

US011541481B2

(54) ADDITIVE MANUFACTURING SYSTEM USING A PULSE MODULATED LASER FOR TWO-DIMENSIONAL PRINTING

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- (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 329 days.
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(65) **Prior Publication Data** (Continued)

US 2020/0198060 A1 Jun. 25, 2020

Related U.S. Application Data

- (60) Provisional application No. $62/781,996$, filed on Dec. 19, 2018.
- (51) Int. Cl.
 $B23K\,26/342$ B33Y 10/00 (2014.01) (2015.01)
	- (Continued)
- (52) U.S. Cl.
CPC **B23K 26/342** (2015.10); **B23K 26/032** (2013.01) ; **B23K 26/064** (2015.10); (Continued)

(12) United States Patent (10) Patent No.: US 11,541,481 B2
Bayramian et al. (45) Date of Patent: Jan. 3, 2023

(45) Date of Patent: Jan. 3, 2023

(58) Field of Classification Search CPC .. B23K 26/342; B23K 26/144; B23K 26/703; B23K 15/0013; B23K 15/0086;
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(57) ABSTRACT

A method of additive manufacture is disclosed. The method may include providing a powder bed and directing a shaped laser beam pulse train consisting of one or more pulses and having a flux greater than 20 kW/cm² at a defined two dimensional region of the powder bed. This minimizes adverse laser plasma effects during the process of melting and fusing powder within the defined two dimensional region.

13 Claims, 6 Drawing Sheets

(52) U.S. Cl.
CPC B23K 26/0622 (2015.10); B23K 26/0626 (2013.01); **B23K 26/073** (2013.01); **B23K** 26/125 (2013.01); **B23K 26/127** (2013.01); B33Y 10/00 (2014.12); B33Y 50/02 (2014.12);

B33Y 70/00 (2014.12) (58) Field of Classification Search CPC B23K 26/032; B23K 26/702; B23K 15/0006; B23K 15/002; B23K 15/0026; B23K 15/0093; B23K 15/06; B23K 2101/001; B23K 2101/008; B23K 2101/02; B23K 2101/24; B23K 2103/00; B23K 2103/42; B23K 2103/50; B23K 26/0006; B23K 26/03; B23K 26/0622; B23K 26/0643; B23K 26/066; B23K 26/082; B23K 26/083; B23K 26/0846; B23K 26/1224; B23K 26/123; B23K 26/127; B23K 26/142; B23K 26/16; B23K 26/36; B23K 26/704; B23K 37/0408; B23K 37/0426; B23K 15/02; B23K 26/034; B23K 26/04; B23K 26/042; B33Y 10/00; B33Y 30/00; B33Y 50/02; B33Y 40/00; B33Y 70/00; B33Y 80/00; B33Y 99/00 USPC 219 / 76.1

See application file for complete search history.

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Fig. $1A$

Fig. $1B$

Fig. $1C$

Fig. 3C

400

Fig. 4

The present disclosure is part of a non-provisional patent SUMMARY
application claiming the priority benefit of U.S. Patent

material powder layer using a high flux laser beam. How-
eases less than 95% by weight of powder particles are
ever, higher peak power in the optical train translates to 30 ejected into areas outside the defined two dimens

and drastic volume expansion of the plasma. When plasma In some embodiments, the shaped laser beam pulse train
sustains and expands its volume, shockwaves are created 35 is provided by a system including an arbitrary pulse areas. Effectively, this chain reaction of laser beam irradia-
 GW/cm^2 , and the defined two dimensional region of the

tion, plasma generation, plasma sustaining and expansion,

powder bed selected to be between 0.000025

fusion based additive manufacturing systems. Typical con-
ventional powder bed fusion additive manufacturing sys-
pulsed laser intensity <10 GW/cm², and in selected emboditems currently available use individual laser beam of about 45 ments the powder used is \leq 500 um in diameter using a pulse 300 W to 1000 W in power and 50 micrometer (50 um) to intensity $>$ 20 kW/cm².
100 um focused circular laser beam with a focused diameter of 100 um has includes adjusting at least one of the laser beam energy,
a flux of $[1000 \text{ W}/(\pi^*(0.005 \text{ cm})^2)]=12.74 \text{ MW/cm}^2)$, so pulse width, or area of the defined two dimens shockwave to push away powders around the printed area, other embodiments the radius of halo is set to be greater than causing a "Halo effect" that severely and negatively effects 10 microns beyond the defined two dimensio causing a "Halo effect" that severely and negatively effects 10 microns beyond the defined two dimensional region. In the printing process. circular laser beam with a focused diameter of 100 um has

Improved processes and systems are needed to prevent 60 1 micron beyond the defined two dimensional region.

unacceptable halo effects when using high power flux laser In one embodiment, the laser temporal pulse width is
 beam to quickly melt and solidify the powder layer within between 20 nanoseconds and 100 microseconds. A laser the printing area. A useful laser beams power flux for pulse train with number of pulses greater than or equal the printing area. A useful laser beams power flux for pulse train with number of pulses greater than or equal to two-dimensional powder bed fusion based additive manu-
one (1) can be utilized, and the laser pulse peak pow facturing systems can range from tens to hundreds of 65 adjusted as a function of time.
kW/cm² to even GW/cm² level in some scenarios. Unfortu-
natother embodiment a laser system for two-dimen-
nately, in an argon envi

ADDITIVE MANUFACTURING SYSTEM flux are typically sufficient to generate and sustain plasma
USING A PULSE MODULATED LASER FOR that pushes away powder particles to form unacceptable
IWO-DIMENSIONAL PRINTING halos during manu

Tortunately, both damage to optics and unwanted plasma
CROSS-REFERENCE TO RELATED PATENT $\qquad 5$ generation can be reduced or mitigated by suitable pulse ENCE TO RELATED PATENT ⁵ generation can be reduced or mitigated by suitable pulse
APPLICATION shaping and timing of high flux lasers. shaping and timing of high flux lasers.

