ADDITIVE MANUFACTURING BY SPATIALLY CONTROLLED MATERIAL FUSION

Abstract

Methods and apparatuses for additive manufacturing are described. A method for additive manufacturing may include exposing a layer of material on a build surface to one or more projections of laser energy including at least one line laser having a substantially linear shape. The intensity of the line laser may be modulated so as to cause fusion of the layer of material according to a desired pattern as the one or more projections of laser energy are scanned across the build surface.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 18/095,751, filed Jan. 11, 2023, which is a continuation of U.S. application Ser. No. 17/157,315, filed Jan. 25, 2021, which is a divisional of U.S. application Ser. No. 15/745,555, filed Jan. 17, 2018, which is a national stage filing under 35 U.S.C. § 371 of International Application PCT/US2016/042860, filed Jul. 18, 2016, which claims priority to U.S. Provisional Application No. 62/194,218, filed Jul. 18, 2015, the entire contents of each of which are incorporated herein by reference.

FIELD
[0002] Aspects described herein relate to additive manufacturing.
BACKGROUND
[0003] Additive manufacturing by selective laser sintering or melting denotes a process whereby sequential fusion of powder layers is used to create a three-dimensional object. To begin, a thin powder layer is dispensed on a working table (frequently referred to as the 'build platform'), so that at least one layer of powder forms a powder bed. Selected areas of the powder layer are then fused by exposure to a directed energy source, typically a laser beam. The exposure pattern of the laser beam thus forms a cross-section of the three-dimensional object. The part is built through consecutive fusion of so-formed cross-sections that are stacked in the vertical direction, and between the fusion of each layer the build platform is incremented downward and a new layer of powder is deposited onto the build surface. The general process of laser powder-fusion additive manufacturing has become known by several terms including selective laser melting (SLM), selective laser sintering (SLS), and direct metal laser sintering (DMLS); and has been applied to various metals, ceramics, polymers, alloys, and composites.
[0004] During SLM, a liquid track of molten material is formed along a scanning trajectory of a

laser dot. The maximum diameter of the laser ray that can be used is limited by the desired minimum feature size or detail of the part that is to be build. This interdependence of laser beam spot size and feature resolution also limits the build rate and quality achievable by SLM.

[0005] To achieve a higher process rate along with a desired feature resolution, it is therefore necessary to install multiple laser beams or to increase the scan rate of the laser across the build surface. The number of multiple laser beams that can be incorporated in one machine is limited by technical and economic feasibility. The maximum scanning speed is limited by the laser power, the melt-pool stability, and heat transfer.

SUMMARY

[0006] In one embodiment, a method for additive manufacturing includes exposing a layer of material to one or more projections of laser energy, wherein at least one of the one or more projections of laser energy is a line projection having a substantially linear shape. The method further comprises fusing at least a portion of the layer of material by exposure of layer of material to the one or more projections of laser energy, and moving the one or more projections of laser energy relative to the layer of material so as to fuse the portion of the layer of material in a desired shape.

[0007] In another embodiment, a method for additive manufacturing includes providing a layer of material on a build surface, the layer of material comprising a first material having a first melting temperature and a second material having a second melting temperature greater than the first melting temperature, and exposing the first and second materials to one or more projections of laser energy. At least one of the one or more projections of laser energy is a line projection having a substantially linear shape, and exposure of the first and second materials to the projections of laser energy heats the first and second materials to a temperature greater than the first melting temperature and less than the second melting temperature. The method further comprises fusing at least a portion of the first material by exposure of first and second materials to the one or more projections of laser energy.

[0008] In yet another embodiment, an apparatus for additive manufacturing includes a build surface, a material depositing system configured to deposit a layer of material onto the build surface, and one or more sources of laser energy configured to expose the layer of material to one or more projections of laser energy. Exposure of the layer of material to the one or more projections of laser energy fuses at least a portion of the layer of material, and at least one of the one or more sources of laser energy is configured to form a line projection having a substantially linear shape.

[0009] It should be appreciated that the foregoing concepts, and additional concepts discussed below, may be arranged in any suitable combination, as the present disclosure is not limited in this respect. Further, other advantages and novel features of the present disclosure will become apparent from the following detailed description of various non-limiting embodiments when considered in conjunction with the accompanying figures.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0010] The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures may be represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

[0011] FIG. **1** is a schematic representation of an apparatus for additive manufacturing according to one embodiment;

[0012] FIG. **2**A is a prior art schematic representation of exposure of a layer of powder material to laser source of energy with a single laser source having a substantially 'dot' shape;

[0013] FIG. **2**B is a schematic representation of exposure of a layer of powder material to laser source of energy with a single laser source having a substantially 'line' shape as projected on the layer according to one embodiment;

[0014] FIGS. **2**C-**2**D are schematic representations of exposure of a layer of powder material to multiple laser source of energy with linear shapes;

[0015] FIG. **3**A is a schematic representation of an intensity profile of a laser line as projected on to a build surface according to one embodiment;

[0016] FIG. **3**B is a schematic representation of a modulated intensity profile of a laser line as projected on to a build surface according to one embodiment;

[0017] FIG. **3**C is a schematic representation of a modulated intensity profile of a laser line as projected on to a build surface according to another embodiment;

[0018] FIG. **3**D is a schematic representation of a modulated intensity profile of a laser line as projected on to a build surface according to a further embodiment.

