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(54) **APPARATUS AND METHOD FOR DIRECT WRITING OF SINGLE CRYSTAL SUPER ALLOYS AND METALS**

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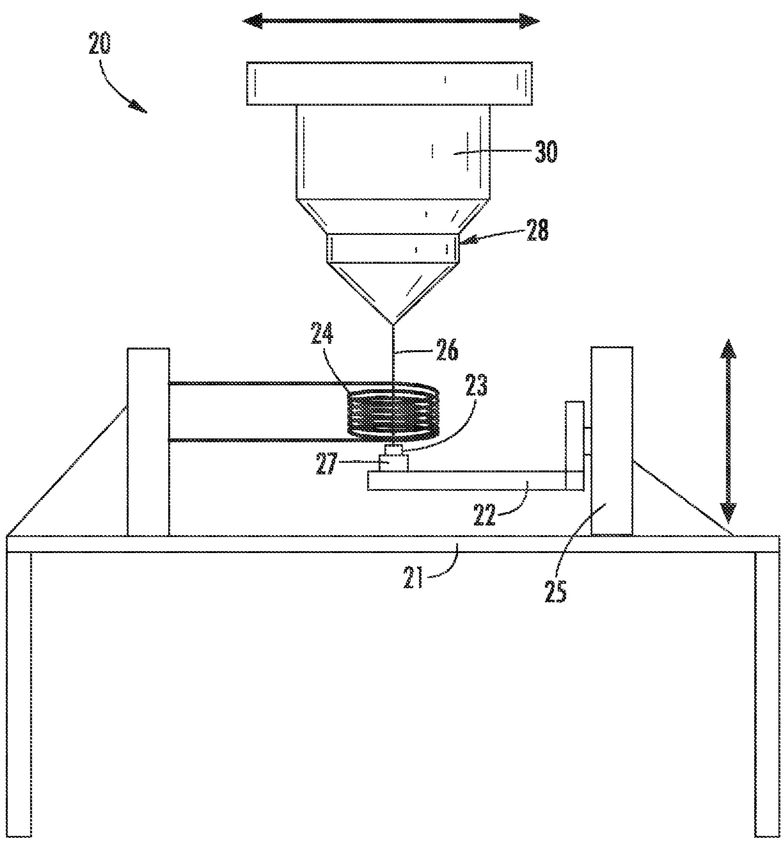
(57) **ABSTRACT**

Apparatus and methods for direct writing of single crystal super alloys and metals are provided. In one method, a substrate is heated to a pretermined temperature below its melting point, and a laser is used to form a melt pool on a surface of a substrate. The substrate is positioned on a base plate, and the laser and the base plate are movable relative to each other, with the laser being used for direct metal deposition and the substrate is heated to a temperature below its melting point. A superalloy powder is introduced to the melt pool, and the temperature of the melt pool is controlled to maintain a predetermined thermal gradient on a solid and liquid interface of the melt pool so as to form a single crystal deposit on the substrate.



