or replacements. It is frequently very expensive to replace such blades altogether, however, some can be repaired for extended lifetime at relatively low cost (as compared to replacement with entirely new blades). Nevertheless, existing repair processes tend to be labor intensive and time consuming.

[0005] For example, a traditional compressor blade tip repair process uses a welding/cladding technique where repair materials are supplied, in either powder or wire form, to the blade tips. The repair materials are melted by focused power source (e.g., laser, e-beam, plasma arc, etc.) and bonded to blade tips. However, blades repaired with such welding/cladding technique need tedious post-processing to achieve the target geometry and surface finish. Specifically, due to the bulky feature size of the welding/cladding repair joint, the repaired blades require heavy machining to remove the extra materials on the tip, and further require a secondary polishing process to achieve a target surface finish. Notably, such a process is performed on a single blade at a time, is very labor intensive and tedious, and results in very large overall labor costs for a single repair.

[0006] Alternatively, other direct-energy-deposition (DED) methods may be used for blade repair, e.g., such as cold spray, which directs high-speed metal powders to bombard the target or base component such that the powders deform and deposit on the base component. However, none of these DED methods are suitable for batch processing or for repairing a large number of components in a time efficient manner, thus providing little or no business value.

[0007] Accordingly, novel systems and methods have been developed and are presented herein for repairing or rebuilding worn compressor blades (or any other components) using a powder bed additive manufacturing process. Specifically, such a repair process generally includes removing the worn portion of each of a plurality of compressor blades, positioning the plurality of compressor blades on a build platform of an additive manufacturing machine, determining the precise location of each blade tip, and printing repair segments directly onto the blade tips, layer by layer, until the compressor blades reach their original dimensions or another suitable target size and shape.

[0008] One of the key challenges with such a novel additive manufacturing DMLM repair procedures described herein relates to aligning the blade tips at the same vertical height to facilitate the powder depositing and recoating processes. Specifically, the recoating process generally uses a recoater blade that scrapes or spreads additive powder into a layer on the powder bed prior to fusing a portion of that layer. However, if a blade tip is too far above a desired height, physical contact

with the recoater may occur, causing a failure of the recoating process. By contrast, if a blade tip is too far below the desired height, proper fusing of the layer of deposited additive powder to the blade may not occur, e.g., because the melt pool is not deep enough to form a proper bond with the blade tip.

[0009] Another challenge in such novel additive manufacturing repair procedures relates to the loading, unloading, and handling additive powder which is used to fill the powder bed. In this regard, to perform a repair process on the tip of a blade, the powder bed must first be loaded with additive powder to the height of the blade tips. Such a process generally includes manually loading the additive powder, which is time-consuming and can also be costly, especially for components with large dimensions in the build orientation, e.g., the height of the blades. Moreover, any unpacked additive powder might collapse during printing, resulting in failure of recoating. In addition, filling the entire volume of the powder bed which is not filled by components to be repaired can require a large volume of powder which must be added prior to printing, removed after printing, and filtered or screened prior to reuse during a subsequent additive manufacturing process.

[0010] Accordingly, an improved system and method for repairing components using an additive manufacturing machine would be useful. More particularly, an additive manufacturing machine including tooling assemblies for aligning multiple components and for minimizing powder usage during a powder bed additive manufacturing process would be particularly beneficial.

BRIEF DESCRIPTION

[0011] Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

[0012] In one exemplary embodiment of the present disclosure, a method of aligning a plurality of components for a repair process is provided. The method includes positioning the plurality of components such that a repair surface of each of the plurality of components contacts an alignment plate, surrounding the alignment plate with containment walls to define a reservoir, the plurality of components being positioned at least partially within the reservoir, and dispensing a fill material into the

reservoir, the fill material being configured for fixing a relative position of the plurality of components when the fill material is solidified.

[0013] In another exemplary aspect of the present disclosure, a tooling assembly for fixing a relative position of a plurality of components is provided. The tooling assembly includes an alignment plate for receiving the plurality of components such that a repair surface of each of the plurality of components contacts the alignment plate, a plurality of walls surrounding the alignment plate to define a reservoir, and a fill assembly for dispensing a fill material into the reservoir, the fill material fixing a relative position of the plurality of components when solidified.

[0014] These and other features, aspects, and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures.

[0016] FIG. 1 shows a schematic representation of an additive repair system that may be used for repairing or rebuilding components according to an exemplary embodiment of the present subject matter.

[0017] FIG. 2 depicts certain components of a controller according to example embodiments of the present subject matter.

[0018] FIG. 3 shows a schematic view of an additive manufacturing machine that may be used as part of the exemplary additive repair system of FIG. 1 according to an exemplary embodiment of the present subject matter.

[0019] FIG. 4 shows a close-up schematic view of a build platform of the exemplary additive manufacturing machine of FIG. 3 according to an exemplary embodiment of the present subject matter.

[0020] FIG. 5 is a schematic cross sectional view of a tooling assembly that may be used to align the repair surfaces of a plurality of components according to an exemplary embodiment of the present subject matter.

[0021] FIG. 6 is a schematic cross sectional view of the exemplary tooling assembly of FIG. 5 filled with a fill material to fix the relative position of the plurality of components according to an exemplary embodiment of the present subject matter.

[0022] FIG. 7 is a schematic cross sectional view of the exemplary tooling assembly of FIG. 5 with a layer of additive powder being deposited according to an exemplary embodiment of the present subject matter.

[0023] FIG. 8 is a schematic cross sectional view of a tooling assembly that may be used to align the repair surfaces of a plurality of components according to another exemplary embodiment of the present subject matter.

[0024] FIG. 9 is a method of aligning a plurality of components in a powder bed additive manufacturing machine according to an exemplary embodiment of the present subject matter.

[0025] Repeat use of reference characters in the present specification and drawings is intended to represent the same or analogous features or elements of the present invention.

DETAILED DESCRIPTION

[0026] Reference now will be made in detail to embodiments of the invention, one or more examples of which are illustrated in the accompanying drawings. Each example is provided by way of explanation of the invention, not limitation of the invention. In fact, it will be apparent to those skilled in the art that various configurations, modifications, and variations can be made in the present invention without departing from the scope or spirit of the invention. For instance, features illustrated or described as part of one embodiment can be used with another embodiment to yield a still further embodiment. Thus, it is intended that the present invention covers such modifications and variations as come within the scope of the appended claims and their equivalents.

[0027] As used herein, the terms “first,” “second,” and “third” may be used interchangeably to distinguish one component from another and are not intended to

signify location or importance of the individual components. In addition, the terms “upstream” and “downstream” refer to the relative direction with respect to the motion of an object or a flow of fluid. For example, “upstream” refers to the direction from which the object has moved or fluid has flowed, and “downstream” refers to the direction to which the object is moving or the fluid is flowing. Furthermore, as used herein, terms of approximation, such as “approximately,” “substantially,” or “about,” refer to being within a ten percent margin of error.

[0028] Aspects of the present subject matter are directed to a system and method for repairing one or more components using an additive manufacturing process. The method includes securing the components in a tooling assembly such that a repair surface of each component is positioned within a single build plane, determining a repair toolpath corresponding to the repair surface of each component using a vision system, depositing a layer of additive powder over the repair surface of each component using a powder dispensing assembly, and selectively irradiating the layer of additive powder along the repair toolpath to fuse the layer of additive powder onto the repair surface of each component.

