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Thermal Compensation for Laser Energy Delivery for Additive Manufacturing

Abstract

A manufacturing system includes a printer chamber having a printer bed that supports manufacturing materials and an internal heating system supported by the printer chamber. The internal heating systems is configured to direct patterned heat energy onto the printer bed and supported manufacturing materials. An external heating system is supported by or positioned near the printer chamber and configured to direct patterned heat energy onto the printer bed and any supported manufacturing materials.

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Background/Summary

CROSS-REFERENCE TO RELATED PATENT APPLICATION [0001] This application is a continuation of U.S. patent application Ser. No. 18/586,756, filed Feb. 26, 2024, which is a continuation of U.S. patent application Ser. No. 17/348,534, filed Jun. 15, 2021, which claims the priority benefit of U.S. Patent Application No. 63/039,315, filed Jun. 15, 2020, all of which are hereby incorporated by reference in their entirety.

TECHNICAL FIELD
[0002] The present disclosure generally relates to a system and method for thermally controlled additive manufacturing. In one embodiment a manufacturing bed, wall, and top can be thermally controlled to compensate for heat losses.
BACKGROUND
[0003] Traditional component machining often relies on removal of material by drilling, cutting, or grinding to form a part. In contrast, additive manufacturing, also referred to as 3D printing, typically involves sequential layer by layer addition of material to build a part. Beginning with a 3D computer model, an additive manufacturing system can be used to create complex parts from a wide variety of materials.
[0004] One additive manufacturing technique known as powder bed fusion (PBF) uses one or more focused energy sources, such as a laser or electron beam, to draw a pattern in a thin layer of powder by melting the powder and bonding it to the layer below to gradually form a 3D printed part. Powders can be plastic, metal, glass, or ceramic. This technique is highly accurate and can typically achieve feature sizes as small as 150-300 um. Typically, this process is carried out with the substrate temperature starting at room temperature or at some moderately elevated temperature such as 250 C. When printing a material such as steel with a melting point around 1400 C, a laser must melt both the powder and the substrate during the layer printing process. Since both of these components start at near room temperature, they must undergo a temperature cycle on the order of 1000 degrees Celsius. As this process is repeated for all the portions of the layer to be printed, thermal stresses can build within the part. Furthermore, depending on the amount of average laser power, this heat load to the printing process causes the temperature of the build plate to increase. This temperature increase during the course of the print can be significant and is dependent on the amount of parts and part geometry printed. This layer to layer variance in average heat load can cause unforeseen errors such as spatially dependent thermal warpage in all three dimensions, higher residual stresses, and even cracking of the printed part. These factors decrease part accuracy, strength, and usefulness of finished 3D parts.
[0005] Additive manufacturing systems can also require the 3D print to be removed from a controlled printing environment when the 3D print is removed from the print chamber. This can

adversely affect 3D prints that require a heat treatment oven for post processing cool down and/or subsequent stress relief, annealing, or heat treatment. While additive manufacturing systems can pre-heat print plates and/or keep prints at a set temperature during printing in the print chamber, temperature control is often not available outside the print chamber. Unfortunately, when the 3D prints are removed from the print chamber, they are typically not temperature controlled and, in many systems, are also exposed to uncontrolled air. These factors can affect the material properties of the 3D print. Furthermore, 3D prints are often too hot to be immediately removed from the print chamber and so must remain in the print chamber for hours after they are done printing. This ties up the print chamber and prevents the system from starting new print jobs.

[0006] Improved thermal control systems for fixed or cartridge based print chambers are needed. This can include providing isothermal conditions, or alternatively, a patterned heat flux that can reduce errors such as spatially dependent thermal warpage in all three dimensions or higher residual stresses.

SUMMARY

[0007] A manufacturing system includes a printer chamber having a printer bed that supports manufacturing materials and an internal heating system supported by the printer chamber. The internal heating system is configured to direct patterned heat energy onto the printer bed and supported manufacturing materials. An external heating system is supported by or positioned near the printer chamber and configured to direct patterned heat energy onto the printer bed and any supported manufacturing materials.

[0008] In one embodiment, the printer chamber further comprises a cartridge.

[0009] In one embodiment, wherein the internal heating system further comprises at least one of heating elements and cooling elements.

[0010] In one embodiment, the external heating system further comprises infrared heating elements.

[0011] In one embodiment, wherein the external heating system further comprises heated gas flow.

[0012] In one embodiment, the external heating system further comprises at least one directed laser.

[0013] In one embodiment, the external heating system further comprises at least one directed laser to provide unpatterned heating.

[0014] In one embodiment, wherein the external heating system further comprises at least one directed laser to provide patterned heating.

[0015] In one embodiment, the external heating system further comprises at least one directed laser that uses recycled light.

[0016] In one embodiment, the sensors further comprise a pyrometer.

[0017] In one embodiment, the sensors further comprise a camera.

[0018] In another embodiment, a manufacturing system, includes a printer chamber having a printer bed that supports a printable material layer. A primary laser source is directable against a sub-portion of printable material layer on the printer bed to print a part pattern. A secondary heating system is configured to direct patterned heat energy into the printable material layer.