[0019] FIG. **3**E is a schematic representation of a laser line source projecting a laser line with the x axis representation the direction of the width and the y-axis representing the direction of the length of the line;

[0020] FIG. **4**A is a schematic representation of exposure of a layer of powder material to a laser source of energy where the source has a substantially linear shape as projected onto the layer of powder according to one embodiment in which some areas of the layer are selectively fused by the line while others remain unfused;

[0021] FIG. **4**B is a schematic representation of the position of a linear projection versus time according to one embodiment;

[0022] FIG. **5**A is a schematic representation of exposure of a powder layer to linearly shaped laser radiation modulated to form a 'checkerboard' pattern, according to one embodiment;

[0023] FIG. **5**B is a schematic representation of exposure of a powder layer to linearly shaped laser radiation modulated to form a 'zebra' pattern, according to one embodiment;

[0024] FIG. **5**C is a schematic representation of exposure of a powder layer to linearly shape laser radiation in two subsequent stages such in which the fused area after exposure forms a desired shape on the powder layer, according to one embodiment;

[0025] FIG. **6**A is a schematic representation of simultaneous exposure of a powder layer with two laser sources of energy with one having a substantially 'line' shape and one having a substantially 'dot' shape as projected on to the layer, according to one embodiment;

[0026] FIG. **6**B is a schematic representation of projections from two laser sources, one having a substantially 'line' shape and one having a substantially 'dot' shape with full overlapping of the line and dot projections, according to one embodiment;

[0027] FIG. **6**C is a schematic representation of projections from two laser sources, one having a substantially 'line' shape and one having a substantially 'dot' shape with partial overlap of the line and dot projections; according to one embodiment;

[0028] FIG. **6**D is a schematic representation of projections from two laser sources, one having a substantially 'line' shape and one having a substantially 'dot' shape where there is no overlap of the line and dot projections, according to one embodiment.

[0029] FIG. **7**A is a schematic representation of simultaneous exposure of a powder layer with two laser sources of energy with one being a modulated line source and one being a non-modulated line source, according to one embodiment;

[0030] FIG. **7**B is a schematic representation of projections from two laser sources, one being a modulated line source and one being a non-modulated line source with full overlap of the modulated line and non-modulated line projection, according to one embodiment;

[0031] FIG. **7**C is a schematic representation of projections from two laser sources, one being a modulated line source and one being a non-modulated line source with full overlap of the modulated line and non-modulated line projections, according to one embodiment;

[0032] FIG. **7**D is a schematic representation of projections from two laser sources, one being a modulated line source and one being a non-modulated line source with partial overlap of the modulated line and non-modulated line projections, according to one embodiment;

[0033] FIG. **7**E is a schematic representation of projections from two laser sources, one being a modulated line source and one being a non-modulated line source where there is no overlap of the modulated line and non-modulated line projections, according to one embodiment; and

[0034] FIG. **8** is a schematic representation of exposure of a layer constructed of two different powder materials by a laser source of energy where the source has a substantially linear shape as projected onto the layer of powder, according to one embodiment.

DETAILED DESCRIPTION

[0035] The spatial and temporal distribution of laser energy onto the powder bed during additive manufacturing by selective laser melting (SLM) is critical to appropriate control of the process. The means by which the energy distribution can be controlled critically influences attributes of interest including the accuracy and achievable smallest feature size of the formed geometry, the microstructure and density of the part, and the productivity of the process which is directly related to the build rate. The laser energy delivery to the powder-bed can be described by attributes including the laser wavelength, the laser power, the intensity profile, the spatial distribution of the laser projection (e.g., the beam profile including the nominal spot size), the laser pulse shape, scanning speed and the scanning pattern.

[0036] However, as described above, prior art laser powder-bed additive manufacturing systems, typically SLM machines, utilize only one or more laser sources having a substantially round beam shape (herein referred to as a 'dot' beam). The spatial distribution of the delivered energy can be modified by 'shaping' the intensity profile of the laser beam, for example, to have a 'Gaussian' or 'top hat' profile. State-of-the-art SLM machines have beam diameters ranging typically within the range of 20-200 micrometers.