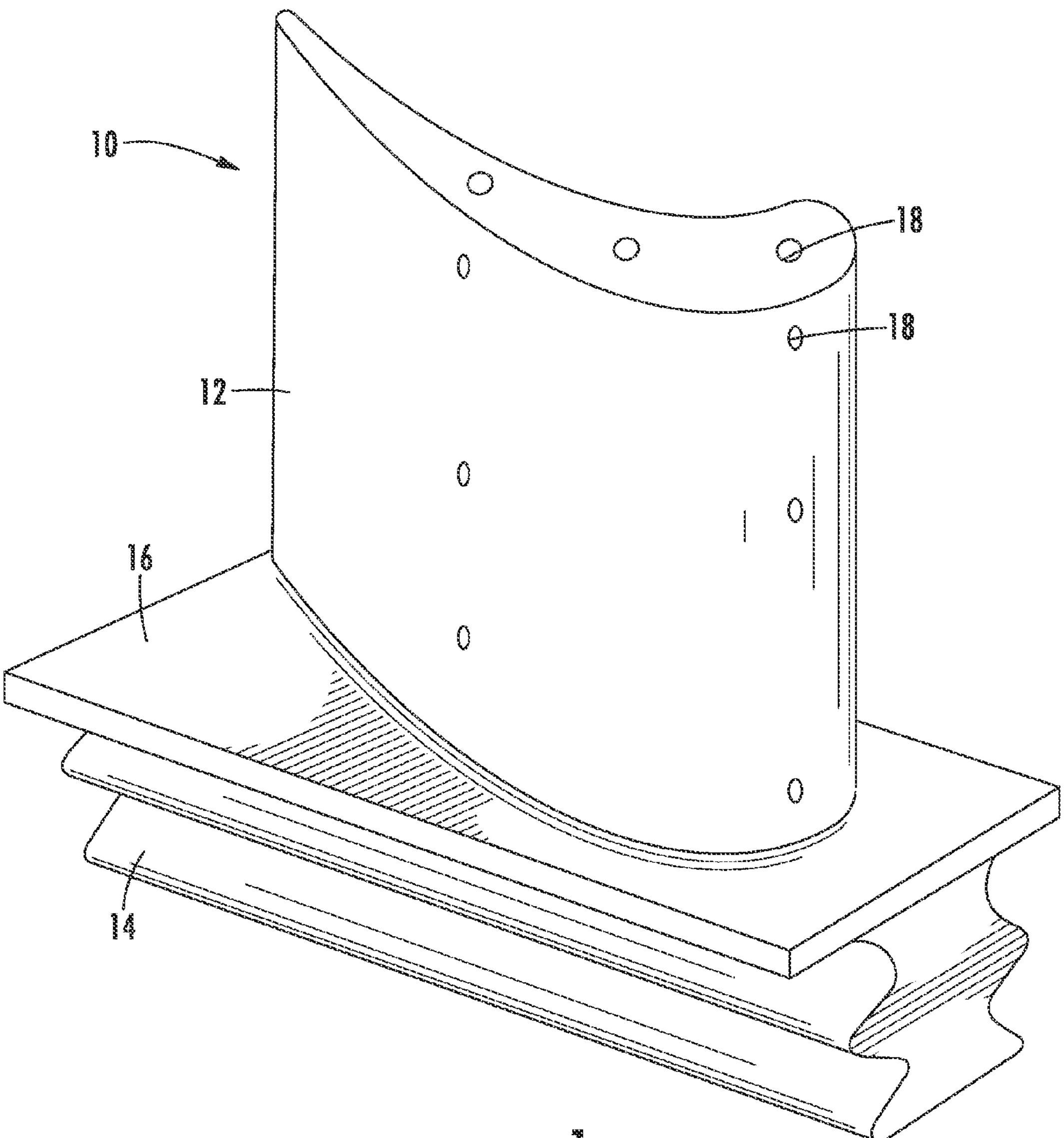



FIG. 1

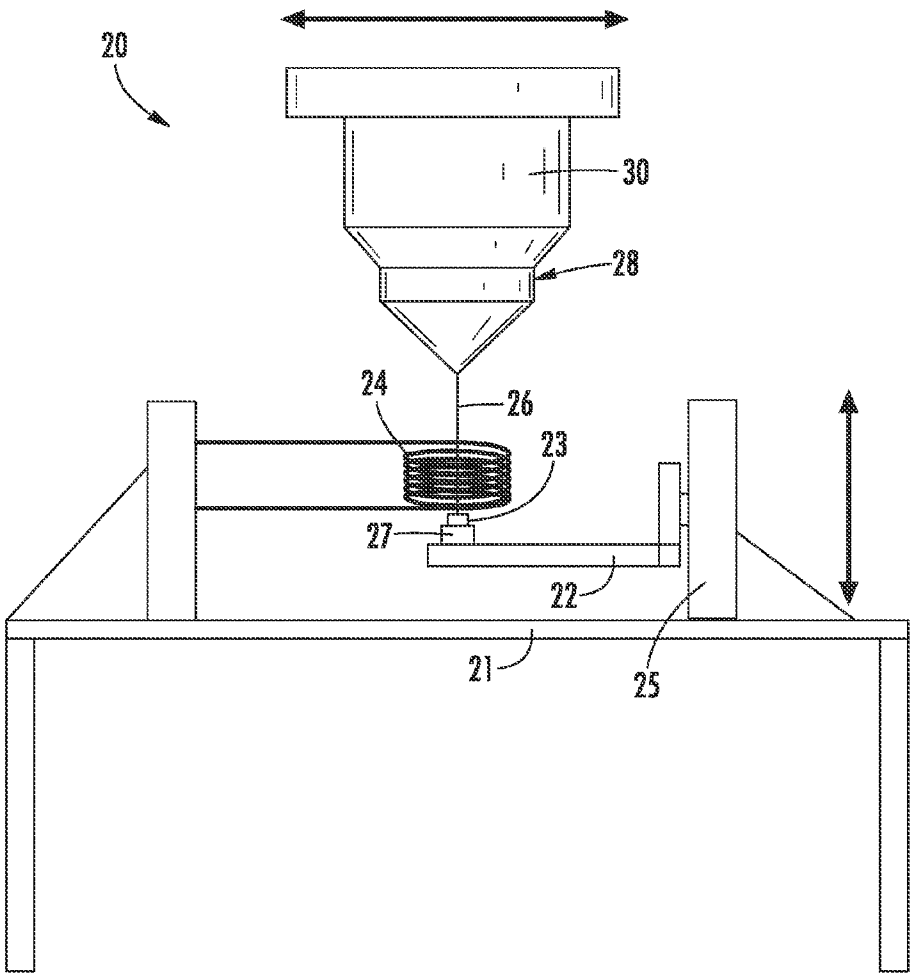



FIG. 2

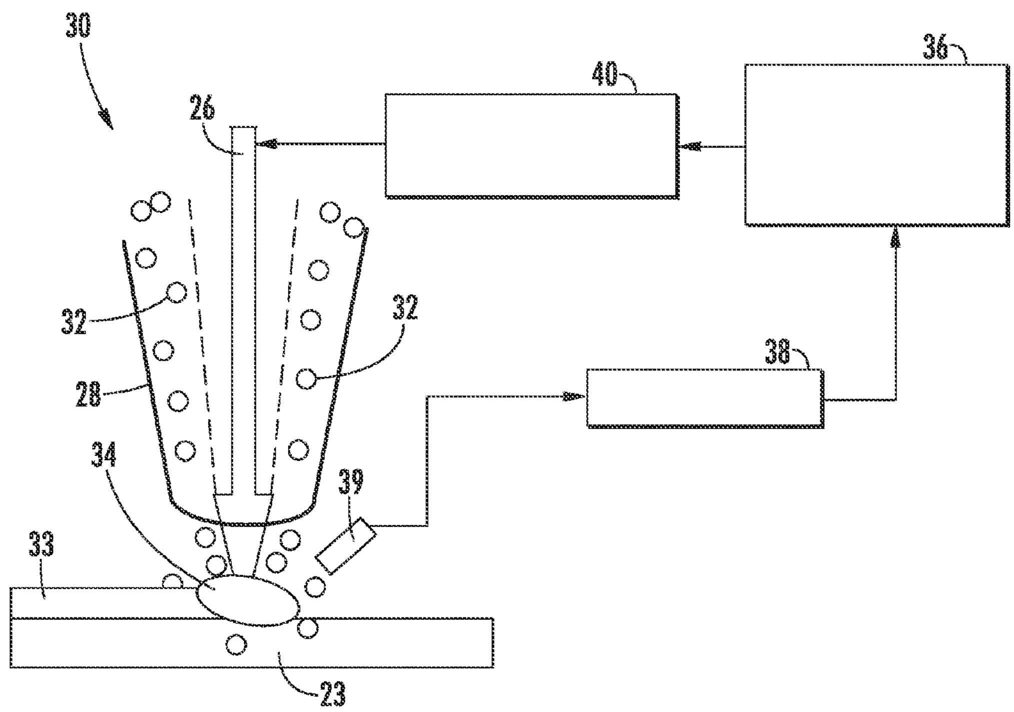



FIG. 3

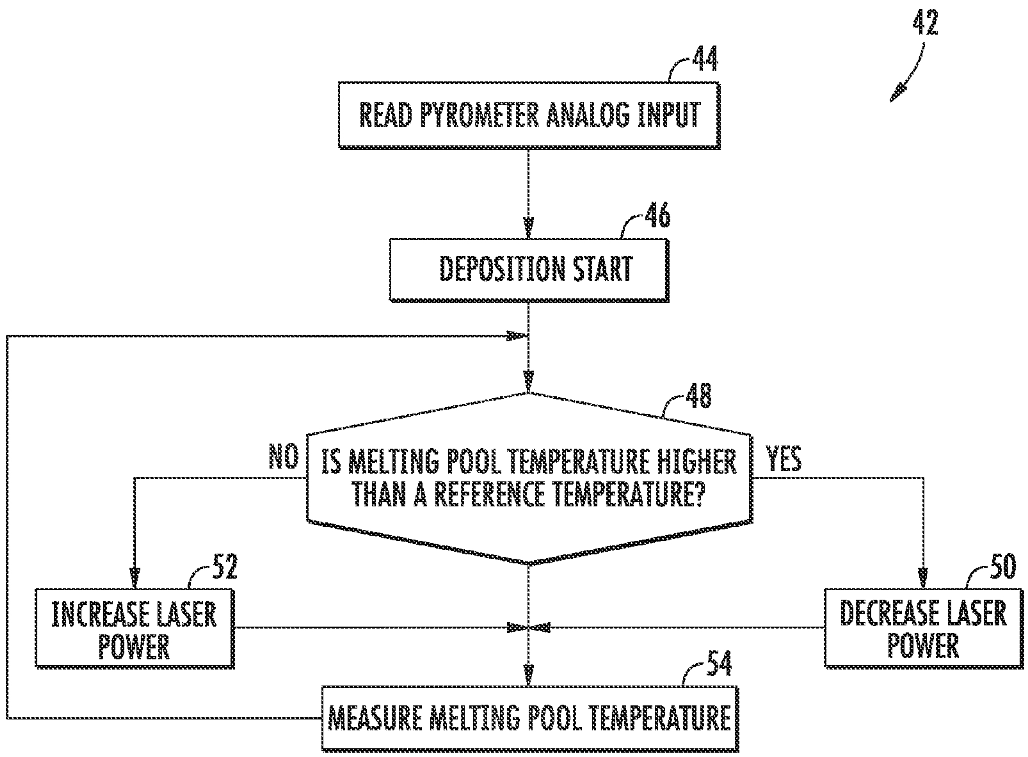

42
44
READ PYROMETER ANALOG INPUT
46
DEPOSITION START
48
IS MELTING POOL TEMPERATURE HIGHER THAN A REFERENCE TEMPERATURE?
NO
YES
52
INCREASE LASER POWER
50
DECREASE LASER POWER
54
MEASURE MELTING POOL TEMPERATURE

FIG. 4

# APPARATUS AND METHOD FOR DIRECT WRITING OF SINGLE CRYSTAL SUPER ALLOYS AND METALS

## PRIORITY INFORMATION

**[0001]** The present application claims priority to U.S. Provisional Patent Application Ser. No. 62/041,884 titled "Apparatus and Method for Direct Writing of Single Crystal Super Alloys and Metals" of Mazumder, et al. filed on Aug. 26, 2014, which is incorporated by reference herein.

## FIELD OF THE INVENTION

**[0002]** The present disclosure relates to an apparatus and method for direct writing of single crystal super alloys and metals.