[0029] Specifically, aspects of the present subject matter provide a tooling assembly and method of aligning a plurality of components for a repair process in an additive manufacturing machine. The method includes positioning the plurality of components such that a repair surface of each of the plurality of components contacts an alignment plate, e.g., under the force of gravity or using biasing members. The method further includes surrounding the alignment plate with containment walls to define a reservoir around the plurality of components and dispensing a fill material, such as wax or a potting material, into the reservoir which is configured for fixing a relative position of the plurality of components when the fill material is solidified. In this manner, a tips of the plurality of components may be aligned for the repair procedure and the amount of additive powder required to fill the powder bed may be reduced.

[0030] As described in detail below, exemplary embodiments of the present subject matter involve the use of additive manufacturing machines or methods. As used herein, the terms “additively manufactured” or “additive manufacturing techniques or processes” refer generally to manufacturing processes wherein

successive layers of material(s) are provided on each other to “build-up,” layer-by-layer, a three-dimensional component. The successive layers generally fuse together to form a monolithic component which may have a variety of integral sub-components.

[0031] Although additive manufacturing technology is described herein as enabling fabrication of complex objects by building objects point-by-point, layer-by-layer, typically in a vertical direction, other methods of fabrication are possible and within the scope of the present subject matter. For example, although the discussion herein refers to the addition of material to form successive layers, one skilled in the art will appreciate that the methods and structures disclosed herein may be practiced with any additive manufacturing technique or manufacturing technology. For example, embodiments of the present invention may use layer-additive processes, layer-subtractive processes, or hybrid processes.

[0032] Suitable additive manufacturing techniques in accordance with the present disclosure include, for example, Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), 3D printing such as by inkjets and laserjets, Stereolithography (SLA), Direct Selective Laser Sintering (DSLS), Electron Beam Sintering (EBS), Electron Beam Melting (EBM), Laser Engineered Net Shaping (LENS), Laser Net Shape Manufacturing (LNSM), Direct Metal Deposition (DMD), Digital Light Processing (DLP), Direct Selective Laser Melting (DSLM), Selective Laser Melting (SLM), Direct Metal Laser Melting (DMLM), and other known processes.

[0033] In addition to using a direct metal laser sintering (DMLS) or direct metal laser melting (DMLM) process where an energy source is used to selectively sinter or melt portions of a layer of powder, it should be appreciated that according to alternative embodiments, the additive manufacturing process may be a “binder jetting” process. In this regard, binder jetting involves successively depositing layers of additive powder in a similar manner as described above. However, instead of using an energy source to generate an energy beam to selectively melt or fuse the additive powders, binder jetting involves selectively depositing a liquid binding agent onto each layer of powder. The liquid binding agent may be, for example, a photo-curable polymer or another liquid bonding agent. Other suitable additive manufacturing methods and variants are intended to be within the scope of the present subject matter.

[0034] The additive manufacturing processes described herein may be used for forming components using any suitable material. For example, the material may be plastic, metal, concrete, ceramic, polymer, epoxy, photopolymer resin, or any other suitable material that may be in solid, liquid, powder, sheet material, wire, or any other suitable form. More specifically, according to exemplary embodiments of the present subject matter, the additively manufactured components described herein may be formed in part, in whole, or in some combination of materials including but not limited to pure metals, nickel alloys, chrome alloys, titanium, titanium alloys, magnesium, magnesium alloys, aluminum, aluminum alloys, iron, iron alloys, stainless steel, and nickel or cobalt based superalloys (e.g., those available under the name Inconel® available from Special Metals Corporation). These materials are examples of materials suitable for use in the additive manufacturing processes described herein, and may be generally referred to as “additive materials.”

[0035] In addition, one skilled in the art will appreciate that a variety of materials and methods for bonding those materials may be used and are contemplated as within the scope of the present disclosure. As used herein, references to “fusing” may refer to any suitable process for creating a bonded layer of any of the above materials. For example, if an object is made from polymer, fusing may refer to creating a thermoset bond between polymer materials. If the object is epoxy, the bond may be formed by a crosslinking process. If the material is ceramic, the bond may be formed by a sintering process. If the material is powdered metal, the bond may be formed by a melting or sintering process. One skilled in the art will appreciate that other methods of fusing materials to make a component by additive manufacturing are possible, and the presently disclosed subject matter may be practiced with those methods.

[0036] In addition, the additive manufacturing process disclosed herein allows a single component to be formed from multiple materials. Thus, the components described herein may be formed from any suitable mixtures of the above materials. For example, a component may include multiple layers, segments, or parts that are formed using different materials, processes, and/or on different additive manufacturing machines. In this manner, components may be constructed which have different materials and material properties for meeting the demands of any particular application. In addition, although the components described herein are constructed

entirely by additive manufacturing processes, it should be appreciated that in alternate embodiments, all or a portion of these components may be formed via casting, machining, and/or any other suitable manufacturing process. Indeed, any suitable combination of materials and manufacturing methods may be used to form these components.

[0037] An exemplary additive manufacturing process will now be described. Additive manufacturing processes fabricate components using three-dimensional (3D) information, for example a three-dimensional computer model, of the component. Accordingly, a three-dimensional design model of the component may be defined prior to manufacturing. In this regard, a model or prototype of the component may be scanned to determine the three-dimensional information of the component. As another example, a model of the component may be constructed using a suitable computer aided design (CAD) program to define the three-dimensional design model of the component.

[0038] The design model may include 3D numeric coordinates of the entire configuration of the component including both external and internal surfaces of the component. For example, the design model may define the body, the surface, and/or internal passageways such as openings, support structures, etc. In one exemplary embodiment, the three-dimensional design model is converted into a plurality of slices or segments, e.g., along a central (e.g., vertical) axis of the component or any other suitable axis. Each slice may define a thin cross section of the component for a predetermined height of the slice. The plurality of successive cross-sectional slices together form the 3D component. The component is then “built-up” slice-by-slice, or layer-by-layer, until finished.

[0039] In this manner, the components described herein may be fabricated using the additive process, or more specifically each layer is successively formed, e.g., by fusing or polymerizing a plastic using laser energy or heat or by sintering or melting metal powder. For example, a particular type of additive manufacturing process may use an energy beam, for example, an electron beam or electromagnetic radiation such as a laser beam, to sinter or melt a powder material. Any suitable laser and laser parameters may be used, including considerations with respect to power, laser beam spot size, and scanning velocity. The build material may be formed by any suitable

powder or material selected for enhanced strength, durability, and useful life, particularly at high temperatures.

[0040] Each successive layer may be, for example, between about 10 μm and 200 μm , although the thickness may be selected based on any number of parameters and may be any suitable size according to alternative embodiments. Therefore, utilizing the additive formation methods described above, the components described herein may have cross sections as thin as one thickness of an associated powder layer, e.g., 10 μm , utilized during the additive formation process.

[0041] In addition, utilizing an additive process, the surface finish and features of the components may vary as need depending on the application. For example, the surface finish may be adjusted (e.g., made smoother or rougher) by selecting appropriate laser scan parameters (e.g., laser power, scan speed, laser focal spot size, etc.) during the additive process, especially in the periphery of a cross-sectional layer which corresponds to the part surface. For example, a rougher finish may be achieved by increasing laser scan speed or decreasing the size of the melt pool formed, and a smoother finish may be achieved by decreasing laser scan speed or increasing the size of the melt pool formed. The scanning pattern and/or laser power can also be changed to change the surface finish in a selected area.