[0037] However, the highly localized nature of such a beam profile limits the rate at which a part can be produced by the SLM method. Increasing the process build rate by increasing the laser scanning speed demands higher laser power. The resulting melt pool of a fast scanning beam, having sufficient power to form a molten track, elongates compared to a slow scanning beam. It has been shown that the instability of a melt pool with a high length-to-width ratio causes undesired defects on the build surface, which form because the molten track breaks into segments each having a greater surface energy than the substantially cylindrical track. Mechanisms of such defects include (i) instabilities caused by the high thermal gradient between the melt and the surrounding powder (ii) liquid track shrinkage during cooling and (iii) break-up of the melted track due to the rapid timescale of capillary flow relative to the timescale of solidification, along with the low viscosity of the liquid metal. Faster laser scan speeds with sufficient energy density lead to longer melt pools, therefore, the morphology of a melt pool that can solidify without balling sets an upper limit for the SLM laser scan speed at which a continuous solidified track is formed.

[0038] Moreover, the rate of SLM is governed by the rate at which the incident laser energy causes melting of the powder material on the build surface. This rate may be increased by increasing the laser power, and consequentially this may permit a faster scan rate. However, there also exists a temperature gradient downward from the build surface (i.e., whereupon the laser is incident), which must consequently be greater if a higher power density is delivered in order to increase the build rate. The requirement to achieve melting of the powder at a specified distance beneath the build surface, where this distance defines the approximate layer thickness, also causes more heat to be lost due to evaporation of the molten material from the build surface. This evaporation, along with disruptions to the melt pool shape due to the velocity of the vapor, leads to reduced energetic efficiency and lower surface quality.

[0039] The inventors have discovered an additive manufacturing process that overcomes these limitations to achieving simultaneously high rate and resolution in selective laser melting. The new

process allows for the use of substantially higher laser power and improved control over the distribution of energy delivered to the build surface, thus increasing the process rate but without the necessity of increasing the scanning speed or sacrificing the spatial resolution (i.e., the minimum feature size).

[0040] Aspects described herein relate to the production of a part from a powder-bed in a layer-by-layer fashion, through spatially selective fusion of powder layers, by scanning the build surface with a pattern of energy using one or more line-shaped laser sources of energy, herein referred to as line lasers. Depending on the desired outcome, fusion may represent joining of the elements of the build surface (e.g. powder granules, wires, or sheets) within the solid state, or by melting, coalescence, and solidification. This is performed in such a way that material fusion is spatially controlled over the length of the line, yet need not occur over the total or a substantial fraction of the length of the instantaneous projection of the line onto the build surface. According to some aspects described herein, fusion of the powder along a line in general can be controlled to form any suitable/desired pattern of fused regions along the line without needing to independently control multiple dot shaped laser sources, as would be required using existing methods.

[0041] A linear source of laser energy, thus a line laser, may be considered to have a length dimension that is at least 10 times greater than its width, at least 100 times greater than its width, or at least 1000 times greater than its width. For example, a line laser used in accordance with one embodiment may have a width ranging from 10-100 micrometers, and a length ranging from 0.1-1 millimeters, 1-10 millimeters, 1-10 centimeters, or as long as 1 meter. In certain embodiments, the length and width may be defined by the respective dimensions at which the intensity reaches $1/e2$ of its maximum intensity. Also, it may be appreciated that a single linear source, as projected on the powder bed, may be achieved by the superposition of more than one linear source with smaller dimensions and or smaller energy densities For example. a superposition of 10 linear sources each with length 1 centimeter may form a single effective linear source of length 10 centimeters or so that the length of the effective linear source is still just 1 centimeter but the energy density is the sum of the 10 linear sources that make up the line as projected on to the powder bed. Such superposition of linear sources may also result in the capability to project a series of parallel lines of laser energy onto the build surface, such that an exemplary amplitude of intensity modulation between parallel lines is also comparable to the width dimension of each individual line. In this manner, a superposition of linear sources may be used to form a two-dimensional array of laser energy.

[0042] According to some embodiments, the distribution of average intensity along and/or across a line laser may be varied (also referred to as 'modulated') in essentially any suitable fashion such that the local intensity ranges from zero to a maximum value. A substantially line-shaped laser source or line laser as projected on to the build surface shall therefore herein not only be defined as a pattern of laser energy as projected on to the build surface having a length to width ratio as defined above with uniform distribution of laser energy along and across said line, but also be defined as such if the distribution of laser energy along and across said line is substantially modulated. The energy of said line can be modulated to such an extent that fusion of the material on the build surface (e.g., a powder) does not occur in some areas exposed to the projection, while fusion of the material occurs in some other areas exposed to the projection. In one example of modulation, the intensity may be set to zero in particular regions along the length of the line, and in other regions the intensity may range between zero and the maximum value, with a spatial amplitude of variation proximate to the width dimension of the line. The line laser can therefore be modulated to such an extent that some or all sections of the line with energies high enough to achieve fusion of the powder at a given scanning speed do not have individual aspect ratios that would define these individual sections of the line as lines in and of themselves. However, it should be understood that these individual sections of fusion are still sections of a modulated line and not multiple, individually controlled substantially dot shaped laser sources. It can be appreciated that

fusion of any region of the material is determined by the energy transferred by the laser projection onto that region, and the duration of the transfer, along with parameters of the material and the surrounding, such that the process of fusion or lack thereof is controlled by not only the modulated intensity but also the other process parameters described herein.

