

DIRECTED ENERGY DEPOSITION APPARATUS AND METHOD

Cross Reference to Related Application(s)

- 5 The present disclosure claims the benefit of Singapore Patent Application No. 10202301426T filed on 22 May 2023, which is incorporated in its entirety by reference herein.

Technical Field

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The present disclosure generally relates to a directed energy deposition apparatus and method. More particularly, the present disclosure describes various embodiments of a directed energy deposition apparatus for additively manufacturing a part, as well as a method for additively manufacturing a part using a directed energy deposition
15 apparatus.

Background

- Directed energy deposition (DED) is a 3D additive manufacturing process that
20 deposits material and melts the material in layers to fabricate parts. Specifically, a nozzle deposits the material onto a build platform or scaffold, and once deposited, the material is melted with a laser or electron beam. During fabrication of a part, some of the heat generated is transferred to the environment by both convection and radiation, while the rest of the heat will be shifted by conduction. When the input heat energy is
25 higher than the heat loss, the part may overheat, resulting in oxidization at unprotected areas of the part and, in some cases, meltdown.

- Various techniques and methods that have been explored by the industry to ensure that the melt pool formation is consistent are to counter meltdown and/or poor or no
30 melt pool. These techniques typically focus on controlling the laser, melt pool size, and distance between the nozzle and build platform. But even with such methods, oxidation and meltdown of the part can still occur due to the high temperatures, especially if the part is thin or has a small cross-sectional area, resulting in part failure.

The DED process may implement a cooling time between each layer during fabrication of the thin part to address these problems, though this would increase the overall manufacturing time which may not be ideal for an industrial situation where the emphasis is on high-throughput production. FIG. 1 (a) shows a heavily oxidized thin part that was fabricated by DED without the cooling time. FIG. 1 (b) shows another thin part with less oxidation that was fabricated by DED with the cooling time between layers. Even though the introduction of the cooling time between layers reduced the level of oxidation, it is still visible in the part and can still result in part failure.

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Therefore, in order to address or alleviate at least one of the aforementioned problems and/or disadvantages, there is a need to provide an improved directed energy deposition apparatus and method.

15 **Summary**

According to a first aspect of the present disclosure, there is a method for additively manufacturing a part using a directed energy deposition apparatus. The method comprises steps:

20 (a) depositing a material onto a build platform of the directed energy deposition apparatus to form a current layer of the part;

(b) melting the material in the current layer;

(c) cooling the part comprising the current layer to thereby cool the melted material;

25 (d) measuring a temperature of the part during said cooling;

(e) after the part has cooled to a predefined temperature, depositing the material onto the current layer to form a next layer of the part; and

(f) repeating steps (a) to (e) to thereby fabricate on the build platform the part comprising a plurality of successive layers.

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According to a second aspect of the present disclosure, there is a directed energy deposition apparatus for additively manufacturing a part. The apparatus comprises:

a build platform for fabricating the part thereon;

a supply chamber comprising a nozzle for depositing a material onto the build platform;

a heat source for melting the material;

a thermal device for measuring temperature of the part;

5 a controller configured for:

(a) depositing the material from the supply chamber onto the build platform to form a current layer of the part;

(b) activating the energy source to melt the material in the current layer;

10 (c) deactivating the energy source to cool the part comprising the current layer to thereby cure the melted material;

(d) measuring, using the thermal device, a temperature of the part during said cooling;

15 (e) after the part has cooled to a predefined temperature, depositing the material from the supply chamber onto the current layer to form a next layer of the part; and

(f) repeating steps (a) to (e) to thereby fabricate on the build platform the part comprising a plurality of successive layers.

20 A directed energy deposition apparatus and method according to the present disclosure is thus disclosed herein. Various features, aspects, and advantages of the present disclosure will become more apparent from the following detailed description of the embodiments of the present disclosure, by way of non-limiting examples only, along with the accompanying drawings.

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Brief Description of the Drawings

FIG. 1 is an illustration of parts fabricated by an existing directed energy deposition process.