Application No. 62/781,996, filed on Dec. 19, 2018, which ¹⁰ In one embodiment of a method of additive manufacture,
is incorporated by reference in its entirety a powder bed of metal, ceramic, polymeric, or other mate-
r one or more pulses and having a flux greater than 20 $kW/cm²$ is directed at a defined two dimensional region or "tile" of the powder bed. This energy is sufficient for melting The present disclosure generally relates to additive manu- 15 "tile" of the powder bed. This energy is sufficient for melting facturing and, more particularly, to powder bed fusion and fusing powder within the defined two lable pulse shape and timing for two-dimensional printing. eters are set in some cases so that less than 10% by weight
of powder particles are ejected into areas outside the defined
BACKGROUND 20 two dimensional region, in weight of powder particles are ejected into areas outside the Traditional component machining often relies on removal defined two dimensional region, in other cases less than 40% of material by drilling, cutting, or grinding to form a part. In by weight of powder particles are ejecte dimensional (3D) printing, typically involves sequential 25 80% by weight of powder particles are ejected into areas layer-by-layer addition of material to build a part.
layer-by-layer addition of material to build a part layer addition of material to build a part.

In one high throughput embodiment, two-dimensional less than 90% by weight of powder particles are ejected into In one high throughput embodiment, two-dimensional less than 90% by weight of powder particles are ejected into regions or "tiles" can be melted from a metal or other areas outside the defined two dimensional region, in ot increased risk of laser damage to optics. The region, in other cases less than 99% by weight of powder
Another problem with standard high flux pulse trains particles are ejected into areas outside the defined two
directed

shockwave propagation, and powder movement reduces 40 cm². In some embodiments, thickness of the powder layer
quality of the printing process.
This is a particular problem for high-power powder bed
trange, a 25-250 µm ra cm^2 . In some embodiments, thickness of the powder layer

to detected area of a halo formed by a preliminary halo test.

sional printing includes a laser pulse signal source and one

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amplifier modules can be positioned to receive a laser beam from the optical isolation device and direct it toward a FIGS. 3A-C illustrates example pulse(s) for a high flux defined two dimensional region of the powder bed. The laser $\frac{1}{2}$ laser; and pulse signal source can provide at least one of a square wave, FIG. 4 illustrates modules of a system for providing a a ramp, or a pulse train and the optical isolation device can suitable pulse train. include at least one of a Pockels cell, a Faraday rotator, a

Faraday isolator an acousto-ontic reflector or a volume

DETAILED DESCRIPTION Faraday isolator, an acousto-optic reflector, or a volume Bragg grating.

the steps of directing a laser pulse signal source toward a accompanying drawings that form a part thereof, and in pre-amplifier module and an optic modulator or isolation which is shown by way of illustrating specific exe device to provide a first laser beam. The first laser beam can
be embodiments in which the disclosure may be practiced.
be directed toward an amplifier module to provide a shaped 15 These embodiments are described in suffi having a flux greater than 20 kW/cm2. Typically, the flux is disclosed herein, and it is to be understood that modifica-
between 200 kW/cm² and 10 GW/cm². A laser temporal tions to the various disclosed embodiments may pulse width can be set to range between 20 nanoseconds and and other embodiments may be utilized, without departing 100 microseconds. A laser pulse train with number of pulses 20 from the scope of the present disclosure. T power can adjusted as a function of time . The shaped laser beam pulse train can be directed at a two-dimensional region sized between 0.000025 cm^2 and $1,000 \text{ cm}^2$.

be directed at an additive manufacturing station. For energy beams. Beam shaping optics may receive the one or
example, the shaped laser beam pulse train can be directed more energy beams from the energy source and form a example, the shaped laser beam pulse train can be directed more energy beams from the energy source and form a
at a defined two dimensional region of an additive manu-
single beam. An energy patterning unit receives or gen facturing powder bed to melt and fuse metal or other the single beam and transfers a two-dimensional pattern to powders within the defined two dimensional region.

includes providing an enclosure surrounding a powder bed
and having an atmosphere including at least 50% inert gas,
desired location on a height fixed or movable build platform optionally at greater than atmospheric pressure. A laser (e.g. a powder bed). In certain embodiments, some or all of beam having a flux greater than 20 kW/cm2 can be directed 35 any rejected energy from the energy patterni beam having a flux greater than 20 kW/cm2 can be directed 35 any rej at a defined two dimensional region of the nowder hed to reused. at a defined two dimensional region of the powder bed to reused.
melt and fuse powder within the defined two dimensional In some embodiments, multiple beams from the laser

and having an atmosphere including at least 50% inert gas,
ordersable light valve. In one embodiment, the pixel
optionally at less than atmospheric pressure. A laser beam
having a flux greater than 20 kW/cm2 can be directe having a flux greater than 20 kW/cm2 can be directed at a having a polarizing element and a light projection unit defined two dimensional region of the powder bed to melt providing a two-dimensional input pattern. The two-

N2O, C2H2, C2H4, C2H6, C3H6, C3H8, i-C4H10, C4H10, An energy source generates photon (light), electron, ion, 1-C4H8, cic-2,C4H7, 1,3-C4H6, 1,2-C4H6, C5H12, or other suitable energy beams or fluxes capable of being n-C5H12, n-C5H12, i-C5H12, n-C6H14, C2H3Cl, C7H16, C8H18, 50 directed, shaped, and patterned. Multiple energy sources can
C10H22, C11H24, C12H26, C13H28, C14H30, C15H32, be used in combination. The energy source can include C10H22, C11H24, C12H26, C13H28, C14H30, C15H32, be used in combination. The energy source can include C16H34, C6H6, C6H5-CH3, C8H10, C2H5OH, CH3OH, lasers, incandescent light, concentrated solar, other light C16H34, C6H6, C6H5-CH3, C8H10, C2H5OH, CH3OH, lasers, incandescent light, concentrated solar, other light and iC4H8.

present disclosure are described with reference to the fol-
lowing figures, wherein like reference numerals refer to like
A Gas Laser can include lasers such as a Helium-neon

or more pre-amplifier modules to receive and direct a laser FIG. 2 illustrates an apparatus for two-dimensional addi-
beam toward an optical isolation device. One or more tive manufacture with reduce plasma formation at hi tive manufacture with reduce plasma formation at high laser
flux levels.