## BACKGROUND OF THE INVENTION

**[0003]** The turbine section of a gas turbine engine is located downstream of a combustor section and contains a rotor shaft and one or more turbine stages, each having a turbine disk (rotor) mounted or otherwise carried by the shaft and turbine blades mounted to and radially extending from the periphery of the disk. Components within the combustor and turbine sections are often formed of superalloy materials to provide acceptable mechanical properties while at elevated temperatures resulting from the hot combustion gases. Higher compressor exit temperatures in modern high pressure ratio gas turbine engines can also necessitate the use of high performance nickel superalloys for compressor disks, bladed disks, and other components. Suitable alloy compositions and microstructures for a given component depend on the particular temperatures, stresses, and other conditions to which the component is subjected.

**[0004]** For example, airfoil components such as blades and vanes are often formed of equiaxed, directionally solidified (DS), or single crystal (SX) superalloys. Directionally solidified (DS) or single-crystal (SX) turbine airfoils have far superior creep strength, thermal fatigue resistance as well as corrosion resistance when compared to equiaxed crystal counterparts. In particular uses, DS or SX turbine airfoils have proven to have as much as nine times more relative life in terms of creep strength and thermal fatigue resistance and over three times more relative life for corrosion resistance, when compared to equiaxed crystal counter parts.

**[0005]** However, single crystal casting is a slow and expensive process. In the event of a change in design, a new mold has to be fabricated. Due to high melting temperature of the Nickel superalloy, often expensive ceramic molds are required. On the other hand, digital manufacturing methods, if successfully applied, can make a single crystal without a mold and thus enable design change economic.

## BRIEF DESCRIPTION OF THE INVENTION

**[0006]** Aspects and advantages of the invention will be set forth in part in the following description, or may be obvious from the description, or may be learned through practice of the invention.

**[0007]** Methods are generally provided for direct writing of single crystal super alloys and metals. In one embodiment, a substrate is heated to a pretermined temperature below its melting point, and a laser is used to form a melt pool on a surface of a substrate. The substrate is positioned on a base plate, and the laser and the base plate are movable relative to each other, with the laser being used for direct metal deposition and the substrate is heated to a temperature below its melting point. A superalloy powder is introduced to the melt pool, and the temperature of the melt pool is controlled to maintain a predetermined thermal gradient on a solid and liquid interface of the melt pool so as to form a single crystal deposit on the substrate.

**[0008]** An apparatus is also generally provided for direct writing of single crystal super alloys and metals. In one embodiment, the apparatus comprises: a laser having a power output; a base plate configured for holding a substrate thereon; a DMD head configured to supply a stream of superalloy powder onto the substrate; an induction heating source positioned to heat the substrate on the base plate to a predetermined temperature; and a controller for controlling the power output of the laser to maintain the predetermined temperature. The controller is responsive to a measured temperature of at least one of a melt pool on the substrate and the superalloy powder.

**[0009]** These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended Figs., in which:

**[0011]** FIG. **1** is a perspective view of an article, such as a gas turbine blade, according to an embodiment of the invention;

**[0012]** FIG. **2** illustrates an experimental setup according to one embodiment;

**[0013]** FIG. **3** illustrates a melt pool temperature control process according to one embodiment; and

**[0014]** FIG. **4** is a flow chart of an algorithm for the melt pool temperature controller according to one embodiment.

**[0015]** Repeat use of reference characters in the present specification and drawings is intended to represent the same or analogous features or elements of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

**[0016]** Reference now will be made in detail to embodiments of the invention, one or more examples of which are illustrated in the drawings. Each example is provided by way of explanation of the invention, not limitation of the invention. In fact, it will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the scope or spirit of the invention. For instance, features illustrated or described as part of one embodiment can be used with another embodiment to yield a still further embodiment. Thus, it is intended that the present invention covers such modifications and variations as come within the scope of the appended claims and their equivalents.

**[0017]** Direct Metal Deposition (DMD), a digital additive manufacturing process, uses an intelligent closed-loop feedback system to provide an economical solution for advanced Gas Turbine Technology. Methods and apparatus are generally provided herein for the direct writing of three dimensional single crystals shapes facilitated by maintaining the temperature gradient at the solid liquid interface within a very narrow window close to being a constant.