[0043] As a specific case of fusion, simultaneous melting of a plurality of small regions of the build surface, as described above, allows the process to achieve a high spatial resolution of melting, while overcoming the limitations of current methods including instability of elongated melt pools, formation of defects due to balling, and inefficiency due to high temperature gradients that arise when a plurality of dot sources alone are used, along with higher power density and scan speed, to increase the process build rate. In one embodiment, the number of distinct locations (i.e., isolated melt pools at any instant in the process) on the powder bed that can be simultaneously melted notably far exceeds the number of isolated melt pools that can be formed by scanning of a plurality of independently controlled dot sources.

[0044] According to one embodiment, spatially controlled material fusion may be achieved by providing at least one line laser source, and modulating the intensity profile along the length of the line, while coordinating this modulation with the motion of the linear profile over the build surface, so as to spatially control the heating, melting, and solidification of the powder layer.

[0045] In another embodiment, spatially controlled material fusion may be achieved by scanning at least one line laser source having a substantially uniform intensity profile along the length of the line, the scanning of the line source coordinated with the scanning of at least one substantially round (dot) source. This plurality of sources is scanned over the build surface such that fusion only occurs in locations where there is at least partial overlap of the areas substantially heated by the line and the area substantially heated by the dot source. For example, the line may heat the powder to a temperature substantially above ambient temperature yet below the melting temperature, and then the dot may raise the temperature above the melting temperature. In this case, the average scanning speed of dot may be, yet need not necessarily be, substantially greater than the scanning speed of the line, and the length of the line may be substantially greater than the diameter of the dot.

[0046] Yet another embodiment includes the construction of a build surface comprising spatial arrangements of at least two powder materials having different melting temperatures, and providing a spatial distribution of laser energy defined by scanning laser sources including at least one substantially linear source, such that exposure to the laser energy causes one yet not both of the materials to melt at selected areas of the surface. The melting temperatures may be separated by as much as 10 degrees Celsius, as much as 100 degrees Celsius, as much as 1000 degrees Celsius or as much as 4000 degrees Celsius. Both materials may be metallic, both may be ceramic, or one may be metallic and the other may be ceramic. The materials also may be polymeric, semiconducting, or ionic compounds. The melting temperature of the build surface may also be spatially varied by depositing a uniform composition of a first material, such as a metal powder, and then locally depositing a second material that acts to alter the melting temperature of the combination of materials, for example by forming a eutectic composition.

[0047] A schematic representation of an apparatus for additive manufacturing according to an embodiment is shown in FIG. **1**. A working table **5** with a powder bed **4** is located inside a chamber **2** with a window **3**, allowing for the powder bed to be exposed to a laser source **1**. The laser source, or other components positioned in the optical path of the laser source, includes means to change position of the laser beam projection relative to the powder bed such as gantry systems and/or mirror-based systems which may include one or more mirror galvanometers, which may be placed within or outside of the chamber. Means of modulating and/or shaping of the laser energy that intersects with the powder bed, include beam modulation devices and light valves (e.g. Grating Light Valves and Planar Light Valves). Controlled energy delivery from the laser source allows for selective fusion within the powder layer upon localized heating and subsequent cooling. The

working table is then lowered, and a new powder layer is distributed on the top of the powder bed. In this embodiment, the powder layer is formed with a recoater system, including mechanism **8** that spreads powder from a vertically actuated powder cartridge **6** in the working table region. Alternative methods of powder layer formation may include deposition of powder by a nozzle mechanism, inkjet deposition, electro-hydrodynamic deposition, or ultrasonic deposition. A three-dimensional part is therefore fabricated (i.e., additively manufactured) as a plurality of consecutively fused cross-sections. It can be appreciated that the cross-sections may be, but need not be, planar.

[0048] FIG. **2**A illustrates a prior art method for producing a three-dimensional object from a plurality of fused layers, including a layer of powder **10** exposed by a laser with control means **11**. The laser source **11** has a substantially 'dot' shape projection **12** on the layer **10**. Selective fusion within the layer is then achieved by scanning the powder layer with a 'dot'-shaped projection along a trajectory confined within a desired cross-section.