[0042] After fabrication of the component is complete, various post-processing procedures may be applied to the component. For example, post processing procedures may include removal of excess powder by, for example, blowing or vacuuming. Other post processing procedures may include a stress relief process. Additionally, thermal, mechanical, and/or chemical post processing procedures can be used to finish the part to achieve a desired strength, surface finish, and other component properties or features.

[0043] Notably, in exemplary embodiments, several aspects and features of the present subject matter were previously not possible due to manufacturing restraints. However, the present inventors have advantageously utilized current advances in additive manufacturing techniques to improve various components and the method of additively manufacturing such components. While the present disclosure is not limited to the use of additive manufacturing to form these components generally,

additive manufacturing does provide a variety of manufacturing advantages, including ease of manufacturing, reduced cost, greater accuracy, etc.

[0044] Also, the additive manufacturing methods described above enable much more complex and intricate shapes and contours of the components described herein to be formed with a very high level of precision. For example, such components may include thin additively manufactured layers, cross sectional features, and component contours. In addition, the additive manufacturing process enables the manufacture of a single component having different materials such that different portions of the component may exhibit different performance characteristics. The successive, additive nature of the manufacturing process enables the construction of these novel features. As a result, components formed using the methods described herein may exhibit improved performance and reliability.

[0045] Referring now to FIG. 1, an exemplary additive repair system 50 will be described according to an exemplary embodiment of the present subject matter. As illustrated, additive repair system 50 generally includes a tooling fixture or assembly 52, a material removal assembly 54, a vision system 56, a user interface panel 58, and an additive manufacturing machine or system 100. Furthermore, a system controller 60 may be operably coupled with some or all parts of additive repair system 50 for facilitating system operation. For example, system controller 60 may be operably coupled to user interface panel 58 to permit operator communication with additive repair system 50, e.g., to input commands, upload printing toolpaths or CAD models, initiating operating cycles, etc. Controller 60 may further be in communication with vision system 56 for receiving imaging data and with AM machine 100 for performing a printing process.

[0046] According to exemplary embodiments, tooling assembly 52 is generally configured for supporting a plurality of components in a desired position and orientation. According to exemplary embodiments, tooling assembly 52 supports twenty (20) high pressure compressor blades 70 during an additive manufacturing repair process. Specifically, the additive manufacturing process may be a powder bed fusion process (e.g., a DMLM or DMLS process as described above). Although the repaired components are illustrated herein as compressor blades 70 of a gas turbine engine, it should be appreciated that any other suitable component may be repaired,

such as turbine blades, other airfoils, or components from other machines. In order to achieve proper recoating and to facilitate the printing process, it may be desirable to position all blades 70 in the same orientation and at the same height such that a repair surface 72 of each blade is in a single build plane. Tooling assembly 52 is a fixture intended to secure blades 70 in such desired position and orientation.

[0047] Material removal assembly 54 may include a machine or device configured for grinding, machining, brushing, etching, polishing, wire electrical discharge machining (EDM), cutting, or otherwise substantively modifying a component, e.g., by subtractive modification or material removal. For example, material removal assembly 54 may include a belt grinder, a disc grinder, or any other grinding or abrasive mechanism. According to an exemplary embodiment, material removal assembly 54 may be configured for removing material from a tip of each blade 70 to obtain a desirable repair surface 72. For example, as explained briefly above, material removal assembly 54 may remove at least a portion of blades 70 that has been worn or damaged, e.g., which may include microcracks, pits, abrasions, defects, foreign material, depositions, imperfections, and the like. According to an exemplary embodiment, each blade 70 is prepared using material removal assembly 54 to achieve the desired repair surface 72, after which the blades 70 are all mounted in tooling assembly 52 and leveled appropriately. However, according to alternative embodiments, material removal assembly 54 may grind each blade 70 as it is fixed in position in tooling assembly 52.

[0048] After the blades are prepared, vision system 56 may be used to obtain an image or digital representation of the precise position and coordinates of each blade 70 positioned in tooling assembly 52. In this regard, according to exemplary embodiments, vision system 56 may include any suitable camera or cameras 80, scanners, imaging devices, or other machine vision device that may be operably configured to obtain image data that includes a digital representation of one or more fields of view. Such a digital representation may sometimes be referred to as a digital image or an image; however, it will be appreciated that the present disclosure may be practiced without rendering such a digital representation in human-visible form. Nevertheless, in some embodiments, a human-visible image corresponding to a field

of view may be displayed on the user interface 58 based at least in part on such a digital representation of one or more fields of view.

[0049] Vision system 56 allows the additive repair system 50 to obtain information pertaining to one or more blades 70 onto which one or more repair segments 74 (see FIG. 4) may be respectively additively printed. In particular, the vision system 56 allows the one or more blades 70 to be located and defined so that the additive manufacturing machine 100 may be instructed to print one or more repair segments 74 on a corresponding one or more blades 70 with suitably high accuracy and precision. According to an exemplary embodiment, the one or more blades 70 may be secured to tooling assembly 52, a mounting plate, a build platform, or any other fixture with repair surface 72 of the respective blades 70 aligned to a single build plane 82.

[0050] The one or more cameras 80 of the vision system 56 may be configured to obtain two-dimensional or three-dimensional image data, including a two-dimensional digital representation of a field of view and/or a three-dimensional digital representation of a field of view. Alignment of the repair surface 72 of the blades 70 with the build plane 82 allows the one or more cameras 80 to obtain higher quality images. For example, the one or more cameras 80 may have a focal length adjusted or adjustable to the build plane 82. With the repair surface 72 of one or more blades 70 aligned to the build plane 82, the one or more cameras may readily obtain digital images of the repair surface 72.

[0051] The one or more cameras 80 may include a field of view that encompasses all or a portion of the one or more blades 70 secured to the tooling assembly 52. For example, a single field of view may be wide enough to encompass a plurality of components, such as each of the plurality of blades 70 secured to tooling assembly 52. Alternatively, a field of view may more narrowly focus on an individual blade 70 such that digital representations of respective blades 70 are obtained separately. It will be appreciated that separately obtained digital images may be stitched together to obtain a digital representation of a plurality of components or blades 70. In some embodiments, the camera 80 may include a collimated lens configured to provide a flat focal plane, such that blades 70 or portions thereof located towards the periphery

of the field of view are not distorted. Additionally, or in the alternative, the vision system 56 may utilize a distortion correction algorithm to address any such distortion.

[0052] Image data obtained by the vision system 56, including a digital representation of one or more blades 70 may be transmitted to a control system, such as controller 60. Controller 60 may be configured to determine a repair surface 72 of each of a plurality of blades 70 from one or more digital representations of one or more fields of view having been captured by the vision system 56, and then determine one or more coordinates of the repair surface 72 of respective ones of the plurality of blades 70. Based on the one or more digital representations, controller 60 may generate one or more print commands (e.g., corresponding to one or more repair toolpaths, e.g., the path of a laser focal point), which may be transmitted to an additive manufacturing machine 100 such that the additive manufacturing machine 100 may additively print a plurality of repair segments 74 on respective ones of the plurality of blades 70. The one or more print commands may be configured to additively print a plurality of repair segments 74 with each respective one of the plurality of repair segments 74 being located on the repair surface 72 of a corresponding blade 70.