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FIG. 2A and FIG. 2B are illustrations of a directed energy deposition apparatus according to embodiments of the present disclosure.

FIG. 3 is a flowchart illustration of a method for additively manufacturing a part using the directed energy deposition apparatus according to embodiments of the present disclosure.

- 5 FIG. 4 is another flowchart illustration of the method for additively manufacturing a part using the directed energy deposition apparatus.

FIG. 5 is an illustration of manufacturing times of sample parts fabricated by the method.

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FIG. 6A and FIG. 6B are illustrations of the sample parts.

FIG. 7A and FIG. 7B are illustrations of temperature profiles of the sample parts.

- 15 FIG. 8A and FIG. 8B are illustrations of tensile tests of the sample parts.

FIG. 9 is an illustration of electron backscatter diffraction images of the sample parts.

FIG. 10A to FIG. 10F are illustrations of pole figures of the sample parts.

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FIG. 11 is another illustration of electron backscatter diffraction images of the sample parts.

Detailed Description

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For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to a directed energy deposition apparatus and method, in accordance with the drawings. While aspects of the present disclosure will be described in conjunction with the embodiments provided herein, it will be understood
30 that they are not intended to limit the present disclosure to these embodiments. On the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims. Furthermore, in the

following detailed description, specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be recognized by an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising
5 from combinations of aspects of particular embodiments. In a number of instances, well-known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure aspects of the embodiments of the present disclosure.

10 In embodiments of the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent, or an analogous element or element number identified in another figure or descriptive material associated therewith.

15 References to “an embodiment / example”, “another embodiment / example”, “some embodiments / examples”, “some other embodiments / examples”, and so on, indicate that the embodiment(s) / example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every
20 embodiment / example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase “in an embodiment / example” or “in another embodiment / example” does not necessarily refer to the same embodiment / example.

25 The terms “comprising”, “including”, “having”, and the like do not exclude the presence of other features / elements / steps than those listed in an embodiment. Recitation of certain features / elements / steps in mutually different embodiments does not indicate that a combination of these features / elements / steps cannot be used in an embodiment.

30 As used herein, the terms “a” and “an” are defined as one or more than one. The use of “/” in a figure or associated text is understood to mean “and/or” unless otherwise indicated. The term “set” is defined as a non-empty finite organization of elements that

mathematically exhibits a cardinality of at least one (e.g. a set as defined herein can correspond to a unit, singlet, or single-element set, or a multiple-element set), in accordance with known mathematical definitions. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range. The terms "first", "second", etc. are used merely as labels or identifiers and are not intended to impose numerical requirements on their associated terms.

In representative or exemplary embodiments of the present disclosure, as shown in FIG. 2A and FIG. 2B, there is a directed energy deposition (DED) apparatus 100 for additively manufacturing a part 200. It will be appreciated that additive manufacturing refers generally to manufacturing processes wherein successive layers of material are provided on each other to build the part 200 up layer-by-layer.

The apparatus 100 includes a build platform 110 for fabricating the part 200 thereon. The apparatus 100 includes a supply chamber 120 having a nozzle 122 for depositing a material onto the build platform 110. The nozzle 122 is preferably mounted on a multi-axis robotic arm so that the material can be deposited onto the build platform 110 from various angles. The material is preferably in the form of a metallic wire and/or metallic powder.

The apparatus 100 includes an energy source 130 for melting the material. For example, the energy source 130 is a laser source configured for emitting a laser to melt the material. Alternatively, the energy source 130 may be configured for emitting a plasma arc or electron beam to melt the material. The apparatus 100 includes a thermal device 140 for measuring temperature of the part 200. For example, the thermal device 140 includes a thermal camera, such as an infrared thermal imaging camera.

With reference to FIG. 3, embodiments of the present disclosure also describe a method 300 for additively manufacturing a part 200 using an apparatus, such as the directed energy deposition apparatus 100. Embodiments of the present disclosure also describe a product comprising the part 200 fabricated by the method 300.