[0019] In one embodiment, the patterned heat energy is determined at least in part by printed part pattern.

[0020] In one embodiment, the patterned heat energy is substantially inversely related to a fraction of the pattern printed.

[0021] In one embodiment, a secondary heating system further comprises a second light emitting heating element.

[0022] In one embodiment, a second light emitting heating element further comprises at least one of an arc lamp, infrared lamp, LED heat system, and laser heat system.

[0023] In one embodiment, the secondary heating system further comprises a printer chamber supported patterned heating element.

[0024] In one embodiment, the printer chamber supported patterned heating element further comprises at least one of an array of resistive heat cartridges, heated fluid in channels, electrically controlled plasma sources, arc heaters, induction heaters, and microwave heaters. In all of these embodiments, cooling or heating elements could be built into the printer bed or surrounding structures, or projected from a distance.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] Non-limiting and non-exhaustive embodiments of the present disclosure are described with reference to the following figures, wherein like reference numerals refer to like parts throughout the various figures unless otherwise specified.

[0026] FIG. **1**A illustrates a thermally controlled additive manufacturing system;

[0027] FIG. **1**B illustrates a thermally controlled print plate on Z-stage before printing starts;

[0028] FIG. **1**C illustrates a printed part buried in the powder on print plate as a Z-stage moves down, with the embedded heating devices positioned in the print plate and print wall;

[0029] FIG. **1**D illustrates a thermally controlled cartridge system;

[0030] FIG. **1**E illustrates use of a segmented infrared heater for patterned heating;

[0031] FIG. **1**F illustrates use of a segmented top-down or angle gas flow for patterned heating;

[0032] FIG. **1**G illustrates use of a segmented cross bed gas flow for patterned heating;

[0033] FIG. **1**H illustrates use of additional heating laser(s) for patterned heating;

[0034] FIG. **1**I illustrates use of additional heating laser(s) for unpatterned heating;

[0035] FIG. **1**J illustrates use of additional heating laser(s) derived from recycled or rejected light for patterned heating;

[0036] FIG. **1**K illustrates a thermography system using a camera and pyrometer;

[0037] FIG. **2** illustrates process flow for a thermally controlled additive manufacturing system; and

[0038] FIG. **3** illustrates a demonstration of a constant thermal load based on multiple patterned and applied thermal loads.

DETAILED DESCRIPTION

[0039] In the following description, reference is made to the accompanying drawings that form a part thereof, and in which is shown by way of illustrating specific exemplary embodiments in which the disclosure may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the concepts disclosed herein, and it is to be understood that modifications to the various disclosed embodiments may be made, and other embodiments may be utilized, without departing from the scope of the present disclosure. The following detailed description is, therefore, not to be taken in a limiting sense.

[0040] FIG. **1**A illustrates a thermally controlled additive manufacturing system **1**A. A print chamber **2**A holds a print plate **3**A that can support powder or other additive or subtractive manufacturing material. A print engine **5**A capable of directing a laser, electron beam, or other directed energy **5**A is externally positioned with respect to the print chamber and used to heat the manufacturing material on the print plate. Sensors **6**A can be used to calibrate or provide feedback control during manufacture.

[0041] An external heating system **7**A and/or an internal heating system **8**A can be used to adjust or control print chamber **2**A temperature, material temperature, or temperature of manufactured parts on the print plate. Both the external heating system **7**A and/or an internal heating system **8**A can be operated to provide differential or patterned heating or cooling using arrays of heating or cooling elements, segmented structures, partitioned structures, scannable structures, or selected on/off operation. In some embodiments, isothermal temperatures are maintained, while in other embodiments, predetermined temperatures in differing selected areas can be selected using