[0053] Each of the components and subsystems of additive repair system 50 are described herein in the context of an additive blade repair process. However, it should be appreciated that aspects of the present subject matter may be used to repair or rebuild any suitable components. The present subject matter is not intended to be limited to the specific repair process described. In addition, FIG. 1 illustrates each of the systems as being distinct or separate from each other and implies the process steps should be performed in a particular order, however, it should be appreciated that these subsystems may be integrated into a single machine, process steps may be swapped, and other changes to the build process may be implemented while remaining within the scope of the present subject matter.

[0054] For example, vision system 56 and additive manufacturing machine 100 may be provided as a single, integrated unit or as separate stand-alone units. In addition, controller 60 may include one or more control systems. For example, a single controller 60 may be operably configured to control operations of the vision system 56 and the additive manufacturing machine 100, or separate controllers 60

may be operably configured to respectively control the vision system 56 and the additive manufacturing machine 100.

[0055] Operation of additive repair system 50, vision system 56, and AM machine 100 may be controlled by electromechanical switches or by a processing device or controller 60 (see, e.g., FIGS. 1 and 2). According to exemplary embodiments, controller 60 may be operatively coupled to user interface panel 58 for user manipulation, e.g., to control the operation of various components of AM machine 100 or system 50. In this regard, controller 60 may operably couple all systems and subsystems within additive repair system 50 to permit communication and data transfer therebetween. In this manner, controller 60 may be generally configured for operating additive repair system 50 or performing one or more of the methods described herein.

[0056] FIG. 2 depicts certain components of controller 60 according to example embodiments of the present disclosure. Controller 60 can include one or more computing device(s) 60A which may be used to implement methods as described herein. Computing device(s) 60A can include one or more processor(s) 60B and one or more memory device(s) 60C. The one or more processor(s) 60B can include any suitable processing device, such as a microprocessor, microcontroller, integrated circuit, an application specific integrated circuit (ASIC), a digital signal processor (DSP), a field-programmable gate array (FPGA), logic device, one or more central processing units (CPUs), graphics processing units (GPUs) (e.g., dedicated to efficiently rendering images), processing units performing other specialized calculations, etc. The memory device(s) 60C can include one or more non-transitory computer-readable storage medium(s), such as RAM, ROM, EEPROM, EPROM, flash memory devices, magnetic disks, etc., and/or combinations thereof.

[0057] The memory device(s) 60C can include one or more computer-readable media and can store information accessible by the one or more processor(s) 60B, including instructions 60D that can be executed by the one or more processor(s) 60B. For instance, the memory device(s) 60C can store instructions 60D for running one or more software applications, displaying a user interface, receiving user input, processing user input, etc. In some implementations, the instructions 60D can be executed by the one or more processor(s) 60B to cause the one or more processor(s)

60B to perform operations, e.g., such as one or more portions of methods described herein. The instructions 60D can be software written in any suitable programming language or can be implemented in hardware. Additionally, and/or alternatively, the instructions 60D can be executed in logically and/or virtually separate threads on processor(s) 60B.

[0058] The one or more memory device(s) 60C can also store data 60E that can be retrieved, manipulated, created, or stored by the one or more processor(s) 60B. The data 60E can include, for instance, data to facilitate performance of methods described herein. The data 60E can be stored in one or more database(s). The one or more database(s) can be connected to controller 60 by a high bandwidth LAN or WAN, or can also be connected to controller through one or more network(s) (not shown). The one or more database(s) can be split up so that they are located in multiple locales. In some implementations, the data 60E can be received from another device.

[0059] The computing device(s) 60A can also include a communication module or interface 60F used to communicate with one or more other component(s) of controller 60 or additive manufacturing machine 100 over the network(s). The communication interface 60F can include any suitable components for interfacing with one or more network(s), including for example, transmitters, receivers, ports, controllers, antennas, or other suitable components.

[0060] Referring now to FIG. 3, an exemplary laser powder bed fusion system, such as a DMLS or DMLM system 100, will be described according to an exemplary embodiment. Specifically, AM system 100 is described herein as being used to build or repair blades 70. It should be appreciated that blades 70 are only an exemplary component to be built or repaired and are used primarily to facilitate description of the operation of AM machine 100. The present subject matter is not intended to be limited in this regard, but instead AM machine 100 may be used for printing repair segments on any suitable plurality of components.

[0061] As illustrated, AM system 100 generally defines a vertical direction V or Z-direction, a lateral direction L or X-direction, and a transverse direction T or Y-direction (see FIG. 1), each of which is mutually perpendicular, such that an orthogonal coordinate system is generally defined. As illustrated, system 100 includes a fixed enclosure or build area 102 which provides a contaminant-free and controlled

environment for performing an additive manufacturing process. In this regard, for example, enclosure 102 serves to isolate and protect the other components of the system 100. In addition, enclosure 102 may be provided with a flow of an appropriate shielding gas, such as nitrogen, argon, or another suitable gas or gas mixture. In this regard, enclosure 102 may define a gas inlet port 104 and a gas outlet port 106 for receiving a flow of gas to create a static pressurized volume or a dynamic flow of gas.

[0062] Enclosure 102 may generally contain some or all components of AM system 100. According to an exemplary embodiment, AM system 100 generally includes a table 110, a powder supply 112, a scraper or recoater mechanism 114, an overflow container or reservoir 116, and a build platform 118 positioned within enclosure 102. In addition, an energy source 120 generates an energy beam 122 and a beam steering apparatus 124 directs energy beam 122 to facilitate the AM process as described in more detail below. Each of these components will be described in more detail below.

[0063] According to the illustrated embodiment, table 110 is a rigid structure defining a planar build surface 130. In addition, planar build surface 130 defines a build opening 132 through which build chamber 134 may be accessed. More specifically, according to the illustrated embodiment, build chamber 134 is defined at least in part by vertical walls 136 and build platform 118. Notably, build platform 118 is movable along a build direction 138 relative to build surface 130. More specifically, build direction 138 may correspond to the vertical direction V, such that moving build platform 118 down increases the height of the part being printed and the build chamber 134. In addition, build surface 130 defines a supply opening 140 through which additive powder 142 may be supplied from powder supply 112 and a reservoir opening 144 through which excess additive powder 142 may pass into overflow reservoir 116. Collected additive powders may optionally be treated to sieve out loose, agglomerated particles before re-use.

[0064] Powder supply 112 generally includes an additive powder supply container 150 which generally contains a volume of additive powder 142 sufficient for some or all of the additive manufacturing process for a specific part or parts. In addition, powder supply 112 includes a supply platform 152, which is a plate-like structure that is movable along the vertical direction within powder supply container 150. More

specifically, a supply actuator 154 vertically supports supply platform 152 and selectively moves it up and down during the additive manufacturing process.