In another embodiment a laser control method includes In the following description, reference is made to the esteps of directing a laser pulse signal source toward a accompanying drawings that form a part thereof, and in

sense.
An additive manufacturing system which has one or more sed between 0.000025 cm² and 1,000 cm². energy sources, including in one embodiment, one or more In one embodiment the shaped laser beam pulse train can 25 laser or electron beams, are positioned to emit one or more powders within the defined two dimensional region. 30 the beam and may reject the unused energy not in the In one embodiment, a method of additive manufacture pattern. An image relay receives the two-dimensional pat-

megion.
In one embodiment a method of additive manufacture combined beam can be directed at an energy patterning unit In one embodiment a method of additive manufacture combined beam can be directed at an energy patterning unit includes providing an enclosure surrounding a powder bed 40 that includes either a transmissive or reflective pi and fuse powder within the defined two dimensional region. 45 sional image focused by the image relay can be sequentially
In one embodiment, an atmosphere can contain at least directed toward multiple locations on a powder

include, but are not limited to: Gas Lasers, Chemical Lasers,
BRIEF DESCRIPTION OF THE DRAWINGS
Solid State Lasers, Solid State Lasers (e.g.
fiber), Semiconductor (e.g. diode) Lasers, Free electron
Non-limiting and non-exh

parts throughout the various figures unless otherwise speci- 60 laser, Argon laser, Krypton laser, Xenon ion laser, Nitrogen fied.

EIG. 1A illustrates a powder layer before response to mer laser. Carbon dioxide laser, Car

FIG. 1A illustrates a powder layer before response to mer laser.

A Chemical laser can include lasers such as a Hydrogen

FIG. 1B illustrates powder movement in response to laser fluoride laser, Deuterium fluoride laser, C

vapor laser, Helium-silver (HeAg) metal-vapor laser, Stron-
tium Vapor Laser, Neon-copper (NeCu) metal-vapor laser, sion of electrons. Copper vapor laser, Gold vapor laser, or Manganese (Mn/ \overline{M} A rejected energy handling unit can be is used to disperse, MnCl₂) vapor laser. Rubidium or other alkali metal vapor 5 redirect, or utilize energy not patt lasers such as a Ruby laser, Nd:YAG laser, NdCrYAG laser, rejected energy handling unit can include passive or active Er:YAG laser, Neodymium YLF (Nd:YLF) solid-state laser, cooling elements that remove heat from the energ Neodymium doped Yttrium orthovanadate(Nd:YVO₄) laser, ing unit. In other embodiments, the rejected energy handling
Neodymium doped yttrium calcium oxoborateNd:YCa₄O 10 unit can include a "beam dump" to absorb and conv laser, Titanium sapphire(Ti:sapphire) laser, Thulium YAG pattern. In still other embodiments, rejected beam energy
(Tm:YAG) laser, Ytterbium YAG (Yb:YAG) laser, Ytter- can be recycled using beam shaping optics. Alternative laser (rod, plate/chip, and fiber), Holmium YAG (Ho:YAG) 15 article processing unit for heating or further patterning. In laser, Chromium ZnSe (Cr:ZnSe) laser, Cerium doped certain embodiments, rejected beam energy can be lithium strontium (or calcium)aluminum fluoride(Ce:LiSAF, to additional energy patterning systems or article processing
Ce:LiCAF), Promethium 147 doped phosphate glass units.
(147Pm⁺³:Glass) solid-state laser, Chromium d

For example, in one embodiment a single Nd:YAG 30 q-switched laser can be used in conjunction with multiple q-switched laser can be used in conjunction with multiple metal, ceramic, glass, polymeric powders, other melt-able
semiconductor lasers. In another embodiment, an electron material capable of undergoing a thermally induce beam can be used in conjunction with an ultraviolet semi-
change from solid to liquid and back again, or combinations
conductor laser array. In still other embodiments, a two-
thereof. The material can further include comp dimensional array of lasers can be used. In some embodi- 35 ments with multiple energy sources, pre-patterning of an ments with multiple energy sources, pre-patterning of an or both components can be selectively targeted by the energy beam can be done by selectively activating and imaging relay system to melt the component that is melt-

imaging optics to combine, focus, diverge, reflect, refract, 40 or otherwise destructive process. In certain embodiments, homogenize, adjust intensity, adjust frequency, or otherwise slurries, sprays, coatings, wires, stri laser beam source toward the energy patterning unit. In one able or recycling by use of blowers, vacuum systems, embodiment, multiple light beams, each having a distinct sweeping, vibrating, shaking, tipping, or inversion tive mirrors (e.g. dichroics) or diffractive elements. In other In addition to material handling components, the article
embodiments, multiple beams can be homogenized or com-
bined using multifaceted mirrors, microlenses,

patterning elements. For example, photon, electron, or ion environmental conditions. The article processing unit can, in beams can be blocked by masks with fixed or movable whole or in part, support a vacuum or inert gas a elements. To increase flexibility and ease of image pattern-
ing, pixel addressable masking, image generation, or trans-
mitigate the risks of fire or explosion (especially with ing, pixel addressable masking, image generation, or trans-
mitigate the risks of fire or explosion (especially with
mission can be used. In some embodiments, the energy 55 reactive metals). patterning unit includes addressable light valves, alone or in