patterned heating systems.
[0042] For example, an external patterned heating system can involve use of externally mounted or positioned assemblies that direct heat flux into a print chamber from above. Patterned assemblies can be one or more heat lamps, one or more lasers (diode, fiber, solid state, or the like), convective flow, or other type of heating element. The patterning can be achieved through a static mask, spatial light modulator such as a liquid crystal display, a light valve, an optically addressed light valve, a micro-mirror array, thermally activated patterned resonator. Heater components such as a heat lamp or heat element can generate a pattern by using a large array of elements and controlling which elements in the array turn on and off and controlling their emission through optics such as lenses, reflectors, or the like to re-direct the light to the bed in the desired pattern. Convective flow can be patterned through the use of an array of nozzles through which gas flows at controlled temperatures as desired/determined by the control system.
[0043] In some embodiments, the print plate **3**A upon which the printing process is executed contains internal heater elements such as resistive heat cartridges, heated cooling fluid in cooling channels, electrically controlled plasma sources such as an arc, induction heaters, microwave heaters, or other heat generating device that are mounted within the print chamber or in contact with the print bed or chamber. Additionally, the print plate **3**A can contain temperature sensing devices such as RTDs, thermocouples, pyrometers, or other temperature sensing device which then communicates the printer control system to modulate the heat flux to the print plate. The same logic is applied to the print wall except with variably controlled heaters as a function of print wall height and where the print is in the process.
[0044] Sensors **6**A can include pyrometers, thermal cameras, or visual cameras. In some embodiments, a camera can take video and stills to provide a virtual window. Camera and lights can illuminate and image in multiple light wavelengths (e.g. IR, visible, or UV). The camera may be an array of several cameras that could record still and or video images from many different angles in one or many light wavelengths. The lights can be one or an array of many lights that illuminate the print chamber **2**A and print plate **3**A from many angles and in many different wavelengths.
[0045] In some embodiments, both the external heating system **7**A and the print engine **4**A can use one or more laser sources. Possible laser types include, but are not limited to: Gas Lasers, Chemical Lasers, Dye Lasers, Metal Vapor Lasers, Solid State Lasers (e.g. fiber), Semiconductor (e.g. diode) Lasers, Free electron laser, Gas dynamic laser, “Nickel-like” Samarium laser, Raman laser, or Nuclear pumped laser.
[0046] A Gas Laser can include lasers such as a Helium-neon laser, Argon laser, Krypton laser, Xenon ion laser, Nitrogen laser, Carbon dioxide laser, Carbon monoxide laser or Excimer laser.
[0047] A Chemical laser can include lasers such as a Hydrogen fluoride laser, Deuterium fluoride laser, COIL (Chemical oxygen-iodine laser), or Agil (All gas-phase iodine laser).
[0048] A Metal Vapor Laser can include lasers such as a Helium-cadmium (HeCd) metal-vapor laser, Helium-mercury (HeHg) metal-vapor laser, Helium-selenium (HeSe) metal-vapor laser, Helium-silver (HeAg) metal-vapor laser, Strontium Vapor Laser, Neon-copper (NeCu) metal-vapor laser, Copper vapor laser, Gold vapor laser, or Manganese (Mn/MnCl2) vapor laser. Rubidium or other alkali metal vapor lasers can also be used. A Solid State Laser can include lasers such as a Ruby laser, Nd: YAG laser, NdCrYAG laser, Er: YAG laser, Neodymium YLF (Nd: YLF) solid-state laser, Neodymium doped Yttrium orthovanadate (Nd: YVO4) laser, Neodymium doped yttrium calcium oxoborateNd: YCa4O(BO3)3 or simply Nd: YCOB, Neodymium glass (Nd: Glass) laser, Titanium sapphire (Ti: sapphire) laser, Thulium YAG (Tm: YAG) laser, Ytterbium YAG (Yb: YAG) laser, Ytterbium: 203 (glass or ceramics) laser, Ytterbium doped glass laser (rod, plate/chip, and fiber), Holmium YAG (Ho: YAG) laser, Chromium ZnSe (Cr: ZnSe) laser, Cerium doped lithium strontium (or calcium) aluminum fluoride (Ce: LiSAF, Ce: LiCAF), Promethium 147 doped phosphate glass (147Pm+3: Glass) solid-state laser, Chromium doped chrysoberyl (alexandrite)

laser, Erbium doped anderbium-ytterbium co-doped glass lasers, Trivalent uranium doped calcium fluoride (U: CaF2) solid-state laser, Divalent samarium doped calcium fluoride (Sm: CaF2) laser, or F-Center laser.

[0049] A Semiconductor Laser can include laser medium types such as GaN, InGaN, AlGalnP, AlGaAs, InGaAsP, GalnP, InGaAs, InGaAsO, GalnAsSb, lead salt, Vertical cavity surface emitting laser (VCSEL), Quantum cascade laser, Hybrid silicon laser, or combinations thereof.

[0050] In operation, heating devices in the print plate, print wall, and from the above the print plate can be used to apply the desired thermal condition for the initiation of printing. Throughout the printing process, thermal load on the printed layer is a variable depending on the part geometry. Use of an internal heating system **8**A with heating devices in the print plate, print wall, and further use of an external heating system **7**A above the print plate can provide temporal modulation of the thermal conditions in the printed part in situ. In some embodiments, use of an internal heating system **8**A with heating devices in the print plate, print wall, and further use of an external heating system **7**A above the print plate can provide spatial modulation of thermal conditions in the printed part in situ. Use of an internal heating system **8**A with heating devices in the print plate, print wall, and further use of an external heating system **7**A above the print plate can provide can be used to apply necessary thermal conditions to the finished printed part to minimize thermal stress and optimize the thermal history in the part.

[0051] Once the printing process in completed, the heating devices can be used to control the cool down of the part, or a lid/thermal insulation can be closed over the top of the print chamber **2**A to maintain uniform cooling rates from all sides. Pre-heating powder or other manufacturing material before and during a print also allows for a reduction in the print energy required to achieve the same print rate, or similarly an increase in print rate for a given fixed print energy.