The method 300 includes a step 302 of depositing a material onto the build platform 110 of the apparatus 100 to form a current layer 210_n of the part 200. The method 300 includes a step 304 of melting the material in the current layer 210_n . The method 300 includes a step 306 of cooling the part 200 comprising the current layer 210_n to thereby cure the melted material. The method 300 includes a step 308 of measuring a temperature of the part 200 during said cooling. The method 300 includes a step 310 of, after the part 200 has cooled to a predefined temperature, depositing the material onto the current layer 210_n to form a next layer 210_{n+1} of the part 200. The method 300 includes a step 312 repeating steps 302,304,306,308,310 to thereby fabricate on the build platform 110 the part 200 comprising a plurality of successive layers 210.

To facilitate performance of the method 300, the apparatus 100 includes a controller 150 communicatively connected to the supply chamber 120, energy source 130, and thermal device 140. The controller 150 includes a processor configured to execute instructions, codes, computer programs, and/or scripts, and includes suitable logic, circuitry, and/or interfaces to execute various operations or steps. Some non-limiting examples of the processor include an application-specific integrated circuit (ASIC) processor, a reduced instruction set computing (RISC) processor, a complex instruction set computing (CISC) processor, a field-programmable gate array (FPGA), and the like. While instructions may be executed by a processor, the instructions may be executed simultaneously, serially, or otherwise executed by one or multiple processors (e.g. in a multi-core configuration).

More specifically, the controller 150 is configured for performing the following steps (a) to (f) to fabricate the part 200 layer-by-layer, such that the part 200 comprises multiple layers 210 formed successively on top of each other.

- (a) depositing the material from the supply chamber 120 onto the build platform 110 to form a current layer 210_n of the part 200;
- (b) activating the energy source 130 to melt the material in the current layer 210_n ;
- (c) deactivating the energy source 130 to cool the part 200 comprising the current layer 210_n to thereby cure the melted material;

(d) measuring, using the thermal device 140, a temperature of the part 200 during said cooling;

(e) after the part 200 has cooled to a predefined temperature, depositing the material from the supply chamber 120 onto the current layer 210_n to form a next layer 210_{n+1} of the part 200; and

(f) repeating steps (a) to (e) to thereby fabricate on the build platform 110 the part 200 comprising the plurality of successive layers 210.

It will be appreciated that the current layer 210_n and the next layer 210_{n+1} respectively refer to any arbitrary n th layer 210_n and its successive $(n+1)$ th layer 210_{n+1} that is layered directly on top of the n th layer 210_n , where n is a positive integer. For example, FIG. 2B shows the 1st layer 210_1 at the bottom of the part 200, the 25th layer 210_{25} around the middle of the part 200, and the 50th layer 210_{50} near the top of the part 200.

FIG. 4 shows a process 400 as an exemplary embodiment of the method 300 to fabricate the part 200. In a step 402, the nozzle 122 starts depositing the material from the supply chamber 120 to form the current n th layer 210_n of the part 200. In a step 404, the laser from the energy source 130 melts the material in the current n th layer 210_n . In a step 406, the current n th layer 210_n has completed deposition and melting, and undergoes a cooling or resting period. A step 408 determines whether the current n th layer 210_n is the final layer of the part 200 and whether fabrication of the part 200 is completed. If yes, the fabrication stops in a step 410. If not, a step 412 measures the temperature of the part 200 comprising the current n th layer 210_n using the thermal device 140 during the cooling period, and determines whether the measured temperature of the part 200 has reached the predefined temperature. For example, the predefined temperature may be 400°C, 500°C, 600°C, or 700°C. If the part 200 comprising the current n th layer 210_n has not cooled to the predefined temperature yet, the cooling period continues in a step 414. If the part 200 comprising the current n th layer 210_n has cooled to the predefined temperature, the process 400 returns to the step 402 for forming the next $(n+1)$ th layer 210_{n+1} of the part 200. For example, the current n th layer 210_n may be the first layer 210_1 and the next $(n+1)$ th layer 210_{n+1} may be the second layer 210_2 , or the current n th layer 210_n may be the 50th layer

210₅₀ and the next $(n+1)$ th layer 210 _{$n+1$} may be the 51st layer 210₅₁. The process 400 repeats until the current n th layer 210 _{n} is the final layer and the part 200 has completed fabrication.