A control processor can be connected to control any

conjunction with other patterning mechanisms to provide

patterning. The light valves can be transmissive or use a combination of transmissive and reflective ele-
meating or cooling systems, monitors, and controllers to
ments. Patterns can be dynamically modified using electrical 60 coordinate operation. A wide range of sensor or optical addressing. In one embodiment, a transmissive imagers, light intensity monitors, thermal, pressure, or gas
optically addressed light valve acts to rotate polarization of sensors can be used to provide informatio pixels forming patterns defined by a light projection source. controller, or alternatively, can include one or more inde-
In another embodiment, a reflective optically addressed light 65 pendent control systems. The contro valve includes a write beam for modifying polarization of a
read beam. In yet another embodiment, an electron pattern-
instructions. Use of a wide range of sensors allows various

 5 6

(HeHg) metal-vapor laser, Helium-selenium (HeSe) metal-
vapor laser, Helium-silver (HeAg) metal-vapor laser, Stron-
photon stimulation source and generates a patterned emis-

calcium fluoride $(U:CAF_2)$ solid-state laser, Divalent to beam shaping optics, the image relay can include optics
samarium doped calcium fluoride(Sm:CaF₂) laser, or F-Cen-
to combine, focus, diverge, reflect, refract, ad

InGaAs, InGaAsO, GaInAsSb, lead salt, Vertical cavity and bed, and a material dispenser for distributing material.
surface emitting laser (VCSEL), Quantum cascade laser, The material dispenser can distribute, remove, mix, thereof. The material can further include composites of melt-able material and non-melt-able material where either denergy sources.
The laser beam can be shaped by a great variety of or causing it to undergo a vaporizing/destroying/combusting
 $\frac{1}{2}$.

tive or diffractive optical elements. The chamber, auxiliary or supporting optics, and sensors and Energy patterning can include static or dynamic energy 50 control mechanisms for monitoring or adjusting material or Energy patterning can include static or dynamic energy 50 control mechanisms for monitoring or adjusting material or tterning elements. For example, photon, electron, or ion environmental conditions. The article processing

instructions. Use of a wide range of sensors allows various

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a heating the powder that a sufficient amount of material can pressure , in other instances it can occur at 0.1 and 1.0 bar of Design, implementation and methods of operation of a laser system with long pulse agility and scalability to reduce laser system with long pulse agility and scalability to reduce between 0 and 100 bar of absolute pressure. In some damage to optics and minimize laser plasma induced "Halo" $\frac{5}{2}$ embodiments, the atmospheric temperatu damage to optics and minimize laser plasma induced "Halo" ⁵ embodiments, the atmospheric temperature of the enclosure effects in the print bed are described. Since both effects are is below atmospheric pressure. In other effects in the print bed are described. Since both effects are is below atmospheric pressure. In other embodiments, the proportional to the peak intensity of the laser source, high atmospheric temperature of the enclosure proportional to the peak intensity of the laser source, high atmospheric temperature of the enclosure is above atmo-
power laser sources having a power flux of 20 kilowatts per spheric pressure. During the process of addit power laser sources having a power flux of 20 kilowatts per spheric pressure. During the process of additive manufac-
square centimeter to more than a gigawatt per square cen-
turing, the laser interacts with the powdered square centimeter to more than a gigawatt per square cen-
turing, the laser interacts with the powdered material and the
timeter at a use point (e.g. the print plane) are particularly 10 substrate, and the melted powder timeter at a use point (e.g. the print plane) are particularly 10 substrate, and the melted powder material begins to susceptible to optics damage and laser induced plasma coalesce. This process has the potential to tra susceptible to optics damage and laser induced plasma coalesce. This process has the potential to trap gas bubbles effects. In some embodiments, plasma related halo effects gaps in the material. By sufficiently reducing th effects. In some embodiments, plasma related halo effects gaps in the material. By sufficiently reducing the pressure of may be initiated from evolved vapor/particulates which are the gas, these bubbles will begin to shrin formed from ablated/evaporated material from the powder $_{15}$ collapse on themselves, generating a higher density material (Fe, Cr, Al, Co, Ti, Si, etc. . . .), in particular from metal during the melting process. In so (Fe, Cr, Al, Co, Ti, Si, etc. \dots), in particular from metal during the melting process. In some cases, this process can components. This evolution of vapor/particulate material occur at between 0.5 and 1.0 bar absolute from the surface can happen at such high speeds due to laser instances it can occur at 0.25 and 1.0 bar of absolute
heating the powder that a sufficient amount of material can pressure, in other instances it can occur at 0 enter the gas area above the area being printed, even while $_{20}$ absolute pressure, in other instances it can occur at 0.01 and the laser is still firing. The evolved material can have an 1.0 bar of absolute pressure, the laser is still firing. The evolved material can have an 1.0 bar of absolute pressure, in other instances it can occur
extremely high absorptivity of the laser light still incident on at 0.001 and 1.0 bar of absolute pr the tile being printed, and as such, it super-heats, generating a plasma which not only creates a blast wave and halo effect, other instances it can occur at 1E-6 and 1.0 bar of absolute but also begins to reflect and disperse any further incident 25 pressure, in other instances it can but also begins to reflect and disperse any further incident 25 laser energy. This rejection effect can lower the amount of laser energy. This rejection effect can lower the amount of of absolute pressure, in other instances it can occur at 1E-10 energy that makes it to print bed and can negatively affect and 1.0 bar of absolute pressure. the quality of the printing process within the tile. High Additionally, adjustments to operating conditions such as thermal conductivity of the process gas allows the gas to high pressure at various temperatures can be use quickly conduct away the heat generated from the laser 30 the quality of parts after or during the additive process.
heating and melting process. High thermal conductivity Historically, the process of Hot Isostatic Pressin before plasma volume expansion sustains and therefore however there are considerable benefits to introducing it minimize the mechanical impact of the shockwave that during the process. The HIP process can be operated minimize the mechanical impact of the shockwave that all during the process. The HIP process can be operated
pushes away the surrounding powders. High thermal con-35 between 500 and 1,000 bar, and 400 to 1500 C. However, i more uniform heating and melting of the powder layer. As end, the pressure needs to be cycled at various stages of the a result, the higher conductivity of the ideal process gas 40 print process. The print process would co a result, the higher conductivity of the ideal process gas 40 print process. The print process would continue at low causes more heat to be transferred into the base (print plate pressure, and then intermittently it would causes more heat to be transferred into the base (print plate pressure, and then intermittently it would pause and pressure or previous printed layer underneath the current layer) and would be increased at elevated tempera or previous printed layer underneath the current layer) and would be increased at elevated temperature to drive out therefor brings the base temperature up closer to the melting pores and gas pockets. point without melting the top of the current powder layer. In still other embodiments, other derivative or alternative
This creates beneficial thermal conditions to bond the pow-45 methods can include recycle and recircula der layer to the base plate or previously printed layer process gas in-situ during the process, or introduction of an underneath the current layer.