[0052] FIG. **1**B illustrates in more detail a system **1**B having a thermally controlled print plate positioned on a Z-stage before printing starts. Initially there is no powder or printed part on a print plate **2**B. Laser energy **14**B can be directed against material to be printed on the print plate **2**B. The printer plate **2**B can contain heater cartridges **3**B and temperature sensing devices for controlling the temperature of the print plate **2**B. Alternately, the print plate may be affixed to and thermally connected to a sub-plate which contains the heating and sensing capabilities. In this case item **2**B is the sub-plate and the print plate (not shown) would be located above **2**B. Below the print plate **2**B, insulation **4**B reduces heat loss. Below the insulation **4**B is the cooling tube housing plate **5**B which contains coolant flow channels **6**B. This coolant flow protects sensitive and accurate system components from excessive heat. The entire print plate assembly is connected to a z-axis motor by a shaft **7**B. Heat flow **8**B from a patterned, unpatterned, or other radiative element is incident onto the print plate **2**B from above. The magnitude of the heat flow **8**B can be selected to be inversely proportional to the laser energy **14**B to better maintain isothermal conditions. The printer side walls **9**B contain heater elements **10**B. Outside the printer side walls **9**B is a layer of insulation **11**B, outside of which is a print wall cooling tube side wall **12**B which contains coolant flow **13**B.

[0053] FIG. **1**C illustrates a system **1**C having a printed part **20**C buried in the powder **15**C on print plate as a Z-stage moves down, with the embedded heating devices positioned in the print plate and print wall. Laser energy **14**C proportional to the material to be printed is incident on the print plate **2**C which contains heater cartridges **3**C and temperature sensing devices for controlling the temperature of the print plate **2**C. Alternately, the print plate may be affixed to and thermally connected to a sub-plate which contains the heating and sensing capabilities. In this case item **2**B is the sub-plate and the print plate (not shown) would be located above **2**B. Below the print plate **2**C, insulation **4**C reduces heat loss. Below the insulation **4**C is the cooling tube housing plate **5**C which contains coolant flow channels **6**C. The entire print plate assembly is connected to a z-axis motor by a shaft **7**C. Heat flow **8**C from a patterned, unpatterned, or other radiative element is incident onto the print plate **2**C from above. The magnitude of the heat flow **8**C can be inversely proportional to the laser energy **1**C. The printer side walls **9**C contain heater elements **10**C. Outside the printer side walls **9**C is a layer of insulation **11**C, outside of which is a print wall cooling tube side wall **12**C which contains coolant flow channels **13**C. Printed part **14**C on the print plate is supported by the print plate **2**C and surrounded by powder **15**C. Conductive heat **16**C from the heater cartridges in the print plate is applied to the printed part **20**C. Conductive heater **17**C from heater cartridges in the print wall is applied to the printed part and surrounding powder.

[0054] FIG. **1**D illustrates a thermally controlled cartridge system. A 3D print cartridge **1**D useful in an additive manufacturing system is shown in partial cross section. The 3D print cartridge (hereinafter "cartridge") separates all of the "dirty" printing functions from the rest of the system and the operator environment. "Dirty" means wherever powder is present, processed for printing, or soot is generated. Whenever the cartridge **1**D is connected to mating equipment such as a print station, powder station, or storage station, the mating equipment can supply services required to operate the cartridge as needed based on which piece of mating equipment it is mated to (e.g. the print station allows full control of the cartridge while the storage station may only provide heating power and gas recycling, and use of the camera and lights). The cartridge **1**D is designed to be sealed when disconnected from mating equipment and can include auxiliary heating or cooling systems to allow for precise thermal conditions within the cartridge.

[0055] The cartridge **1**D is built around a bed or base plate **24**D which can include segmented or patterned internal heaters. Fresh powder for a new print is stored in the powder hoppers **2**D which have the capacity to store all the powder needed for a full volume print. Fresh powder is metered onto the base plate thru the powder door **23**D. Powder is swept across the plate by a powder spreader **4**D using powder spreading blade(s). The powder spreader drive **5**D moves the powder spreader back and forth across the print plate **12**D.

[0056] A window **3**D seals the top of the cartridge **1**D against leaks of powder or gas and allows a laser beam (not shown) to pass through it to weld powder. The window **3**A allows the access to the cartridge for loading print plates, unloading prints, cleaning and servicing the cartridge components (seals, spreader blades etc.). The inside of the cartridge **1**D can be illuminated and imaged by the camera and lights **22**D. The camera and lights can be either inside or outside the sealed chamber, or both, and can be positioned to take pictures and/or focus on scenes on the inside of the cartridge, in particular the print plate. The camera and lights can also be mounted on motion stages allowing the user to pan or zoom on items of interest during a print. This camera can be combined with secondary print diagnostics such as pyrometers, motion detectors, photodiodes, thermal cameras, or other sensors to automatically detect events and pan/zoom the camera to focus on the location of interest. In some embodiments, camera images can be viewed by the operator in an electronic or virtual window instead of directly viewing through a physical port or window in the cartridge.

[0057] Inert gas is supplied to the cartridge by a gas supply duct **6**D so that printing can be performed in whatever atmosphere is best for each print. The gas return duct **7**D removes inert gas. The gas passes thru the HEPA filter **8**D which removes impurities (soot, suspended nano particles of powder, etc.). The gas then travels to a gas recycler (not shown) which is installed on mating equipment. When the cartridge is disconnected from mating equipment, a gas supply port **9**D and a gas return port **10**D are sealed to preserve the atmosphere inside the cartridge. Gas is subsequently purified by removing oxygen, moisture, etc. by other equipment.