- 5 The predefined temperature may optionally be dependent on the material. For example, the predefined temperature should be below the phase transformation temperature for the material, such as 726°C for steel. The predefined temperature may optionally be adjustable based on an ordinal number of the respective layer 210 being formed. The ordinal number refers to order or position of the layers 210 that are
- 10 successfully formed in the part 200. For example, the bottom set of layers 210 may have a first predefined temperature, the middle set of layers 210 may have a different second predefined temperature, and the top set of layers 210 may have a different third predefined temperature. The second predefined temperature may be lower than first predefined temperature, and the third predefined temperature may be lower than
- 15 the second predefined temperature. For example, referring to FIG. 2B, the predefined temperature for the 1st layer 210₁ to the 25th layer 210₂₅ may be 500°C, and the predefined temperature for the 26th layer 210₂₆ to the 50th layer 210₅₀ may be 400°C. It will be appreciated that the predefined temperature may be more finely defined for each layer 210, such that each layer 210 is associated with a respective predefined
- 20 temperature and the predefined temperatures may gradually decrease as the layers 210 are being formed.

Accordingly, the cooling time for the part 200 for each layer 210 that is being formed is variable and depends on how long the part 200 comprising the respective layer 210

25 takes to cool to the predefined temperature. The method 300 implements a temperature-based cooling time feedback loop that generates a time delay for each respective layer 210 to thereby vary the cooling time of the part 200 as each respective layer 210 is being formed. Based on the temperature of the part 200 comprising the n th layer 210 _{n} measured by the thermal device 140, the controller 150 would wait for

30 the part 200 comprising the n th layer 210 _{n} to cool down to the predefined temperature before the forming the next $(n+1)$ th layer 210 _{$n+1$} on the n th layer 210 _{n} . By allowing the part 200 comprising each respective layer 210 to cool down before printing the next layer 210, there is lower risk of the part 200 overheating and melting down. Further,

the increase in overall manufacturing time is minimized as the cooling time for each layer 210 being formed varies and there is no fixed cooling time that can adversely affect parts 200 with various geometries or sizes.

- 5 The apparatus 100 and method 300 can be used to additively manufacture various parts 200 using DED, including thin parts like thin walls. Thin walls are sometimes required in situations such as the manufacturing of small features on large parts, such as turbine blades or hollow pipes for manifolds. Additionally, the thin wall can be used as a means for repair in tools and moulds. For example, if a mould has some area that
- 10 has worn out over time, it can be reused by machining down that surface, printing a new material on the surface using DED, and then machining down to achieve the final finishing, thus extending the mould's life. Suitable materials for DED and moulding applications include high thermal conductivity stainless steel which also has high corrosion resistance against molten plastic. One example of such materials is Corrax
- 15 which has the following element composition.

Element	C	Si	Mn	Cr	Mo	Ni	Al	Fe
Amount	0.03%	0.3%	0.3%	12%	1.4%	9.2%	1.6%	Balance

The apparatus 100 and method 300 were used in an experiment to fabricate seven sample parts 200 with the Corrax material. Each sample part 200 is a thin wall and

20 was to be fabricated to a desired height of 30 mm.

1. SNC – No cooling time between each layer 210
2. S10 – Fixed cooling time of 10 seconds between each layer 210
3. S25 – Fixed cooling time of 25 seconds between each layer 210
4. S400 – Variable cooling time between each layer 210 until the part 200 reaches

25 a predefined temperature of 400°C.

5. S500 – Variable cooling time between each layer 210 until the part 200 reaches a predefined temperature of 500°C.
6. S600 – Variable cooling time between each layer 210 until the part 200 reaches a predefined temperature of 600°C.
- 30 7. S700 – Variable cooling time between each layer 210 until the part 200 reaches a predefined temperature of 700°C.