**[0018]** Such three dimensional single crystal shapes have a particular utility as a blade of a gas turbine engine. Referring to the drawings, FIG. **1** depicts an article **10** of a gas turbine engine, illustrated as a gas turbine blade. The gas turbine blade **10** includes an airfoil **12**, a laterally extending platform **16**, an attachment **14** in the form of a dovetail to attach the gas turbine blade **10** to a turbine disk (not shown). In some components, a number of cooling channels extend through the interior of the airfoil **12**, ending in openings **18** in the surface of the airfoil **12**.

**[0019]** In an exemplary embodiment, the component article **10** is substantially a single crystal. That is, the component article **10** is at least about 80 percent by volume, and more preferably at least about 95 percent by volume, a single grain with a single crystallographic orientation. There may be minor volume fractions of other crystallographic orientations and also regions separated by low-angle boundaries. The single-crystal structure is prepared by the directional solidification of an alloy composition, usually from a seed or other structure that induces the growth of the single crystal and single grain orientation.

**[0020]** The use of exemplary alloy compositions discussed herein is not limited to the gas turbine blade **10**, and it may be employed in other articles such as gas turbine nozzles, vanes, shrouds, or other components for gas turbine engines.

**[0021]** Referring to FIG. **2**, an apparatus **20** is generally shown for providing a stable temperature gradient and environment for SX growth using a process similar to the floating zone method used for manufacturing semiconductors. The apparatus **20** generally includes a worktable **21** with which other components are arranged. A single crystal base plate **22** is used to initiate epitaxial growth. A single-crystal substrate **23** is shown positioned on a platform **27** on the single-crystal base plate **22**. The single-crystal base plate **22** is movable in the vertical direction with respect to the apparatus **20**. As shown, a linear motion stage **25** is positioned on the work table **21** to control the vertical movement of the single-crystal base plate **22**.

**[0022]** In one embodiment, the substrate is a single-crystal seed having substantially the same composition as the deposit. For example, both the substrate and the material deposited can be a nickel-based super alloy, such as the nickel-base superalloy commercially known as René N5, disclosed in U.S. Pat. No. 6,074,602.

**[0023]** An induction heat source **24** is introduced in order to keep a steady temperature gradient on the single-crystal substrate **23**. As shown, the induction heat source **24** is a heating coil that is static with respect to the apparatus **20**. As such, the single-crystal base plate **22** can be moved vertically with respect to the induction heating source **24** to control the distance of the single-crystal substrate **23** from the induction heating source **24**. When positioned on the platform **27**, the substrate **23** can be positioned within the induction heat source **24**.

**[0024]** A laser **26** is shown exiting the DMD head **28** for growing a single-crystal on the single-crystal substrate **23**. As shown, a 4 kW laser **26** is used for forming single crystal Ni-based superalloy specimens. However, any laser or heat source such as electron beam with enough power to melt metal powder will be adequate for the process. The experiments described in the embodiment shown only uses few hundred watts out of 4 KW. The DMD head **28** is movable in the horizontal plane, in both the X and Y axis, to allow control of the location of the laser **26**. Thus, the apparatus **10** allows for a 3-axis motion stage for forming single crystal specimens.

**[0025]** As more particularly shown in FIG. **3**, the DMD head **28** utilizes a DMD powdered metal delivery system **30** for flowing a superalloy powder **32** to the melt pool **34** generated by the laser **26**. In one embodiment, the superalloy powder **32** includes a nickel-based superalloy powder. However, any suitable superalloy can be included in the powder **32** as desired.

**[0026]** By using the induction heating source **24**, the temperature of the single crystal substrate **23** is increased to near melting temperature (e.g., about 1200° C. when the substrate **23** is a Ni-based superalloy). The induction heating source **24** helps to maintain the thermal gradient on the solid and liquid interface.

**[0027]** The powder **32** is then deposited onto the single crystal substrate **23** when a melt pool **34** is formed from the clad **33** due to the addition of the laser **26** contacting the powder **32** and the substrate **23**. That is, the addition of energy from the laser **26** raises the local temperature of the powder **32** and the single-crystal substrate **23** to form the melt pool **34**.