[0058] The Z-axis lowers the print plate after each layer is printed so that a new layer of powder can be spread and subsequently printed. A Z-axis frame **11**D holds the Z-axis components in this design. The print plate (AKA build plate) **12**D is where powder is welded during printing. The print plate heater **13**A contains a heating mechanism for the print plate **12**D and can also insulate and/or cool a seal plate **14**D. The seal plate **14**D carries seals **15**D, which confines the powder to the Z-axis frame **11**D. The Z-axis bottom plate **16**D closes off the lower end of the Z-axis frame **11**D and has features to contain any powder that may slip past the seals **15**D. The Plunger **17**D has an interface so that it can remotely, automatically, and accurately interface with the Z-axis drive. A plunger seal **18**D mates with the bottom plate **16**D and further seals the cartridge **1**D against powder and/or gas leaks.

[0059] An interface plate **19**D contains all the inputs and outputs for the cartridge (compressed air, power, input and output signal, gas, cooling water, etc.). It is designed to make all these connections when the cartridge is connected to mating equipment. The interface can also contain a mechanism to electronically identify each cartridge when mated with mating equipment. Rollers **20**D allow the cartridge **1**D to be rolled onto the mating rails of mating equipment. Forklift tubes **21**D allow the cartridge to be picked up and moved by a forklift.

[0060] In one embodiment, the cartridge **1**D can include electronic identification such as an electronically readable memory **25**D or other electronically readable indicia such as attached text or bar codes. The memory **25**D can provide electronic information about the cartridge or cartridge components can be used to identify its make, model, type, powder type, or any other defining details about the unit, its sub-components, or their intended uses. This information can be used to inform a print engine about what material is to be printed, desired atmosphere (pressure and temperature), or other print related aspect so the print engine can adapt as needed to accommodate the print cartridge, sub-cartridge, or sub-assembly. The change induced could involve an action such as the automatic swapping of internal lens assemblies, adjustment of z-height/final optical throw of the lens assembly, laser parameter adjustment such as power per unit area, pulse shape, pulse duration, pulse repetition rate, wavelength, spatial pulse shape, tile size, spatial energy distribution within a tile, modify data diagnostics, data feedback algorithms, print process feedback algorithms, or algorithmic change to how tiles are put down during the print process. Electronic information from electronic memory **25**D that is associated with a print cartridge or sub-cartridge can be read by a printer, de-powdering station, or storage rack to collect data on how much printing has occurred and other key metrics such as number of spreader cycles, z-axis adjustments, temperature cycles, pressure cycles, or other attribute that the cartridge or sub-cartridge have undergone along the way. This information can also be stored in a central database by the print engine, one of the subsystems, the factory automation system, de-powdering station, cartridge storage station, the cartridge itself, or other mating/interfacing equipment.

[0061] FIG. **1**E illustrates a system **1**E supporting use of a segmented infrared heater for patterned heating suitable for use with a print chamber. Laser energy **17**E proportional to the material to be printed is incident on the print plate **2**E which contains heater cartridges **3**E and temperature sensing devices for controlling the temperature of the print plate **2**E. Below the print plate **2**E, insulation **4**E reduces heat loss. Below the insulation **4**E is the cooling tube housing plate **5**E which contains coolant flow **6**E. The entire print plate assembly is connected to a z-axis motor by a shaft **7**E. Heat flow **8**E from a patterned radiative element is incident onto the print plate **2**E from above. The magnitude of the heat flow **8**E can be inversely proportional to the laser energy **17**E. The printer side walls **9**E contain heater elements **10**E. Outside the printer side walls **9**E is a layer of insulation **11**E, outside of which is a print wall cooling tube side wall **12**E which contains coolant flow **13**E. Printed part **14**E on the print plate is supported by the print plate **2**E and surrounded by powder **15**E. Conductive heat **16**E from heater cartridge in print plate is applied to the printed part **20**E. Conductive heater **17**E from heater cartridge in the print wall is applied to the printed part and surrounding powder. In this embodiment, multiple segments of infrared heaters **18**E are installed above the print plate **2**E. Each segment is independently controlled such that portions of the print plate can be heated. This mechanism can spatially modulate the temperature distribution on the print plate caused by the variation of printed surface from layer to layer. All infrared heater segments can also work together to temporally modulate the overall thermal load variation caused by the variation of laser energy delivered to the bed from layer to layer. The heaters receive power from a power source **19**E and can be connected in series or parallel.

[0062] FIG. **1**F illustrates use of a segmented top-down or angle gas flow for patterned heating. In this embodiment, the print chamber and general operation of system **1**F is similar to that previously described with respect to FIG. **1**E, with similar numbers indicating similar structures. In this embodiment, a vertical gas flow **18**F can provide extra heating to the top surface. Using a segmented approach, spatially dependent temperatures can be tuned to some extent. This can be achieved through a series of units combined together, or from one unit with multiple sub-sections.