generation and "Halo" issues. In some embodiments, pre- 50 Advantageously, using the described gas and operating
dominantly inert gases including helium can enhance bond-
ing and operation of powder bed fusion based additi ing and operation of powder bed fusion based additive suppressed or minimized during printing process. Powder
manufacturing process within controlled temperature and movement and mechanical impact on the surrounding metal

enhance the desired heat conduction or heat transfer coef-
ficient away from the tile surface. For example, in the case
of an engineered He gas at 1 bar, the thermal conductivity
"blocking" or "scattering" effect of the pl of an engineered He gas at 1 bar, the thermal conductivity "blocking" or "scattering" effect of the plasma to the laser can double from ~ 0.15 to ~ 0.3 between 0 C. and 600 C. 60 beam above the printing area. Increasing the pressure in turn can also help this process by Figh thermal conductivity of the engineered He contain-
increasing the heat transfer coefficient and increasing the ing process gas also helps to reduce the ver amount of energy required to move a blast wave. Enclosure gradient across the depth of metal powder layer and there-
atmospheric temperatures can be set between 20 degrees fore create more uniform heating and melting condi atmospheric temperatures can be set between 20 degrees fore create more uniform heating and melting condition. It
Kelvin (i.e. cryogenic) and 5000 degrees Kelvin. In some 65 enables using high power flux laser(s) to quickl embodiments, the atmospheric temperature of the enclosure and solidify the metal powders for bonding with a base
can be set between 200 and 600 degrees Celsius. The material. can be set between 200 and 600 degrees Celsius.

7 8

it can occur at 0.0001 and 1.0 bar of absolute pressure, in other instances it can occur at $1E-6$ and 1.0 bar of absolute feedback control mechanisms that improve quality, manu-
facturing throughput, and energy efficiency.
Design. implementation and methods of operation of a halo effects. Atmosphere in an enclosure can be maintained occur at between 0.5 and 1.0 bar absolute pressure, in other instances it can occur at 0.25 and 1.0 bar of absolute at 0.001 and 1.0 bar of absolute pressure, in other instances

In some embodiments, use of an engineered gas forming chamber where laser beam melting the metal powder hap-
an atmosphere in an enclosure acts to mitigate plasma pens.

manufacturing process within controlled temperature and movement and mechanical impact on the surrounding metal
pressure ranges.
providers ("Halo") in response to laser beam melting and powders ("Halo") in response to laser beam melting and fusing is minimized and has insignificant impact on the In addition to engineering the species of gas, the operating 55 fusing is minimized and has insignificant impact on the conditions such as temperature can be used to further continuation of aspects of an additive printing

and top section before response to a laser. Cross-sectional embodiments, greater than 1% He can be used, while in view 101, taken from slice 107, shows a layer of powder 103 other embodiments, greater than 10% He can be us view 101, taken from slice 107, shows a layer of powder 103 other embodiments, greater than 10% He can be used, while containing possible tiles to be printed, resting on a substrate in other embodiments, greater than 20% H 102. Top view 104 shows the view of the same grouping of 5 while in other embodiments, greater than 40% He can be tiles from above. In this example, there is powder in the used, while in other embodiments, greater than 80% region of a tile to be printed 106. The tile to be printed is be used, while in other embodiments, 95% or greater He can surrounded by powder making up future potential tiles to be used. In addition to the composition of t

formerly in a nice uniform layer 103, out of the "Halo" zone 25 and top section responding to a laser beam having a flux generation and improve printing quality. Complex mol-
greater than 20 megawatts per square centimeter and typi- ecules and large atomic weight gasses can have benefi cally ranging between 100 megawatts and 10 gigawatts per related to having larger mass and taking much more force or square centimeter. At such power flux levels, significant energy to move. While larger molecules such as square centimeter. At such power flux levels, significant energy to move. While larger molecules such as sulfur
amounts of laser induced plasma is formed at a use point. 15 hexafluoride have a lower thermal conductivity th amounts of laser induced plasma is formed at a use point. 15 hexafluoride have a lower thermal conductivity than He
Cross-sectional view 101, taken from slice 107, shows a (similar to Ar), the gas is much denser, and would layer of powder 103 containing possible tiles to be printed, out other gasses (O2, H2O vapor, N2, etc....) that are resting on a substrate 102. Top view 104 shows the view of evolved from the powder during the printing pro heating of the powder become super-heated by the laser 108, vibrational and rotational energy storage modes which noble
forming a gas 109 expansion wave which pushes powder gasses do not. These additional energy modes incr 110 next to printed tile 106. The movement of this powder to reduce ionization potential of the gas by absorbing more causes further mounding on nearby tiles 112 which changes energy from the surrounding metal vapor. Addit causes further mounding on nearby tiles 112 which changes energy from the surrounding metal vapor. Additionally, in their layer thickness. The displacement of powder from the the case of SF6 (sulfur hexafluoride) if the ma