[0049] FIG. **2**B broadly illustrates an embodiment for additive manufacturing by powder fusion. Powder layer **20** is exposed to a laser source with control means **21** with a laser source having a substantially linear shape **22** as projected on the layer **20**. Laser source **21** includes means to modulate the intensity distribution of the line projection **22**, for example, light valves such as the grating light valve (GLV) to modulate the intensity along the line or a planar light valve (PLV) to modulate the intensity along and across the line. The exemplary GLV modulator system utilizes the ability to spatially control output light intensity across a projected line using a row of dynamically actuated highly reflective micro-ribbons. The linear distribution of laser intensity is controlled spatially and temporally, in order to direct the local fusion of the powder, or other material form on the build surface such as a fabric or sheet, during scanning of the line across the build surface. Further examples of how the intensity is modulated are provided later. It is apparent that the GLV or PLV modulation are just two means of modulating the intensity of the projected line, and that other means of spatial light modulation may be employed. These may include intersecting the laser with a medium having locally tunable optical transmission, so only a portion of the laser energy, in a desired spatial pattern, is transmitted through the medium and incident upon the build surface.

[0050] FIGS. **3**A-**3**E schematically illustrate that the intensity profile of a projection **32** of a line laser source **31** (FIG. **3**E) can be modulated along such line (y-direction). In an alternative embodiment the intensity profile of the line laser source **31** as projected on to the part **32** can be modulated along (y-direction) and across (x-direction) such line. The intensity profile of the line laser source can be changed from mostly uniform at I0 **30** (FIG. **3**A) to non-uniform (FIG. **3**B). Here, parameters of the setup are chosen so that layer exposure at **10 40** causes local fusion of the powder. At the same time, lower intensity regions as those designated with an intensity of 0 or kI0 with k being a number between 0 and 1 (**41**, **42** and **43**), allow for the powder not to be fused at correspondent regions, thus achieving selective fusion of the powder within separated areas of the line projection. Other examples of the intensity profile include rectangular and sinusoidal profiles (FIG. **3**C, D).

[0051] FIG. **4**A illustrates that coordinated, simultaneous control of intensity profile modulation and line laser scanning allows for the creation of desired spatial and temporal intensity patterns on the build surface. The line laser **301** projects a modulated line **302** on to the build surface **300**. The intensity profile of the line projection is thereby modulated in coordination with the scanning of the line in x-direction so that that a desired area **303** is fused. The intensity profile of the line projection can be modulated in such a fashion that not only the outer shape of the fused area **303** is controlled by the process but also so that any desired pattern of fused and unfused areas e.g. **304** can be created within. FIG. **4**B illustrates that the scanning of such line as depicted here along the x axis during time t does not need to occur at uniform speed and can even alternate back and forth during the scanning of a layer. This scanning motion may be, for example, the summation of a constant velocity and a sinusoidally varying velocity, and occur in concert with modulation of the intensity

along the line such that a plurality of individual melt pools exist due to the projection of the laser, and completion of one or more such scans results in complete fusion of the entire area of the build surface that is desired to be fused.

[0052] As shown in FIG. **5**A and **5**C, a 'checkerboard' pattern may be used to form a plurality of individual melt pools when scanning with a line laser. In this example, the exposure pattern includes at least two stages for each layer. During the first stage, the laser energy is modulated spatially and temporally to induce at fusion only in regions marked as **311** on the build surface **313**. During the second stage, at least partial fusion is induced in regions marked as **312**, if needed according to the cross-section. Thus, the 'checkerboard' pattern serves as a mask for the exposure area according to the cross-section. The time-varying position of the line projection on the build surface, the width of the projection, and the distribution of intensity along the projection are varied to achieve such an exemplary checkerboard pattern to result in fusion of the material on the build surface having a desired final density and/or microstructure. In this case, the 'checkerboard' is a generic representation of a scan pattern where the relative orientation of locally parallel scan lines is changed within and/or between consecutive cross-sections of the part being additively manufactured.

[0053] As another example, delivering energy in a 'zebra' pattern, as shown in FIG. **5**B, also allows for control of melt pool morphology. During the first scan fusion is induced in regions marked as **321**. Fusion in areas marked as **322** is induced during one or several subsequent scans, which may overlap with regions **321**. In contrast to 'dot' laser melting, the width of the melt pool is not set by the size of the laser 'dot', but is directly controlled by the modulation of the intensity along the line laser, and the scan parameters. Other examples include patterns with exposure profiles overlapping for consequent stages, which would allow for more uniform consolidation between areas exposed in different stages. Although a checkerboard and zebra pattern have been described, other patterns that either spatially separate many continuous melt pools such as the zebra pattern (e.g. wave and chevron patterns) or alternate small discontinuous melt pools such as the checkerboard pattern (e.g. herringbone pattern) are possible as well.

[0054] It can be appreciated that the effect of multiple stages may be achieved using multiple coordinated linear sources in a shorter amount of time, such that the action of the multiple linear sources is coordinated in the same fashion as the multiple stages described above.