[0065] AM system 100 further includes recoater mechanism 114, which is a rigid, laterally-elongated structure that lies proximate build surface 130. For example, recoater mechanism 114 may be a hard scraper, a soft squeegee, or a roller. Recoater mechanism 114 is operably coupled to a recoater actuator 160 which is operable to selectively move recoater mechanism 114 along build surface 130. In addition, a platform actuator 164 is operably coupled to build platform 118 and is generally operable for moving build platform 118 along the vertical direction during the build process. Although actuators 154, 160, and 164 are illustrated as being hydraulic actuators, it should be appreciated that any other type and configuration of actuators may be used according to alternative embodiments, such as pneumatic actuators, hydraulic actuators, ball screw linear electric actuators, or any other suitable vertical support means. Other configurations are possible and within the scope of the present subject matter.

[0066] As used herein, “energy source” may be used to refer to any device or system of devices configured for directing an energy beam of suitable power and other operating characteristics towards a layer of additive powder to sinter, melt, or otherwise fuse a portion of that layer of additive powder during the build process. For example, energy source 120 may be a laser or any other suitable irradiation emission directing device or irradiation device. In this regard, an irradiation or laser source may originate photons or laser beam irradiation which is directed by the irradiation emission directing device or beam steering apparatus.

[0067] According to an exemplary embodiment, beam steering apparatus 124 includes one or more mirrors, prisms, lenses, and/or electromagnets operably coupled with suitable actuators and arranged to direct and focus energy beam 122. In this regard, for example, beam steering apparatus 124 may be a galvanometer scanner that moves or scans the focal point of the laser beam 122 emitted by energy source 120 across the build surface 130 during the laser melting and sintering processes. In this regard, energy beam 122 can be focused to a desired spot size and steered to a desired position in plane coincident with build surface 130. The galvanometer scanner in powder bed fusion technologies is typically of a fixed position but the movable

mirrors/lenses contained therein allow various properties of the laser beam to be controlled and adjusted. According to exemplary embodiments, beam steering apparatus may further include one or more of the following: optical lenses, deflectors, mirrors, beam splitters, telecentric lenses, etc.

[0068] It should be appreciated that other types of energy sources 120 may be used which may use an alternative beam steering apparatus 124. For example, an electron beam gun or other electron source may be used to originate a beam of electrons (e.g., an “e-beam”). The e-beam may be directed by any suitable irradiation emission directing device preferably in a vacuum. When the irradiation source is an electron source, the irradiation emission directing device may be, for example, an electronic control unit which may include, for example, deflector coils, focusing coils, or similar elements. According to still other embodiments, energy source 120 may include one or more of a laser, an electron beam, a plasma arc, an electric arc, etc.

[0069] Prior to an additive manufacturing process, recoater actuator 160 may be lowered to provide a supply of powder 142 of a desired composition (for example, metallic, ceramic, and/or organic powder) into supply container 150. In addition, platform actuator 164 may move build platform 118 to an initial high position, e.g., such that it substantially flush or coplanar with build surface 130. Build platform 118 is then lowered below build surface 130 by a selected layer increment. The layer increment affects the speed of the additive manufacturing process and the resolution of a components or parts (e.g., blades 70) being manufactured. As an example, the layer increment may be about 10 to 100 micrometers (0.0004 to 0.004 in.).

[0070] Additive powder is then deposited over the build platform 118 before being fused by energy source 120. Specifically, supply actuator 154 may raise supply platform 152 to push powder through supply opening 140, exposing it above build surface 130. Recoater mechanism 114 may then be moved across build surface 130 by recoater actuator 160 to spread the raised additive powder 142 horizontally over build platform 118 (e.g., at the selected layer increment or thickness). Any excess additive powder 142 drops through the reservoir opening 144 into the overflow reservoir 116 as recoater mechanism 114 passes from left to right (as shown in FIG. 3).

Subsequently, recoater mechanism 114 may be moved back to a starting position.

[0071] Therefore, as explained herein and illustrated in FIG. 3, recoater mechanism 114, recoater actuator 160, supply platform 152, and supply actuator 154 may generally operate to successively deposit layers of additive powder 142 or other additive material to facilitate the print process. As such, these components may collectively be referred to herein as powder dispensing apparatus, system, or assembly. The leveled additive powder 142 may be referred to as a “build layer” 172 (see FIG. 4) and the exposed upper surface thereof may be referred to as build surface 130. When build platform 118 is lowered into build chamber 134 during a build process, build chamber 134 and build platform 118 collectively surround and support a mass of additive powder 142 along with any components (e.g., blades 70) being built. This mass of powder is generally referred to as a “powder bed,” and this specific category of additive manufacturing process may be referred to as a “powder bed process.”

[0072] During the additive manufacturing process, the directed energy source 120 is used to melt a two-dimensional cross-section or layer of the component (e.g., blades 70) being built. More specifically, energy beam 122 is emitted from energy source 120 and beam steering apparatus 124 is used to steer the focal point 174 of energy beam 122 over the exposed powder surface in an appropriate pattern (referred to herein as a “toolpath”). A small portion of exposed layer of the additive powder 142 surrounding focal point 174, referred to herein as a “weld pool” or “melt pool” or “heat effected zone” 176 (best seen in FIG. 4) is heated by energy beam 122 to a temperature allowing it to sinter or melt, flow, and consolidate. As an example, melt pool 176 may be on the order of 100 micrometers (0.004 in.) wide. This step may be referred to as fusing additive powder 142.

[0073] Build platform 118 is moved vertically downward by the layer increment, and another layer of additive powder 142 is applied in a similar thickness. The directed energy source 120 again emits energy beam 122 and beam steering apparatus 124 is used to steer the focal point 174 of energy beam 122 over the exposed powder surface in an appropriate pattern. The exposed layer of additive powder 142 is heated by energy beam 122 to a temperature allowing it to sinter or melt, flow, and consolidate both within the top layer and with the lower, previously-solidified layer. This cycle of moving build platform 118, applying additive powder 142, and then

directed energy beam 122 to melt additive powder 142 is repeated until the entire component (e.g., blades 70) is complete.

[0074] Referring again briefly to FIG 1, tooling assembly 52 is generally configured for receiving one or more components, e.g., shown here as blades 70, and securely mounting such components for a subsequent additive manufacturing process. Specifically, tooling assembly 52 may secure each of the plurality of blades 70 in a desired position and orientation relative to AM machine 100. In this regard, as used herein, the “position” of a blade 70 may refer to the coordinates of a centroid of blade 70 in the X-Y plane. In addition, the “orientation” of a blade 70 may refer to an angular position of blade 70 about the Z-direction. In this regard, according to an exemplary embodiment, the orientation of each blade 70 may be defined according to the angular position of its chord line (not shown). In this regard, for example, two blades 70 are said to have the same “orientation” when their chord lines are parallel to each other.

[0075] As explained briefly above, it is desirable to support a plurality of components, such as blades 70, such that the repair surface 72 of each blade 70 is positioned within a build plane 82. In this manner, a layer of additive powder (e.g., build layer 172) may be deposited over each repair surface 72 at a desired thickness for forming a first layer of repair segments 74 (FIG. 4) on the tip of each blade 70. Notably, however, due to the height of each blade 70 relative to a height of repair segments 74, conventional additive manufacturing processes require a substantial amount of additive powder 142. Specifically, a substantial volume of additive powder 142 must typically be provided into build chamber 134 to form a powder bed that supports the top layer of additive powder or build layer 172.