[0063] FIG. **1**G illustrates use of a segmented cross bed gas flow for patterned heating. In this embodiment, the print chamber and general operation of system **1**G is similar to that previously described with respect to FIG. **1**E, with similar numbers indicating similar structures. In this embodiment, a horizontal gas flow **18**G can provide extra heating to the top surface. Temperature of the gas flow can be modulated based on the variation of thermal load as printing goes on.

[0064] FIG. **1**H illustrates use of additional heating laser(s) for patterned heating in a system **1**H. System **1** H includes a print chamber system including a print plate **2**H, heater cartridges **3**H inside the print plate, insulation **4**H below the print plate, a cooling tube housing plate **5**_h_, and a cooling tube holding coolant **6**H. A Z-axis shaft **7**H is connected to a motor. A print wall or side wall **8**H contains a heater cartridge **9**H. There is insulation **10**H outside the print wall, a cooling tube housing side wall/plate **11**H, and a cooling tube **12**H holding coolant. A printed part **13**H is formed on the print plate from powder **14**H spread on the print plate. Thermal conditions can be maintained in the system **1**H at least in part using conductive heat **15**H from the heater cartridge in print plate and/or conductive heat **16**H from heater cartridge in print wall. Laser energy **17**H can be proportional to print tile fill fraction (2×2 mm-10×10 mm).

[0065] An additional laser source provides focused energy to heat up smaller and more specific area of the print plate. The laser beam delivery can be fixed and optics set up to project to fill the entire plate, or the laser can be mounted on a scanning device such that it can scan cover the entire print plate. The laser can be patterned using a spatial light modulator such as an optically addressed light valve, DMD, or other patterning device. The laser may need to be homogenized before the SLM to allow for high uniformity of the beam. Homogenizers can be reflective tubes, TIR tubes, diffractive elements, lens let arrays, or similar. Geometry of the homogenizer is generally square but can be any geometrical shape configured to fit in a pattern.

[0066] Components include an additional laser source **18**H (scanning and/or fixed & patterned). A beam **19**H is emitted from a laser source and directed toward a relay optic assembly **20**H between laser source **18**H and laser homogenizer **21**H. In some embodiments, an image relay optic assembly **34**H is positioned between the laser homogenizer and the light valve. A homogenized beam **22**H emitted from laser homogenizer is directed into a patterned address light source **23**H for light valve at 445 nm wavelength. Blue light **24**H emitted from patterned address light source is directed into a Blue/IR combiner **25**H to co-linearly align blue and IR lasers/light sources. A light valve **26**H for patterning makeup heat laser source passes some light to a polarizer **27**H for rejecting unused light not included in the pattern. Components can also include an electrical drive source **28**H for light valve operation that, along with components **25**H, **26**H, **27**H together form a patterning unit assembly **29**H. Light from the patterning unit assembly **29**H is directed into an image relay optic assembly **30**H for relaying the light valve patterned image to the powder bed. A turning mirror **31**H is used for directing light into the build chamber, or otherwise controlling where the laser light goes. A laser beam **32**H can reflect off of scanning mirror and be focused to a sub-portion of the print bed for thermal management of print bed. Alternatively, a laser beam **33**H reflecting off a fixed mirror can be focused to the full print bed area (or a substantial fraction of it)

[0067] FIG. **1**I illustrates use of additional heating laser(s) for unpatterned heating. In this embodiment, the print chamber of system **1**I is similar to that previously described with respect to FIG. **1**H, with similar numbers indicating similar structures. As illustrated, a laser area printer can include input from homogenized image plane **18**I. The laser has already been homogenized to arrive at this plane either through a reflective tube, TIR tube, diffractive optic, lenslet array, or similar mechanism. From plane **18**I, beam **19**I, which has a single majority polarization state, propagates to an image relay optic assembly **21**I which changes the size of the beam at plane **19**I and recreates its intensity profile on the light valve **26**I. En route to the light valve **26**I, beam **19**I also passes through a beam combiner **25**I which combines patterned blue light **24**I at 445 nm emitting from projector unit **23**I, with the infrared beam **19**I at 1000/1064 nm. Both beams are incident upon the light valve **26**I which allows the pattern on the blue beam **24**I to be transferred in polarization space to the infrared beam **19**I. This action by the light valve **26**I forms two majority polarization states in the beam in the desired pattern according to the dynamically adjustable projector unit **23**I. Upon hitting the polarizer **27**I, the beam is split into both negative and positive images. The positive image is transmitted to optical image relay lens assembly **30**I which relays the light valve positive image to the print bed in the desired tile size by reflecting off of movable gimbal mirror **20**I. F-Theta optics may be present in some configurations between the mirror **201** and the print bed. The negative image is reflected off polarizer **27**I to be incident on mirror **221** which directs the negative image light to an image relay **24**I which couples the light into the rejected light homogenizer **35**I. In some instances, mirror **221** is also a dichroic filter, allowing 1064 nm light to pass through it and only reflecting 1000 nm light. The goal in this instance is to use separate methods to homogenize lasers of different types. A tube homogenizer is suitable for homogenizing relatively long pulse, low coherence, low intensity light whereas diffractive elements are better suited for homogenizing low divergence, high coherence light. At the output of the rejected light homogenizer **35**I, the homogenized image is passed to the final rejected light image relay which performs an image relay operation between the rejected light homogenizer **35**I output and the print bed. This image relay can be fixed, or dynamically adjustable to change the focus. The focus can be tight such that a small fraction of the bed is illuminated, or it can be large such that the entire bed is illuminated. The final turning mirror **31**I can be fixed or allowed to move to further accommodate the make-up heat delivery process.