[0055] FIGS. **6**A-**6**D illustrate a further embodiments using combinations of 'dot' and 'line' shaped energy sources. One example is using a linear shaped projection of laser energy to heat the powder to a significant fraction of its melting point, and one or more 'dot' shaped sources that cause rapid local melting. In some cases, this may occur upon intersection of the linear projection with the dot projection. Alternatively, this may occur by sequential exposure of an area with the dot and line lasers without intersection of the laser sources but within a short interval of time such that the powder does not substantially cool between the exposures. As schematically depicted in FIGS. **6**A-**6**D, the line shaped laser source **201** and dot shaped laser source **202** are both used to deliver energy to powder bed **200**. Parameters of the laser sources may be chosen such that exposing the powder layer only with a line shaped source brings the powder to a substantial fraction of its melting temperature, and melting is spatially controlled by further raising the powder to its melting temperature using a separately controlled laser energy source such as using the dot source. A closer view **210** of the linear projection **204** and dot projection **205** on the powder layer is shown on FIGS. **6**B-**6**D. Full overlapping of the linear projection **212** and the dot projection **213** (FIG. **6**B) causes powder fusion within at least a portion of the dot projection, while partial overlapping of the projections **222** and **223** (FIG. **6**C) may, for example, cause fusion within at least some of the intersection of the area that is exposed to both the line and dot projections. No fusion takes place within the linear projection **232** if the projections **232** and **233** do not intersect (FIG. **6**D); as explained above, in this case fusion can however take place within an area exposed by the dot projection if the dot projection intersects an area of the build surface that was before intersected by

the line projection within a sufficient time such that the powder has not substantially cooled from the elevated temperature caused by the line projection. It should be appreciated that the influence of the line and dot sources in the foregoing embodiment may be reversed, for example the dot source may act to raise the temperature yet not cause it to surpass the melting point, and the modulated line source may cause certain areas of the build surface to melt.

[0056] FIGS. **7**A-**7**E illustrate a further embodiment for selective powder fusion using combinations of at least one laser line source **702** with a modulated line projection **704** on to the build surface **700** and one laser line source **701** with a non-modulated line projection **703** on to the build surface **700**. One example is using the non-modulated linear shaped projection of laser energy to heat the powder to a significant fraction of its melting point, and one or more modulated linear shaped projections that cause local melting. Similar to the embodiment described above in connection with FIGS. **6**A-**6**D, this may occur upon intersection of the non-modulated linear projection with the modulated linear projection, or separately from the non-modulated linear projection yet within a sufficient time such that the powder has not substantially cooled from the elevated temperature. As schematically depicted in FIG. **7**A, the non-modulated line shaped laser source **701** and modulated line shaped laser source **702** are both used to deliver energy to powder bed **700**. Parameters of the laser sources may be chosen such that exposing the powder layer only with a non-modulated line shaped source brings the powder close to its melting temperature, and melting takes place if additional energy is delivered, such as using the modulated line source. A closer view **705** of the non-modulated linear projection **702** and modulated linear projection **704** on the powder layer is shown on FIGS. **7**B-**7**E.

[0057] Full overlapping of the non-modulated linear projection **707** and the modulated linear projection **706** so that the modulated linear projection lies within the non-modulated linear projection (FIG. **7**B) causes powder fusion at least within some of the overlapped area. Full overlapping of the non-modulated linear projection **709** and the modulated linear projection **708** so that the non-modulated linear projection lies within the modulated linear projection (FIG. **7**C) causes powder fusion within at least some of the overlapped area. Partial overlapping of the projections **710** and **711** (FIG. **7**D) may, for example, cause fusion within at least some of their intersection. No fusion takes place within the non-modulated linear projection **713** if the projections **713** and **712** do not intersect (FIG. **7**E); as explained above, in this case fusion can however take place within the modulated linear projection **712** if the modulated linear projection intersects an area of the build surface that was before intersected by the not modulated linear projection within a sufficient time such that the powder has not substantially cooled from the elevated temperature caused by the not modulated linear projection.

[0058] It can be appreciated that a non-modulated line projection on to the powder that does not intersect with a modulated line or a dot can also be used for heat treatment purposes other than fusion, for example heating the build surface to an elevated temperature so as to relieve residual stress or control its microstructure, after the layer is fused yet before application of the next layer of unfused material.

[0059] FIG. **8** illustrates a further embodiment that includes the construction of a build surface **801** comprising spatial arrangements of at least two materials, such as powders, having different melting temperatures. The so constructed build surface with areas comprised of powder material P**1** **804**, **805**, **807** and areas comprised of powder material P**2** **803**, **806** is then scanned with at least one line laser source **800** with a linear projection on to the build surface, **802**. The exposure to the laser energy source at a given power and scanning speed causes one yet not both of the powder materials to fuse. In FIG. **8** the line scans the build surface in the positive x direction. The build surface on the left side of the linear projection has already been exposed to the laser including areas **806** and **807**, yet only area **806** comprised of powder material P**2** was fused while area **807**, comprised of powder material P**1** was not fused due to the exposure. The part of the build surface to the right of the linear projection including areas **803** and **804** has not been exposed to the laser

yet and is thusly not fused at any point. Once this area is exposed to the laser, again only area **803** comprised of powder material P**2** will be fused while area **804** comprised of powder material P**1** will remain unfused.