FIG. 1C illustrates a powder layer system 100C in cross and top section in response to a laser beam having a flux and top section in response to a laser beam having a flux including species from the powder alloy, etc. . . .) the greater than 20 megawatts per square centimeter and typi-
radicals formed from the breakup would help to s greater than 20 megawatts per square centimeter and typi-
cally ranging between 100 megawatts and 10 gigawatts per
evolved gas during the printing process (O, O2, H, OH,
square centimeter, under a predominantly helium cont layer of powder 103 containing possible tiles to be printed, beam 201 is directed to the powder bed by mirror 211 resting on a substrate 102. Top view 104 shows the view of 40 forming the printing laser beam 202. An insign resting on a substrate 102. Top view 104 shows the view of 40 forming the printing laser beam 202. An insignificant part of the same grouping of tiles from above. In this example, there the beam transmits through mirror 21 the same grouping of tiles from above. In this example, there is a tile 106 , which has been printed with laser 108 , in a is a tile 106, which has been printed with laser 108, in a flux sensor 205 to detect laser flux. A vision system 206 is predominantly Helium environment 109. The printed tile is targeted at the printing area 203 on the bas surrounded by powder making up future potential tiles to be
primage taken by the vision system 206 is transferred to
printed 105. Because the printing was carried out using 45 a computer processor 207. The controller 208 u shaped laser pulse trains, vapor generated from the heating result of image processing to generate control signals to of the powder does not become super-heated by the laser modulate shape, power, and format of the laser p of the powder does not become super-heated by the laser modulate shape, power, and format of the laser pulse. In one 108, the gas expansion wave which has the potential to push embodiment, the amount of helium supplied to powder out of a formerly uniform layer 103 is mostly or chamber 210 from the helium tank 209 can also be modu-
completely eliminated, allowing for the powder 105 next to 50 lated, as well as adjustments to printing chamber completely eliminated, allowing for the powder 105 next to 50 lated, as well as adthe printed tile 106 to be printed in future shots. Further spheric temperature. more, powder layer 103 is not increased, preventing issues FIGS. 3A-C illustrate general types of output pulsed
waveforms that could be used to eliminate or minimize laser

nefium or other inert gases can be used to provide an 55 print process. As seen with respect to graph 300A of FIG.
atmospheric environment in an additive manufacturing 3A, a square pulse can be used, with a width and ampli i-C4H10, C4H10, 1-C4H8, cic-2,C4H7, 1,3-C4H6, 1,2- cause unwanted powder movement and halo formation.
C4H6, C5H12, n-C5H12, i-C5H12, n-C6H14, C2H3Cl, 60 FIG. 3B illustrates graph 300B having a shaped pulse
C7H16, C8H18, C1 C2H5OH, CH3OH, iC4H8 can be used. In some embodi-
membodi-
membodiangle and powder movement. At laser flux levels of
membodiangle and powder movement. At laser flux levels of ments, refrigerants or large inert molecules (including but damage and powder movement. At laser flux levels of not limited to sulfur hexafluoride) can be used. An enclosure 65 between 20 kW/cm² and 10 GW/cm² output, t atmospheric composition to have at least about 1% He by will not typically use a simple oscillator (such as a mode volume (or number density), along with selected percent-
locked oscillator), since such a system would have

 9 10

FIG. 1A illustrates a powder layer system 100A in cross ages of inert/non-reactive gasses can be used. In some and top section before response to a laser. Cross-sectional embodiments, greater than 1% He can be used, while printed 105. gas, ranges of the operating temperature and pressure of the FIG. 1B illustrates a powder layer system 100B in cross 10 engineered gas can also be selected to minimize plasma ecules and large atomic weight gasses can have benefits related to having larger mass and taking much more force or is a tile 106, which has been printed with laser 108. The 20 change. These lighter gasses would effectively float atop the printed tile is surrounded by powder making up future much denser gas, and rapidly remove themselve potential tiles to be printed 105. Vapor generated from the process area. Additionally, more complex molecules have heating of the powder become super-heated by the laser 108, vibrational and rotational energy storage mode gasses do not. These additional energy modes increase the specific heat of the gas at high temperatures and would help "Halo" zone 110 and mounding of powder in nearby tiles molecule was to be broken up (either through plasma
112 cause problems for printing future layers.
FIG. 1C illustrates a powder layer system 100C in cross as O, C, H,

future layers.
In selected embodiments, greater or lesser amounts of plasma formation and its associated "Halo" effect on the In selected embodiments, greater or lesser amounts of plasma formation and its associated "Halo" effect on the helium or other inert gases can be used to provide an 55 print process. As seen with respect to graph 300A of F a

locked oscillator), since such a system would have insuffi-

cient timing and pulse shape flexibility to reliably work The arbitrary pulsed laser source 401 includes a pulse without optic damage or inadvertent plasma creation. Feed-
ing a simple pulse train into an amplifier system and trailing pulses low). This is due to saturation of the gain 5 accomplished via a fiber laser or fiber launched laser source in the amplifiers, with the first pulses into a saturated which is then modulated by an acoust