[0076] As explained above, the powder loading process is typically a manual process that takes a significant amount of time and can result in recoating or print errors when pockets or voids collapse within the additive powder 142. In addition, additive manufacturing machine 100, or build platform 118 more specifically, is typically configured for only supporting a specific volume or weight of additive powder 142 during the build process, thus introducing process limitations when powder bed is filled with additive powder 142. Finally, even to the extent some unfused additive powder 142 may be reused during subsequent additive

manufacturing processes, such used additive powder 142 must be carefully screened, filtered, or otherwise reconditioned prior to reuse. Aspects of the present subject matter are directed both to aligning the repair surface of components and to minimizing the amount of additive powder required for an additive repair process as described herein.

[0077] Referring now generally to FIGS. 5 through 8, a tooling assembly 200 that may be used with AM system 100 will be described according to an exemplary embodiment of the present subject matter. For example, tooling assembly 200 may be a part of or used in conjunction with tooling assembly 52 as described in relation to FIG. 1. Because tooling assembly 200 can be used as part of additive repair system 50 or in AM system 100, like reference numerals may be used in FIGS. 5 through 8 to refer to like features described with respect to FIGS. 1 through 4.

[0078] As illustrated, tooling assembly 200 includes an alignment plate 202 which is configured for receiving a plurality of components, e.g., blades 70 such that a repair surface 72 of each of the plurality of blades 70 contacts the alignment plate 202. In this regard, alignment plate 202 is typically a flat, rigid plate that serves to align repair surfaces 72 of all blades 70 in a single build plane 82. In this manner, each blade 70, regardless of its height, may have a repair surface 72 positioned in the build plane 82 (e.g., when urged against the alignment plate 202).

[0079] Notably, in order to facilitate a powder bed repair process, alignment plate 202 must be removed from repair surfaces 72 of blades 70 while blades 70 remain fixed relative to each other. Therefore, according to an exemplary embodiment, tooling assembly 200 further includes a fill assembly 210 which is configured for dispensing a fill material 212 around blades 70 when they are positioned against alignment plate 202. As used herein, “fill material” may be used to refer to any material or composition which may be solidified to fix the position of blades 70. In this regard, for example, fill material 212 may be wax, a potting material, a photopolymer resin, or molten glass. Alternatively, fill material 212 may be any other material that may be poured around blades 70 which may become less viscous or more rigid to secure the position of blades 70 when solidified.

[0080] Notably, according to exemplary embodiments, fill material 212 is a fluid material which flows around blades 70 to fill in gaps and ensure contact against all

portions of blades 70, e.g., to provide firm support when solidified. Therefore, according to exemplary embodiments, tooling assembly 200 may further include a plurality of walls 220 which surround alignment plate 202 to define a reservoir 222. In this regard, fill assembly 210 may dispense fill material 212 directly into reservoir 222 until the level of fill material 212 reaches a height is suitable to support blades 70 when the fill material 212 is solidified.

[0081] Notably, after fill material 212 has been poured into reservoir 222 such that it surrounds blades 70, fill material 212 must be solidified or its composition must be otherwise changed in order to rigidly couple and fix the relative positions of blades 70. After fill material 212 is solidified, the solidified fill material 212 and the components fixed therein (e.g., blades) are generally referred to as a fixed component assembly 230. It should be appreciated that fixed component assembly 230 may be removed from alignment plate 202 and walls 220 as a standalone, rigid structure having repair surfaces 72 of blades 70 positioned in a single plane, e.g., build plane 82. In this manner, as will be described below, fixed component assembly 230 may then be positioned at a known location on build platform 118 of an additive manufacturing machine 100 and an additive repair process may begin directly on the repair surface 72 of each blade 70.

[0082] It should be appreciated that such a solidification process may vary depending on the type of fill material 212 used. For example, if fill material 212 is liquid wax, tooling assembly 200 may be left at room temperature for an amount of time sufficient for the wax to solidify. Alternatively, tooling assembly 200 may be positioned in a refrigerated environment or may otherwise be cooled, e.g., by attaching cooling coils to walls 220 and the alignment plate 202. By contrast, if fill material 212 is a photopolymer resin, a light source sufficient for curing the photopolymer resin may be directed toward fill material 212 until it is solidified. It should further be appreciated that other fill materials are possible, other methods of solidification may be used, and other variations and modifications may be made to tooling assembly 200 while remaining within the scope of the present subject matter.

[0083] In addition, although the illustrated embodiments shown in FIGS. 5 through 8 illustrate three blades 70 which have been fixed and are formed into fixed component assembly 230 using tooling assembly 200, it should be appreciated that

tooling assembly 200 and the methods described herein may be used to prepare any other suitable number, type, position, and configuration of components according to alternative embodiments. The exemplary embodiments described herein are not intended to limit the scope of the present subject matter in any manner.

[0084] Referring now specifically to FIGS. 5 through 7, one exemplary use of tooling assembly 200 will be described according to an exemplary embodiment of the present subject matter. According to this embodiment, blades 70 are mounted against the alignment plate 202 under the force of gravity. Specifically, as shown in FIG. 5, blades 70 are mounted against the alignment plate 202 such that repair surfaces 72 are aligned against a top surface 240 of alignment plate 202. In other words, repair surfaces 72 face down along the vertical direction V toward alignment plate 202. Blade 70 may then be held in position in any suitable manner while walls 220 are positioned to surround alignment plate 202 and define reservoir 222.

[0085] After blades 70 are placed such that repair surfaces 72 are face down on alignment plate 202, fill assembly 210 may supply fill material 212 into reservoir 222, e.g., through a nozzle 242. According to the illustrated embodiment shown in FIG. 6, fill material 212 is added until a top of the component is covered, e.g., until dovetail 244 of each blade 70 is covered. However, it should be appreciated that according to alternative embodiments, blades 70 need only be surrounded by fill material 212 sufficiently to fix their relative position. Thus, the amount of fill material 212 needed may depend, for example, on the rigidity of fill material 212 when solidified, on the number and size of blades 70 in fixed component assembly 230, and on the amount of handling which might occur to fixed component assembly 230 prior to the additive repair process.

[0086] Notably, after fixed component assembly 230 has solidified, it may be desirable to remove a top layer or top portion 250 of fill material 212 from fixed component assembly 230. In this regard, for example, fill material 212 may contaminate repair surface 72 of each blade 70, may melt during the additive printing process and contaminate melt pool 176, or may otherwise compromise the additive printing process. Therefore, as illustrated in FIG. 7, tooling assembly 200 may further include a cleaning device 252 which is generally configured for removing the top portion 250 of fill material 212 from fixed component assembly 230. For example,

cleaning device 252 may be a heat source 254 which passes along top portion 250 of fixed component assembly 230 after it is removed from alignment plate 202. In this manner, heat source 254 may melt top portion 250 which may can flow away from blades 70 and off of fixed component assembly 230. According to alternative embodiments, cleaning device 252 may include any other suitable material removal device, such as a grinding wheel, sandpaper, or any other suitable machine or device configured for grinding, machining, brushing, etching, polishing, or otherwise substantively modifying a component, e.g., by subtractive modification or material removal.