[0060] Additionally, in some embodiments, one or more sensors may be used to monitor temperature and morphology of build surface, and the information may be used to control beam positions, beam intensity profile, powder bed temperature and other parameters in real time. Means of sensing may include photodiodes or infrared cameras, wave propagation and reflection sensors (e.g., ultrasonic, RF). Information from the sensors, in combination with control algorithms may be used to modulate the spatial and temporal distribution of laser energy. For example, the modulation of energy may be programmed to maintain a desired surface temperature, maintain the temperature within a threshold, fuse the material locally to eliminate voids after the primary fusion step, etc. A feedback control scheme may involve spatial imaging of the temperature of the build surface in the vicinity of the area undergoing fusion (e.g., underneath and around the linear exposure pattern), and control of the position and the intensity parameters of the laser source(s), to establish a desired transient temperature field on the build surface, during the processing of each layer of the part. Further feedback control schemes could be used to monitor and control the height of the fused layer, by measuring the height of the build surface during or after the fusion of each layer, and determining the subsequent scan patterns of the laser sources and/or the amount of material delivered in the next layer. The desired transient temperature field may be, for example, programmed to correspond with the desired cross-section of each layer to be fused, and may be informed by a computational simulation of the build process. In accordance with one embodiment described above, wherein at least one laser source such as a line is used to heat the build surface to an elevated temperature below the melting temperature, and a second laser source such as a dot is used to melt the build surface in a desired spatial pattern, the above mentioned sensing and control means may be used to modulate the intensity and position of the laser sources such that prescribed areas of the build surface remain below and above the melting temperature according to a desired program.

[0061] Depending on the particular embodiment, a laser line as projected onto the build surface can be as long as 100 micrometers, as long as 1 mm, as long as 10 mm, as long as 100 mm, or as long as 1 m. The average width of such a line can be as wide as 1 micrometer, as wide as 10 micrometers, as wide as 100 micrometers, as wide as 1 mm, as wide as 10 mm or as wide as 100 mm. The average width of the sections of such line that can be modulated individually (herein also referred to as 'pixels') can be as much as 1 micrometer, as much as 10 micrometers, as much as 100 micrometers, as much as 1 mm, as much as 10 mm or as much as 100 mm while being as long as the maximum width of the line. In a further embodiment where the intensity cannot only be modulated along the length of the line but also across the width of the line, the length of the pixels can be smaller than the maximum width of the line. The pixels can be as long as 1 micrometer, as long as 10 micrometers, as long as 100 micrometers, as long as 1 mm, as long as 10 mm or as long as 100 mm. The total power of such a line as projected onto the build surface can be as much as 1 W, as much as 10 W, as much as 100 W, as much as 1,000 W, as much as 10,000 W, as much as 100,000 W or as much as 1,000,000 W. The scanning speed of such a line relative to the build surface can be as much as 1 mm/s, as much as 10 mm/s, as much as 100 mm/s, as much as 1 m/s, as much as 10 m/s, as much as 100 m/s or as much as 1000 m/s. All types of lasers capable of material processing can be used for the line projections such as but not limited to gas laser (e.g. carbon monoxide and dioxide lasers), chemical lasers (e.g. COIL and AGIL lasers), dye lasers, solid-state lasers especially bulk lasers and fiber lasers (e.g. Nd:YAG, NdCrYAG, Er:YAG), as well as semiconductor lasers (e.g. GaN).

[0062] It should be understood that a build surface may have any suitable shape. The average width maybe as wide as 10 mm, as wide as 100 mm, as wide as 1 m or as wide as 10 m. The average length may differ from the width and maybe as wide as 10 mm, as wide as 100 mm, as wide as 1

m, as wide as 10 m or as wide as 100 m.

[0063] Various materials can be applied to the build surface for processing with a laser to form the 3D part, such as metals, ceramics, polymers, alloys, and composites. Metals may herein refer to, but are not limited to stainless steels (e.g. 316L and 17-4), construction steels (e.g. maraging **300**), light metals and alloys (titanium, aluminum and aluminum-lithium alloys), superalloys (e.g. nickel base alloys such as Inconel and Hastelloy), hard and refractory metals (e.g. tungsten and molybdenum), precious metals (e.g. gold), heat and electrically conductive metals (e.g., copper and silver). Ceramics may herein refer to, but are not limited to inorganic, non-metallic solids comprised of metallic, metalloid or non-metallic atoms. Examples are carbides, nitrides and borides (e.g. tungsten and titanium carbide, silicon nitride and carbide and boron nitride) as well as oxides such as aluminum oxide, zinc oxide and zirconia. Polymer may herein refer to, but are not limited to photopolymers, thermoplastics and thermosetting polymers.