[0068] FIG. **1**J illustrates use of additional heating laser(s) derived from recycled or rejected light for patterned heating. In this embodiment, the print chamber of system **1**I is similar to that previously described with respect to FIGS. **1**H and **1**I, with similar numbers indicating similar structures. This figure shows the configuration for a laser area printer starting from an input homogenized image plane **18**J. The laser has already been homogenized to arrive at this plane either through a reflective tube, TIR tube, diffractive optic, lenslet array, or similar mechanism. From plane **18**J, beam **19**J, which has a single majority polarization state, propagates to an image relay optic assembly **21**J which changes the size of the beam at plane **19** J and recreates its intensity profile on the light valve **26**J. En route to the light valve **26**J, beam **19**J also passes through a beam combiner **25**J which combines patterned blue light **24**J at 445 nm emitting from projector unit **23**J, with the infrared beam **19**J at 1000/1064 nm. Both beams are incident upon the light valve **26**J which allows the pattern on the blue beam **24**J to be transferred in polarization space to the infrared beam **19**J. This action by the light valve **26**J forms two majority polarization states in the beam in the desired pattern according to the dynamically adjustable projector unit **23**J. Upon hitting the polarizer **27**J, the beam is split into both negative and positive images. The positive image is transmitted to optical image relay lens assembly **30**J which relays the light valve positive image to the print bed in the desired tile size by reflecting off of movable gimbal mirror **20**J. F-Theta optics may be present in some configurations between the mirror **20**J and the print bed. The negative image is reflected off polarizer **27**J to be incident on mirror **22**J which directs the negative image light to an image relay **24**J which couples the light into the rejected light homogenizer **35**J. In some instances, mirror **22**J is also a dichroic filter, allowing 1064 nm light to pass through it and only reflecting 1000 nm light. The goal in this instance is to use separate methods to homogenize lasers of different types. A tube homogenizer is suitable for homogenizing relatively long pulse, low coherence, low intensity light whereas diffractive elements are better suited for homogenizing low divergence, high coherence light. At the output of the rejected light homogenizer **35**J, the homogenized image is passed to an image relay to the second patterning unit assembly which recreates the rejected image homogenizer **35**J output onto the second light valve. The positive image of this new light valve is allowed to transmit through the entire rejected light patterning unit assembly to transmit to final image relay optics **38**J which performs an image relay operation between the rejected energy light valve output and the print bed. This image relay can be fixed, or dynamically adjustable to change the focus. The focus can be tight such that a small fraction of the bed is illuminated, or it can be large such that the entire bed is illuminated. The final turning mirror **31**J can be fixed or allowed to move to further accommodate the make-up heat delivery process.

[0069] FIG. **1**K illustrates a thermography system using a camera and pyrometer. Detailed thermography can be achieved on each layer of the print if desired. In one embodiment a color CCD or CMOS camera **7**K is used to image the print bed **4**K containing printed articles on top of a print substrate or print plate **5**K. The resolution of the camera **7**K is chosen to be enough to resolve printed part features to determine if there are temperature differentials across the layer. For example, if we choose a 16 Mpixel camera (4000×4000 pixels) can be used to image a 40 cm bed, providing pixel resolution of nominally 100 microns. A 64 Mpixel camera (8000×8000) can be used to provide 50 micron pixel resolution. In operation, due to the very high speeds associated with some embodiments of additive manufacturing systems, the average temperature of the print bed is relatively high. The bed **4**K will visibly glow or glow in infrared camera systems. Even a modest temperature of 500 C yields a blackbody curve with similar emission at 1050 nm to the red glow one visibly sees at 700 C. Alternatively one can use a FLIR type camera. Temperature can be calibrated in the image by using an optical pyrometer **2**K to benchmark the temperature at a single location **6**I in the print bed. By taking a few temperature measurements with the pyrometer and correlating these with corresponding images it is possible to create a spatial temperature profile of the bed at low cost. Once calibrated the pyrometer is no longer strictly required and the images can be used as a stand-alone monitor of bed temperature. Images taken at the beginning and end of each recoating layer can be used to track recoating uniformity, print health, and the print temperature uniformity. If the temperature is too low or high, the control system can be used to correct the temperature nonuniformity or overall amplitude by adjusting the level of surface heating potentially with spatial dependence or adjust bed/wall heating levels as required to maintain the desired isothermal environment for the print. Typically, a window **3**K is needed to protect the imaging equipment **2**K and **7**K from any powders, soot, dust, or other particulates that may come off the print bed **4**K during the printing process.