[0087] After fixed component assembly 230 is formed to position repair surfaces 72 in build plane 82, and after top portion 250 of fill material 212 and fixed component assembly 230 is removed and repair surfaces 72 are suitably prepped, fixed component assembly 230 may be positioned on build platform 118 of AM machine 100 in preparation for the additive repair process. In this regard, recoater mechanism 114 may then deposit a layer of additive powder 142 over fixed component assembly 230 and the repair surfaces 72 of each of the plurality of blades 70, as illustrated schematically in FIG. 7. In this manner, build layer 172 may be positioned at the top of each repair surface 72 and have substantially even thickness and the additive printing process may proceed by fusing a portion of build layer 172 onto repair surfaces 72 of each blade 70.

[0088] Referring now specifically to FIG. 8, an alternative method of forming fixed component assembly 230 will be described according to an exemplary embodiment of the present subject matter. Notably, due to the similarity of components described with respect to FIGS. 5 through 7, like reference numerals may be used to refer to the same or similar elements in FIG. 8. The primary difference between these two embodiments is that the previously discussed fixed component assembly 230 is formed with repair surfaces 72 facing down on alignment plate 202, whereas the fixed component assembly 230 described with respect to FIG. 8 is formed with repair surfaces 72 facing up toward the bottom surface 260 of alignment plate 202.

[0089] In order to ensure flush contact with repair surface 72 of each blade 70 against bottom surface 260 of alignment plate 202, tooling assembly 200 may further

include one or more biasing members 262 which are configured for urging each of the blades 70 upward against the alignment plate 202. In this regard, biasing members 262 may be any suitable device or mechanism for exerting a biasing force on blades 70 upward along the vertical direction V. Biasing members 262 may be, for example, one or more mechanical springs, magnet pairs (e.g., permanent magnets or electromagnets), linear actuators, piezoelectric actuators, etc. The biasing force generated by biasing members 262 allows repair surfaces 72 to seat flush against the alignment plate 202 such that they are aligned in the same build plane 82.

[0090] Notably, after the blades 70 are urged upward against the alignment plate 202, fill assembly 210 may dispense fill material 212 into reservoir 222 in the same manner as described above. However, it should be appreciated that by mounting blades 70 with their repair surfaces 72 facing up, the fill material 212 need only be filled to a level suitable for forming a rigid fixed component assembly 230, but preferably does not cover repair surfaces 72 themselves. In this manner, potential contamination of repair surfaces 72 may be avoided and cleaning device 252 may not be needed for removing top portion 250 of fill material 212 from fixed component assembly 230.

[0091] Thus, tooling assembly 200 as described above is generally configured for forming a fixed component assembly 230 which includes a plurality of components, e.g., blades 70, surrounded by a solidified fill material 212 which fixes repair surfaces 72 of each blade 70 in a single horizontal plane, e.g., the build plane 82. Notably, in addition to securing repair surfaces 72 and build plane 82 to facilitate improved recoating and printing operations, performing repair procedures with fixed component assembly 230 also requires much less additive powder within build chamber 134. In this regard, solidified fill material 212 acts as a raised support surface for forming the powder bed, such that the process for supplying or loading additive powder 142 into powder bed is simplified. For example, an operator need only fill build chamber 134 above fill material 212. In this manner, the time required to prepare the additive manufacturing machine 100 for the print process is reduced, as is the amount of additive powder 142 that must be used and the required time for post processing of blades 70 and additive powder 142.

[0092] Now that the construction and configuration of additive repair system 50 has been described according to exemplary embodiments of the present subject matter, an exemplary method 300 for mounting and aligning a plurality of components for a repair or rebuild process using an additive repair system will be described according to an exemplary embodiment of the present subject matter. Method 300 can be used to repair blades 70 using additive repair system 50, AM machine 100, and tooling assembly 200, or to repair any other suitable component using any other suitable additive manufacturing machine or system. In this regard, for example, controller 60 may be configured for implementing some or all steps of method 300. Further, it should be appreciated that the exemplary method 300 is discussed herein only to describe exemplary aspects of the present subject matter, and is not intended to be limiting.

[0093] Referring now to FIG. 9, method 300 includes, at step 310, positioning the plurality of components such that a repair surface of each of the plurality of components contacts an alignment plate. In this regard, continuing the example from above, the plurality of blades 70 may be urged against the alignment plate 202 under the force of gravity (e.g., as shown in FIGS. 5 through 7) or by a biasing member 262 (e.g., as shown in FIG. 8). In this manner the repair surface 72 of each blade 70 is positioned in a desired build plane 82.

[0094] Method 300 further includes, at step 320, surrounding the alignment plate with containment walls to define a reservoir, the plurality of components being positioned at least partially within the reservoir. Furthermore, step 330 includes dispensing a fill material into the reservoir, the fill material being configured for fixing the relative position of the plurality of components when the fill material is solidified. Step 340 may further include solidifying the fill material to form a fixed component assembly comprising fill material and the plurality of components fixed therein. In this regard, for example, a potting material, liquid wax, a photopolymer resin, or molten glass may be poured into reservoir 222 and solidified, e.g., by cooling to room temperature. After the fill material is solidified, fixed component assembly 230 includes the plurality of components, e.g., blades 70, which are fixed in relative position and have their repair surfaces 72 aligned for the additive printing process.

[0095] In the event fixed component assembly 230 was formed with the repair surfaces 72 of blades 70 facing down, step 350 may further include removing a top layer of the fill material from the fixed component assembly proximate the repair surface of each of the plurality of components. For example, heat source 254 may be used to melt wax, a grinding assembly may be used to remove potting material, etc. After fixed components assembly 230 has been prepped and repair surfaces 72 are cleaned, fixed component assembly 230 may be positioned on a build platform 118 of an additive manufacturing machine 100 for printing process.

[0096] Thus, according to an exemplary embodiment, method 300 may further include additively printing repair segments 74 onto repair surfaces 72 of each blade 70 using AM machine 100. In this regard, step 360 includes depositing a layer of additive powder over the fixed component assembly using a powder dispensing assembly. Step 370 includes selectively irradiating the layer of additive powder to fuse the layer of additive powder onto the repair surfaces of the components. In this manner, an energy source may fuse additive powder onto each blade tip layer by layer until the component is repaired to an original CAD model or to another suitable geometry.

[0097] FIG. 9 depicts an exemplary control method having steps performed in a particular order for purposes of illustration and discussion. Those of ordinary skill in the art, using the disclosures provided herein, will understand that the steps of any of the methods discussed herein can be adapted, rearranged, expanded, omitted, or modified in various ways without deviating from the scope of the present disclosure. Moreover, although aspects of the methods are explained using additive repair system 50, AM machine 100, and tooling assembly 200 as an example, it should be appreciated that these methods may be applied to repairing or rebuilding any other number, type, and configuration of components using any suitable tooling assembly or additive manufacturing machine or system.

[0098] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other

examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

[0099] Further aspects of the invention are provided by the subject matter of the following clauses:

[00100] 1. A method of aligning a plurality of components for a repair process, the method comprising: positioning the plurality of components such that a repair surface of each of the plurality of components contacts an alignment plate; surrounding the alignment plate with containment walls to define a reservoir, the plurality of components being positioned at least partially within the reservoir; and dispensing a fill material into the reservoir, the fill material being configured for fixing a relative position of the plurality of components when the fill material is solidified.

[00101] 2. The method of any preceding clause, wherein positioning the plurality of components comprises: positioning the plurality of components such that the repair face of each of the plurality of components is positioned face down on the alignment plate, the alignment plate at least partially defining the reservoir.