1399 degrees Celsius) can be printed with >8 Joules per Pre-amplifier modules 402 can include single pass pre-
square centimeter at the print bed with pulse widths >200 amplifiers usable in systems not overly concerned square centimeter at the print bed with pulse widths > 200 amplifiers usable in systems not overly concerned with nanoseconds in a helium environment at room temperature. 30 energy efficiency. For more energy efficient sys Alternatively, aluminum powder (which has a lower melting tips as pre-amplifiers can be configured to extract much of point 659 degrees Celsius) will require less flux to print but the energy from each pre-amplifier 402 be due to its low density (light weight per powder particle), the halo effect will be emphasized. To reduce powder movement halo effect will be emphasized. To reduce powder movement particular system is defined by system requirements and the long pulse widths of >200 nanoseconds can be used. As 35 stored energy/gain available in each amplifier another example, tungsten powder (with a very high melting tipass pre-amplification can be accomplished through angu-
point metal of 3399 degrees Celsius) will minimize plasma lar multiplexing or polarization switching (e. fused silica, a potential optical component has a very high Alternatively, pre-amplifiers 402 can include cavity strucmelting point which will require a lot of laser flux but having 40 tures with a regenerative amplifier type configuration. While a relatively low density will benefit from very long pulse such cavity structures can limit t

properties of a finished printed part by changing how the "white cell" is a multipass cavity architecture in which a energy is delivered to the powder, and effectively controlling 45 small angular deviation is added to eac

400 with ability to create arbitrary and adaptable pulsed amplifier. One example of a white cell would be a confocal waveforms to minimize probability of laser damage, reduce 50 cavity with beams injected slightly off axis waveforms to minimize probability of laser damage, reduce 50 or effectively eliminate laser plasma induced "Halo" in or effectively eliminate laser plasma induced "Halo" in such that the reflections create a ring pattern on the mirror
powder on a print bed, and adjust finished material proper-
after many passes. By adjusting the injectio powder on a print bed, and adjust finished material proper-
ties of the additively manufactured parts. An arbitrary pulsed angles the number of passes can be changed. laser source 401 can be constructed from an arbitrary
were amplifier modules 403 are also used to provide
waveform generator coupled with a fiber coupled diode laser 55 enough stored energy to meet system energy requiremen are used in multipass format for efficiency, with stored operation at system required repetition rate whether they are energy and size being adjustable to match system require-
diode or flashlamp pumped. ments. Faraday rotators 404, Faraday isolators and Pockels The spatial and temporal amplitude of the amplified laser cells 405 are used to keep parasitic reflections from dam- 60 beam is difficult to control. Nearly every aging low energy portions of the system and minimize lost amplifier system induces negative effects on the laser beam
energy to output pulse. A laser relay and imaging systems including: optic aberrations, thermally induce energy to output pulse. A laser relay and imaging systems including: optic aberrations, thermally induced wavefront 406 are used to minimize laser spatial modulation and errors, hardware vibrations, thermal birefringence p expand the beam as energy grows, helping avoid laser ion losses, temperature dependent gain, interference of the damage and allow for efficient extract of energy. Output of 65 laser pulse with itself, amplified reflections damage and allow for efficient extract of energy. Output of 65 laser pulse with itself, amplified reflections from surfaces the laser system 407 can directed to the print engine, and within the laser, and many others. All waveform generator coupled with a fiber coupled diode laser 55

accomplished via a fiber laser or fiber launched laser source as a laser diode. In some embodiments this could also be in the amplifier stealing available energy.
FIG. 3C is a graph 300C showing a shaped pulse (or pulse in pulsed source which uses a Pockels cell can be used to create

train) which changes the amplitude of the laser peak power an arbitrary length pulse train.
over time to improve overall performance while minimizing 10 Various pre-amplifier modules 402 are used to provide
laser damage an As will be understood, other improvements in system isolators can be distributed throughout the system to reduce operation due to shaped laser pulse operation can include or avoid optical damage, improve signal contrast, a minimizing laser energy requirements and/or adjusting vent damage to lower energy portions of the system 400.

In operation, pulse lengths can be tailored to bring the limited to Pockels cells, Faraday rotators, Faraday is peak intensity down below optical damage thresholds for
optic reflectors, or volume Bragg gratings. Pre-
optics with limited capability.
Pulse lengths can be tailored to bring peak intensity at the
pumped amplifiers and co improved two-dimensional tile printing.
Pulse length ranges can be tailored to specific materials are not limited thermally (i.e. they are smaller) versus power which have different laser absorption, melting point, and amplifiers 403 (larger). Power amplifiers will typically be heat of fusion to minimize laser plasma generation which positioned to be the final units in a laser sys prohibits efficient printing due to the "Halo" effect. 25 the first modules susceptible to thermal damage, including
As a further example of improved operation, case 316 but not limited to thermal fracture or excessive the

the energy from each pre-amplifier 402 before going to the next stage. The number of pre-amplifiers 402 needed for a

lengths of >500 nanoseconds to avoid serious halo problems due to typical mechanical considerations (length of cavity),
Pulse lengths can be tailored to improve the mechanical in some embodiments "white cell" cavities can the temperature evolution and consequent stresses and/or an entrance and exit pathway, such a cavity can be designed
crystallographic properties.
FIG. 4 illustrates an example of a high flux laser system and exit allowing and exit allowing for large gain and efficient use of the amplifier. One example of a white cell would be a confocal

ultimately to the powder bed. $\frac{1}{2}$ can be the print engine of the spatial and/or temporal homogeneity of a

propagating beam. In general, laser applications demand
and As will be appreciated, laser flux and energy can be scaled
uniformity and high brightness. One solution is to try to
in this architecture by adding more pre-ampl focused to a very small spot or imaged to a delivery location. 5 Many modifications and other embodiments of the inven-
This is a very difficult problem which typically results in tion will come to the mind of one skilled lower efficiency and in the case of imaging still often yields
in the benefit of the teachings presented in the foregoing
imperfect amplitude control. Another avenue is beam
descriptions and the associated drawings. Theref many samples of the beam and overlaying them in the 10 nearfield. This method adds divergence to the beam and nearfield. This method adds divergence to the beam and embodiments are intended to be included within the scope of increases the minimum spot size achievable but yields the the appended claims. It is also understood that o increases the minimum spot size achievable but yields the the appended claims. It is also understood that other embodi-
benefit of achieving nominal flat top profile beams in both ments of this invention may be practiced i the near field or far field as desired. The difficulty with this an element/step not specifically disclosed herein.