[0070] FIG. **2** illustrates process flow **200** and selected components for a thermally controlled additive manufacturing. system. In this embodiment, part geometry and printing thermal load history **202** are fed as input parameters. A feedforward controller **204** uses part geometry and print thermal load history to proactively generate control signals. Heater cartridge in print wall **206** applies heating to the printed part and surrounding powder. Radiant heater **208** applies heating to the printed part and surrounding powder. A heater cartridge in print plate **210** applies heating to the printed part and surrounding powder. Printed part **212** is supported by the print plate and surrounded by powder. Laser energy **214** is applied to the powder layer **216** to melt the powder and facilitate the solidification process.

[0071] FIG. **3** illustrates a demonstration of thermal load on different part of the printing enclosure, with a combination of thermal load from differing sources being balanced to maintain substantially isothermal conditions for a printed part. Isothermal manufacturing conditions can reduce layer to layer variance in average heat load, prevent or reduce spatially dependent thermal warpage in all three dimensions, reduce higher residual stresses, and even prevent cracking of a printed part. Providing such isothermal conditions is seen with respect to an average thermal load as shown in graph **300** as a function of time or layer number on the bed from laser energy. Makeup energy **302** is required to balance the thermal load **306** from the patterning laser(s) such that total thermal load on the bed is constant (dotted isothermal line **307**). For example, a thermal load **303** is applied to the print plate from below. Thermal load **304** is applied to a heater on the side wall **1/3** of the way down the print wall. Thermal load **305** is applied to a heater on the side wall **2/3** of the way down the print wall. When these thermal loads are added together, a substantially constant thermal load

307 is yielded. In some embodiments, the amount of patterned heat energy providing a thermal load is determined at least in part by printed part pattern. Additionally, supplied patterned heat energy can be provided in an amount that is substantially inversely related to fraction of the pattern printed. Typically, printing a relatively large with part or layer sub-portion (with respect to the print chamber or print bed) would require little supplied pattern heating energy, while printing a small part or layer sub-portion would require substantial supplied pattern heating energy.
[0072] Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims. It is also understood that other embodiments of this invention may be practiced in the absence of an element/step not specifically disclosed herein.

Claims

1. A method comprising: performing additive manufacturing to print an object by using a patterning laser to fuse powdered material on a powder bed in a print chamber, wherein the print chamber comprises one or more side walls and a print plate that supports the powder bed, wherein the print plate and the one or more side walls comprise a plurality of heating elements; and providing a patterned heat energy comprising energy emitted at the plurality of heating elements according to a predetermined heating schedule specified for the object being printed, wherein the heating schedule specifies a heat load for each heating element in the plurality of heating elements for different layers of the additive manufacturing.
2. The method of claim 1, wherein the patterned energy is configured to maintain an isothermal condition by balancing a thermal load of the patterning laser with the patterned heat energy.
3. The method of claim 1, wherein the patterned energy is configured to provide a constant thermal load on the powder bed.
4. The method of claim 1, wherein the patterned heat energy is determined at least in part by a pattern printed on the powder bed.
5. The method of claim 1, wherein the patterned heat energy is substantially inversely related to a pattern printed on the powder bed.
6. The method of claim 1, wherein heating elements at different positions of the print plate and the one or more side walls emit different amount of energy according to the heating schedule.
7. The method of claim 1, wherein at least one heating element in the plurality of heating elements emits different amount of energy for different layers of the additive manufacturing according to the heating schedule.
8. The method of claim 1, wherein the plurality of heating elements are controlled by a feedforward controller according to the heating schedule.
9. The method of claim 8, wherein the feedforward controller is configured based on a geometry of the object being printed.
10. The method of claim 8, wherein the feedforward controller is configured based on a printing thermal load history of the object being printed.
11. The method of claim 1, wherein the plurality of heating elements are positions at different vertical positions of the one or more sidewalls and at different horizontal positions of the print plate.
12. A system comprising: a patterning laser; a feedforward controller; a print chamber; and a plurality of heating elements embedded in different position of the print chamber, wherein the patterning laser performs additive manufacturing to print an object by fusing powdered material on a powder bed supported by the print chamber, wherein the feedforward controller controls the plurality of heating elements to provide a patterned energy according to a predetermined heating

schedule specified for the object being printed, wherein the heating schedule specifies a heat load for each heating element in the plurality of heating elements for different layers of the additive manufacturing.

13. The system of claim 12, wherein the print chamber comprises a print plate supporting the powder bed and one or more side walls, wherein the plurality heating elements are embedded in different positions of the powder bed and one or more side walls.

14. The system of claim 12, wherein the patterned energy is configured to maintain an isothermal condition by balancing a thermal load of the patterning laser with the patterned heat energy.

15. The system of claim 12, wherein the patterned heat energy is determined at least in part by a pattern printed on the powder bed.

16. The system of claim 12, wherein the patterned heat energy is substantially inversely related to a pattern printed on the powder bed.

17. The system of claim 12, wherein heating elements at different positions of the print plate and the one or more side walls emit different amount of energy according to the heating schedule.

18. The system of claim 12, wherein at least one heating element in the plurality of heating elements emits different amount of energy for different layers of the additive manufacturing according to the heating schedule.

19. The system of claim 12, wherein the feedforward controller is configured based on a geometry of the object being printed.

20. The system of claim 12, wherein the feedforward controller is configured based on a printing thermal load history of the object being printed.