[00102] 3. The method of any preceding clause, further comprising: solidifying the fill material to form a fixed component assembly comprising the fill material and the plurality of components; and removing a top layer of the fill material from the fixed component assembly proximate the repair surface of each of the plurality of components.

[00103] 4. The method of any preceding clause, wherein removing the top layer of the fill material comprises: melting the top layer of fill material using a heat source.

[00104] 5. The method of any preceding clause, wherein positioning the plurality of components comprises, for each of the plurality of components: positioning the component such that the repair surface faces up toward a bottom surface of the alignment plate; and urging the component upward with a biasing member to ensure contact between the repair surface and the alignment plate.

- [00105] 6. The method of any preceding clause, wherein the biasing member comprises one or more springs, one or more magnet pairs, and/or one or more piezoelectric actuators.
- [00106] 7. The method of any preceding clause, wherein the fill material is selected from a group consisting of a potting material, a wax, a photopolymer resin, or molten glass.
- [00107] 8. The method of any preceding clause, further comprising: solidifying the fill material to form a fixed component assembly comprising the fill material and the plurality of components; and mounting the fixed component assembly on a build platform, the build platform being movable along a build direction.
- [00108] 9. The method of any preceding clause, further comprising: depositing a layer of additive powder over the fixed component assembly using a powder dispensing assembly; and selectively irradiating the layer of additive powder to fuse the layer of additive powder onto the repair surface of each of the plurality of components.
- [00109] 10. The method of any preceding clause, wherein the plurality of components comprise at least one airfoil of a gas turbine engine.
- [00110] 11. The method of any preceding clause, wherein the repair surface is a blade tip of a high pressure compressor blade of a gas turbine engine.
- [00111] 12. A tooling assembly for fixing a relative position of a plurality of components, the tooling assembly comprising: an alignment plate for receiving the plurality of components such that a repair surface of each of the plurality of components contacts the alignment plate; a plurality of walls surrounding the alignment plate to define a reservoir; and a fill assembly for dispensing a fill material into the reservoir, the fill material fixing a relative position of the plurality of components when solidified.
- [00112] 13. The tooling assembly of any preceding clause, wherein the plurality of components are positioned such that the repair face of each of the plurality of components is face down on the alignment plate.
- [00113] 14. The tooling assembly of any preceding clause, wherein the fill material is solidified when the plurality of components are positioned face down on the alignment plate to form a fixed component assembly, the tooling assembly further

comprising: a cleaning device for removing a top layer of the fill material from the fixed component assembly proximate the repair surface of each of the plurality of components.

[00114] 15. The tooling assembly of any preceding clause, wherein the cleaning device comprises: a heat source for melting the top layer of fill material.

[00115] 16. The tooling assembly of any preceding clause, wherein the plurality of components are positioned such that the repair face of each of the plurality of components is face up toward a bottom surface of the alignment plate.

[00116] 17. The tooling assembly of any preceding clause, further comprising: one or more biasing members for urging each of the plurality of components upward to ensure contact between the repair surface of each of the plurality of components and the alignment plate.

[00117] 18. The tooling assembly of any preceding clause, wherein the one or more biasing members comprise one or more springs, one or more magnet pairs, and/or one or more piezoelectric actuators.

[00118] 19. The tooling assembly of any preceding clause, wherein the fill material is selected from a group consisting of a potting material, a wax, a photopolymer resin, or molten glass.

[00119] 20. The tooling assembly of any preceding clause, wherein the plurality of components comprise at least one airfoil of a gas turbine engine.

CLAIMS

WHAT IS CLAIMED IS:

1. A tooling assembly for fixing a relative position of a plurality of components, the tooling assembly comprising:

an alignment plate for receiving the plurality of components;

one or more biasing members for urging each of the plurality of components upward to ensure contact between a repair surface of each of the plurality of components and the alignment plate;

a plurality of walls surrounding the alignment plate to define a reservoir; and

a fill assembly for dispensing a fill material into the reservoir, the fill material fixing a relative position of the plurality of components when solidified, wherein the fill material is solidified when the plurality of components are positioned on the alignment plate to form a fixed component assembly;

a cleaning device for removing a top layer of the fill material from the fixed component assembly proximate the repair surface of each of the plurality of components, the cleaning device comprising a heat source for melting the top layer of the fill material or a material removal device, the material removal device being a device configured for grinding, machining, or etching the top layer of the fill material.

2. The tooling assembly of claim 1, wherein the one or more biasing members comprise one or more springs, one or more magnet pairs, or one or more piezoelectric actuators.

3. The tooling assembly of claim 1, wherein the one or more biasing members comprise one or more electromagnets.

4. The tooling assembly of claim 1, wherein the one or more biasing members comprise one or more permanent magnets.

5. The tooling assembly of claim 1, wherein the plurality of components are positioned such that the repair surface of each of the plurality of components is face down on the alignment plate.

6. The tooling assembly of claim 1, wherein the cleaning device comprises the heat source for melting the top layer of the fill material.
7. The tooling assembly of claim 1, wherein the plurality of components are positioned such that the repair surface of each of the plurality of components is face up toward a bottom surface of the alignment plate.
8. The tooling assembly of claim 1, wherein the fill material is selected from a group consisting of a potting material, a wax, a photopolymer resin, or molten glass.
9. The tooling assembly of claim 1, wherein the plurality of components comprise at least one airfoil of a gas turbine engine.
10. The tooling assembly of claim 1, wherein the cleaning device comprises the material removal device, the material removal device being the device configured for grinding.
11. A tooling assembly for fixing a relative position of a plurality of components, the tooling assembly comprising:
 - an alignment plate for receiving the plurality of components such that a repair surface of each of the plurality of components contacts the alignment plate;
 - one or more biasing members for urging each of the plurality of components upward to ensure contact between the repair surface of each of the plurality of components and the alignment plate;
 - a plurality of walls surrounding the alignment plate to define a reservoir; and
 - a fill assembly for dispensing a fill material into the reservoir, the fill material fixing a relative position of the plurality of components when solidified.
12. The tooling assembly of claim 11, wherein the one or more biasing members comprise one or more springs, one or more magnet pairs, or one or more piezoelectric actuators.
13. The tooling assembly of claim 11, wherein the plurality of components are positioned such that the repair surface of each of the plurality of components is face down on the alignment plate.

14. The tooling assembly of claim 11, wherein the fill material is solidified when the plurality of components are positioned face down on the alignment plate to form a fixed component assembly, the tooling assembly further comprising:

a cleaning device for removing a top layer of the fill material from the fixed component assembly proximate the repair surface of each of the plurality of components.

15. The tooling assembly of claim 14, wherein the cleaning device comprises a heat source for melting the top layer of fill material.

16. The tooling assembly of claim 14, wherein the cleaning device comprises a material removal device.

17. The tooling assembly of claim 16, wherein the material removal device comprises a device configured for grinding, machining, or etching the top layer of the fill material.

18. The tooling assembly of claim 11, wherein the plurality of components are positioned such that the repair surface of each of the plurality of components is face up toward a bottom surface of the alignment plate.

19. The tooling assembly of claim 11, wherein the fill material is selected from a group consisting of a potting material, a wax, a photopolymer resin, or molten glass.

20. The tooling assembly of claim 11, wherein the plurality of components comprise at least one airfoil of a gas turbine engine.