method is the presence of laser "speckle" which is essen-15 The invention claimed is:

tially the interfe tially the interference peaks and valleys of all the beam 1. A samples. This speckle causes problems in the laser system prising: samples. This speckle causes problems in the laser system prising:
itself as intensity spikes can damage optics, and also results performing preliminary halo test; itself as intensity spikes can damage optics, and also results performing preliminary halo test in non-uniform flux at the laser use-point for exposure, providing a powder bed; in non-uniform flux at the laser use-point for exposure, providing a powder bed;
cutting, welding, joining, or powder bed fusion additive 20 directing a shaped laser beam pulse train including one or cutting, welding, joining, or powder bed fusion additive 20 manufacture.

sting" the speckle in time including beam deflectors and
(acousto-optic, electro-optic, mechanical), RF phase modu-
melting and fusing powder within the defined two-dimen-(acousto-optic, electro-optic, mechanical), RF phase modu-
lators, and wavelength division multiplexing. In addition, 25 sional region; lators, and wavelength division multiplexing. In addition, 25 sional region;
one can diminish the spatial or temporal coherence of the wherein the method further comprises a calibration step laser beam itself through the addition of spectral bandwidth, that includes adjusting at least one of a laser beam increased angular content, and even by brute force of energy, pulse width, or area of the defined two-dimen multiple uncorrelated sources which together can diminish sional region in response to a detect
the contrast of the speckle and improve the robustness and 30 formed by the preliminary halo test.

slabs, disks), cooling direction (edge cooling, face cooling), 3. The method of claim 1, wherein the shaped laser beam and cooling media (solid conduction, liquid, or gas). In one 35 pulse train is provided by a system inc embodiment, fluid cooling of slab amplifier transmission pulsed laser source, at least one pre-amplifier, and at least surfaces can provide a scalable method to achieve high one power amplifier. average power. One characteristic of the laser systems for **4.** The method of claim **1**, wherein the flux is between 20 printing is the important of uniformity and homogeneity of kW/cm^2 and 10 GW/cm² at the powder bed. that is transparent to the laser wavelength. In the case that dimensional region of the powder bed is between 0.000025 the laser wavelength is between 900 and 1100 nm, fluids $cm²$ and 1,000 cm². such as silicone oil, water, distilled water, noble or inert $\overline{6}$. The method of claim 1, thickness of the powder bed is gasses (such as helium), or other gasses such as H2, N2, O2, between at least one of 1-2000 µm r or CO2, can be used. An added benefit of the gas cooling 45 and $50-100 \mu m$ range.
method is that the turbulent flow of the gas can enhance the $\frac{7}{100,000 \mu m}$. The method of claim 1, wherein the powder used is homog gasses (such as helium), or other gasses such as H2, N2, O2,

and/or multi-pass or cavity type architectures. Amplifier 9. The method of claim 1, wherein a laser temporal modules can include single pass amplifiers usable in systems pulsewidth of the shaped laser beam pulse train is b energy efficient systems, multipass amplifiers can be con- 55 10. The method of claim 1, wherein a laser pulse train is figured to extract much of the energy from each amplifier utilized with number of pulses greater th before going to the next stage. The number of amplifiers 11. The method of claim 1 wherein a laser pulse peak needed for a particular system is defined by system require-
method of claim 1 wherein a laser pulse peak needed module. Multipass pre-amplification can be accomplished 60 12. A method of additive manufacture, the method com-
through angular multiplexing, polarization switching (wave-
prising: plates, Faraday rotators). performing preliminary halo test;
Alternatively, power amplifiers 403 can include cavity providing a powder bed;

Alternatively, power amplifiers 403 can include cavity structures with a regenerative amplifier type configuration. As discussed with respect to pre-amplifier modules 402 , in 65 more pulses and having a flux greater than 20 kW/cm² some embodiments white cell cavities can be used for power at a defined two-dimensional region of the some embodiments white cell cavities can be used for power at a amplification 403.

understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and

- more pulses and having a flux greater than 20 kW/cm²
Several methods for combatting laser "speckle" by "wig-
at a defined two-dimensional region of the powder bed;
	-
	- energy, pulse width, or area of the defined two-dimensional region in response to a detected area of a halo

effectiveness of the overall laser system.

2. The method of claim 1, wherein less than 10% by

The thermal management of power amplifiers can include

weight of powder particles in the powder bed are ejected into

many em

print performance and protect downstream optics from high **8.** The method of claim 1, wherein the powder used is peak intensities which could cause laser damage. $50 \le 500$ um in diameter using a pulse intensity >20 kW/ ak intensities which could cause laser damage. $50 \le 500$ um in diameter using a pulse intensity >20 kW/cm² at Power amplifier modules 403 can be configured in single the powder bed.

directing a shaped laser beam pulse train including one or more pulses and having a flux greater than 20 kW/cm^2

melting and fusing powder within the defined two-dimensional region;
wherein the method further comprises a calibration step

time in response to detected area of a halo formed by that includes adjusting at least one of pulse shape, number of pulses, or pulse peak power as a function of 5

the preliminary halo test.

13. The method of claim 1, further comprising A method

of additive manufacture, the method comprising:

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providing a powder bed;

performing preliminary halo test;

- directing a shaped laser beam pulse train including one or more pulses and having a flux greater than 20 kW/cm² at a defined two-dimensional region of the powder bed; and 15
- melting and fusing powder within the defined two-dimensional region;
- wherein the method further comprises a step of detecting a halo area formed by the preliminary halo test, with detected radius of the halo area being set greater than 20 50 microns beyond the defined two-dimensional region.

 \ast $*$ * *