[0064] In case of the material being applied to the build surface as powder, such powder particles can be of various sizes, size (and average size) distributions as well as different geometrical shapes. Powder size (and average size) distributions may range from 1-1000 nanometers, 1-100 micrometers, 10 micrometers to 1 mm. In addition, nanostructures may be added to such powders, i.e., base material is a powder and the second material is nanostructures such as carbon nanotube (CNT's) or nanoparticles, with at least one dimension in the range of 1-100 nm. Yet these nanostructures do not need to differ in material from the base material of the powder, though the nanoparticles may have a suppressed melting/sintering temperature due to their size.

[0065] While the present teachings have been described in conjunction with various embodiments and examples, it is not intended that the present teachings be limited to such embodiments or examples. On the contrary, the present teachings encompass various alternatives, modifications, and equivalents, as will be appreciated by those of skill in the art. Accordingly, the foregoing description and drawings are by way of example only.

Claims

1. (canceled)

2. An additive manufacturing system comprising: a build surface; a first laser energy source and a second laser energy source, the first laser energy source is configured to emit a first projection of laser energy, the second laser energy source is configured to emit a second projection of laser energy; and a gantry system configured to scan the first and second projections of laser energy across the build surface to form one or more tracks on the build surface.

3. The additive manufacturing system of claim 2, wherein the gantry system is configured to scan the first and second laser projections of laser energy across the build surface by adjusting a position of the first and second projections of laser energy relative to the build surface.

4. The additive manufacturing system of claim 3, further comprising a sensor configured to measure a property associated with the build surface, and the gantry system is configured to adjust the position of the first and second projections of laser energy based on the measured property.

5. The additive manufacturing system of claim 2, wherein the first projection of laser energy comprises at least one first pixel, the second projection of laser energy comprises at least one second pixel, and the gantry system is configured to form the one or more tracks on the build surface by moving the at least one first pixel and the at least one second pixel.

6. The additive manufacturing system of claim 2, wherein the gantry system is configured to form the one or more tracks on the build surface by moving the first and second laser projections of laser energy across the build surface to fuse a portion of a layer of material on the build surface.

7. The additive manufacturing system of claim 2, wherein the gantry system is configured to partially overlap the first and second projections of laser energy on the build surface.

8. The additive manufacturing system of claim 7, wherein the gantry system is configured to cause

fusion of a portion of a layer of material on the build surface by at least partially overlapping the first and second projections of laser energy.

9. The additive manufacturing system of claim 2, wherein the first projection of laser energy is a dot projection and the second projection of laser energy is a line projection, and the gantry system is configured to scan the dot projection in the same direction as the line projection and alongside the line projection.

10. The additive manufacturing system of claim 2, wherein the first laser energy source is configured to emit the first projection of laser energy to heat a portion of a layer of material on the build surface to a first temperature below a melting temperature of the layer of material.

11. The additive manufacturing system of claim 10, wherein the second laser energy source is configured to emit the second projection of laser energy to heat the portion of the layer of material to a second temperature higher than the melting temperature of the layer of material.

12. A method for additive manufacturing comprising: emitting a first projection of laser energy from a first laser energy source; emitting a second projection of laser energy from a second laser energy source; and scanning, using a gantry system, the first and second projections of laser energy across a build surface to form one or more tracks on the build surface.

13. The method of claim 12, wherein scanning the first and second laser projections of laser energy across the build surface comprises adjusting, using the gantry system, a position of the first and second projections of laser energy relative to the build surface.

14. The method of claim 13, further comprising measuring a property associated with at least one of the build surface, and adjusting the position of the first and second projections of laser energy is based on the measured property.

15. The method of claim 12, wherein the first projection of laser energy comprises at least one first pixel, the second projection of laser energy comprises at least one second pixel, and forming the one or more tracks on the build surface comprises moving the at least one first pixel and the at least one second pixel.

16. The method of claim 12, wherein forming the one or more tracks on the build surface comprises: moving the first and second laser projections of laser energy across the build surface; and fusing a portion of a layer of material on the build surface.

17. The method of claim 12, further comprising partially overlapping the first and second projections of laser energy on the build surface.

18. The method of claim 17, further comprising fusing a portion of a layer of material on the build surface by at least partially overlapping the first and second projections of laser energy.

19. The method of claim 12, wherein the first projection of laser energy is a dot projection and the second projection of laser energy is a line projection, and scanning the first and second projections of laser energy comprises scanning the dot projection in the same direction as the line projection and alongside the line projection.

20. The method of claim 12, wherein emitting the first projection of laser energy comprises heating a portion of a layer of material on the build surface to a first temperature below a melting temperature of the layer of material.

21. The method of claim 20, wherein emitting the second projection of laser energy comprises heating the portion of the layer of material to a second temperature higher than the melting temperature of the layer of material.