**[0028]** The cladding is a composition similar to the composition of the substrate. The metal powder is generally gas-atomized metal powder of a suitable size and chemical composition for achieving the desired chemistry in the cladding.

**[0029]** In a particular embodiment, the deposition atmosphere is formed from an inert gas (e.g., Ar, He, $N_2$, etc.) for oxidation protection. For example, an inert gas can flow through the deposition chamber (not shown) containing the apparatus **10**.

**[0030]** Referring now to FIG. **3**, a melt pool temperature controller **36** is generally shown. The melt pool temperature controller **36** is configured to maintain a substantially constant melt pool temperature, maintaining the thermal gradient on the solid and liquid interface. A pyrometer **38** and its lens **39** measures a temperature of the melt pool **34** and sends an analog signal to the controller **36**. The controller **36** processes converting the analog signal to actual temperature of the melt pool **34** and compares between the temperature of melt pool **34** and a reference temperature, which gives the best quality of deposition.

**[0031]** If the temperature of melt pool **34** is higher than the reference temperature, the controller **36** sends a lower voltage of a signal to the laser power controller **40** to decrease the laser power. In case the melt pool temperature is lower than the reference temperature, the controller **36** increases a laser power. As the crystal grows, the lower part will begin to cool since laser heat source is farther away, resulting in perturbation of the solid-liquid interface temperature gradient. The induction heating source **24** rectifies this problem.

**[0032]** FIG. **4** shows an exemplary method **42** for use by the controller **36**. At **44**, the pyrometer analog input is read to determine the temperature of the melt pool. At **46**, the deposition process starts. At **48**, the melting pool temperature is compared to the reference temperature. If the melting point temperature is higher than the reference temperature, then a signal is sent to the laser power controller to decrease the laser power, at **50**. Conversely, if the melting point temperature is lower than the reference temperature, then a signal is sent to the laser power controller to increase the laser power, at **52**. At

**54**, the melting pool temperature is measured, and the process repeats. Thus, the melting pool temperature can be controlled in real-time during deposition.

**[0033]** In one embodiment, the controller **36** and/or the laser power controller **40** may comprise a computer or other suitable processing unit. Thus, in several embodiments, the controller **36** may include suitable computer-readable instructions that, when implemented, configure the controller **36** to perform various different functions, such as receiving, transmitting and/or executing laser power output control signals.

**[0034]** A computer generally includes a processor(s) and a memory. The processor(s) can be any known processing device. Memory can include any suitable computer-readable medium or media, including, but not limited to, RAM, ROM, hard drives, flash drives, or other memory devices. Memory stores information accessible by processor(s), including instructions that can be executed by processor(s). The instructions can be any set of instructions that when executed by the processor(s), cause the processor(s) to provide desired functionality. For instance, the instructions can be software instructions rendered in a computer-readable form. When software is used, any suitable programming, scripting, or other type of language or combinations of languages may be used to implement the teachings contained herein. Alternatively, the instructions can be implemented by hard-wired logic or other circuitry, including, but not limited to application-specific circuits.

**[0035]** Memory can also include data that may be retrieved, manipulated, or stored by processor(s). For instance, after receiving the temperature measured from the pyrometer, memory can store the temperature information. Additionally, memory can store reference temperatures for various substrate materials and/or powder materials.

**[0036]** The computing device can include a network interface for accessing information over a network. The network can include a combination of networks, such as Wi-Fi network, LAN, WAN, the Internet, cellular network, and/or other suitable network and can include any number of wired or wireless communication links. For instance, computing device could communicate through a wired or wireless network with the pyrometer and/or the laser power controller.

**[0037]** Growth rate of the single crystal is dependent on the temperature gradient in the solid as shown in the Equation 1:

$$R_{max}=(K_s \cdot G_s)/(p_s \cdot H)$$

where: $R_{max}$ is the maximum crystal growth rate, $K_s$ is the thermal conductivity of the solid deposited crystal, $G_s$ is the temperature gradient at the solid-liquid interface, $P_s$ is the solid density, and H is the latent heat of fusion. It should be noted that $K_s$, $P_s$ and H are materials properties and cannot be controlled by the process, but $G_s$ can be. Therefore, combined Laser and Induction heating provides additional parameters to increase the growth rate.

**[0038]** The present teachings thereby remove the need for an expensive mold for growing single crystal and thus the lead time from concept to realization. Thus, the dual heating system provides the process flexibility and route to increase the productivity. It is anticipated that, in some embodiments, alternative heat sources, other than Laser and Induction, can be used. Such alternative heat sources can include Electron Beam, Plasma arc, electric arc, resistive heating etc. However, a revised control algorithm may be required for the particular heat source used.

**[0039]** This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

**1**. A method for direct writing of single crystal super alloys and metals, the method comprising:

heating a substrate to a predetermined temperature below its melting point;

using a laser to form a melt pool on a surface of the substrate, wherein the substrate is positioned on a base plate, and wherein the laser and the base plate are movable relative to each other, the laser being used for direct metal deposition;

introducing a superalloy powder to the melt pool; and

controlling the temperature of the melt pool to maintain a predetermined thermal gradient on a solid and liquid interface of the melt pool so as to form a single crystal deposit on the substrate.

**2**. The method of claim **1**, wherein the laser has a variable power source, and wherein controlling the temperature of the melt pool comprises:

adjusting the variable power source of the laser.

**3**. The method of claim **1**, wherein the laser has a variable power output controllable by a laser power controller, and wherein controlling the temperature of the melt pool comprises:

measuring the temperature of the melt pool;

receiving the temperature measured at a controller;

comparing the temperature measured to a reference temperature; and

adjusting the variable power output of the laser.

**4**. The method of claim **3**, wherein the temperature measured is lower than the reference temperature, and wherein adjusting the variable power output of the laser comprises:

increasing the variable power output of the laser.

**5**. The method of claim **4**, wherein increasing the variable power output of the laser comprises:

increasing the voltage supplied by the laser power controller.

**6**. The method of claim **3**, wherein the temperature measured is higher than the reference temperature, and wherein adjusting the variable power output of the laser comprises:

decreasing the variable power output of the laser.

**7**. The method of claim **6**, wherein decreasing the variable power output of the laser comprises:

decreasing the voltage supplied by the laser power controller.

**8**. The method of claim **1**, wherein the laser and the base plate are movable in 3 directions with respect to each other.

**9**. The method of claim **1**, further comprising:

moving the laser in a horizontal plane with respect to the substrate.

**10**. The method of claim **1**, further comprising:

moving the base plate in a vertical direction with respect to the laser.

**11**. An apparatus for direct writing of single crystal super alloys and metals comprising:
- a laser having a power output;
- a base plate configured for holding a substrate thereon;
- a DMD head configured to supply a stream of superalloy powder onto the substrate;
- an induction heating source positioned to heat the substrate on the base plate to a predetermined temperature; and
- a controller for controlling the power output of the laser to maintain the predetermined temperature, wherein the controller is responsive to a measured temperature of at least one of a melt pool on the substrate and the superalloy powder.

**12**. The apparatus of claim **11**, further comprising:
- a pyrometer configured to measure the temperature of the at least one of the melt pool on the substrate and the superalloy powder.

**13**. The apparatus of claim **12**, wherein the pyrometer is in communication with the controller.

**14**. The apparatus of claim **13**, wherein the laser has a variable power output controlled by a laser power controller.

**15**. The apparatus of claim **14**, wherein the laser power controller is in communication with the controller.

**16**. The apparatus of claim **11**, wherein the laser passes through the DMD head onto the substrate to form a melt pool.

**17**. The apparatus of claim **11**, wherein the laser and the base plate are movable in 3 directions with respect to each other.

**18**. The apparatus of claim **11**, wherein the laser is movable in a horizontal plane with respect to the substrate.

**19**. The apparatus of claim **11**, wherein the base plate is movable in a vertical direction with respect to the laser.

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