The predefined temperatures for the various sample parts 200 are below the phase transformation temperature for steel which is about 726°C. The thermal device 140 is a thermal camera with a maximum threshold temperature of 926°C so that it can
5 measure the instantaneous temperatures of the sample parts 200.

The manufacturing time for each sample parts 200 was recorded from the start of fabrication until the sample part 200 is completed and has cooled down to 250°C, as measured by the thermal device 140. The sample parts SNC, S10, and S25 had fixed
10 cooling times of 0 seconds, 10 seconds, and 25 seconds, respectively, and are used as benchmarks for the other sample parts S400, S500, S600, and S700 with variable cooling times. The manufacturing times for all seven sample parts 200 are shown in FIG. 5. The sample part SNC has the shortest manufacturing time of 858 seconds and the sample part S25 has the longest manufacturing time of 1997 seconds. The other
15 sample parts S400, S500, S600, and S700 have 10% to 40% shorter manufacturing times compared to the sample part S25.

FIG. 6A and FIG. 6B show photos of all seven fabricated sample parts 200. As shown in FIG. 6A, the sample part SNC has severe oxidation which resulted in poor geometry
20 and an over-melted exterior. The shape and oxidation made the sample part SNC difficult to post-process. As a result, the overall dimensions of the sample part SNC cannot be accurately measured due to its rough surface on all sides. The height of the sample part SNC was approximately 20 mm, which is lower than the desired 30 mm height because of the oxidation and meltdown. Moreover, based on the location where
25 oxidation begins, the sample part SNC suggests that it starts to overheat after about ten layers 210. As there is no cooling time between the layers 210, the sample part SNC just continues to heat up, and all the trapped heat results in a higher overall temperature of the sample part SNC, leading to a larger melt pool formation that oxidizes when exposed to air.

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As shown in FIG. 6B, the sample part S25 has the best overall surface finish, but it also has the longest manufacturing time. The sample parts S400, S500, S600, and S700 had variable cooling times and shorter manufacturing times than the sample part

S25, but achieved relatively good surface finishes that are comparable to the sample part S25. The photos of the various sample parts 200 in FIG. 6B show that the level of oxidization, which is indicated by surface darkening, correlates to the manufacturing time. Specifically, sample parts 200 that require a longer manufacturing time have less oxidation.

The oxidization level can be further explained by looking at the temperature profiles of the sample part 200 exposed to the environment. The temperature profiles were measured by the thermal device 140 close to the completion of the fabrication. FIG. 7A and FIG. 7B show the temperature profiles of the sample parts S10 and S25, respectively. The hottest spot of the sample parts S10 and S25 are at about 925°C and 500°C, respectively, when they are close to completion. The hottest spot of the sample part S25 is cooler than the hottest spot of the sample part S10 due to the longer cooling time between layers 210, which resulted in the sample part S25 having the best surface finish.

While shorter manufacturing times can lead to faster time-to-market parts 200, the quicker production is at the expense of poorer quality parts 200, as seen in the sample part SNC which has the shortest manufacturing time but the worst oxidation and geometry. A long cooling time is also not ideal as this would increase the time to market, resulting in lower efficiency and production output. The results of the sample parts 200 with fixed and variable cooling times demonstrate that the variable cooling time between the layers 210 is able to strike a balance between the increase in manufacturing time of the part 200 and the reduction in oxidation of the part 200, which would improve part quality.

The sample parts 200 were tested for their tensile strength to evaluate the part quality. The surfaces of the sample parts 200 were first ground to remove the oxidized layers and expose the metallic material. The sample part SNC was omitted in this tensile test due to the severe surface oxidation which made it difficult to grind down. The sample part SNC was also underbuilt and there was not enough material to extract any useable specimens. The remaining sample parts 200 were then cut using wire electrical discharge machining (EDM) into various tensile specimens or coupons 220

for tensile testing. No further polishing was done for the tensile coupons 220. For each sample part 200, its tensile coupons 220 were arranged in both vertical and horizontal directions, as shown in FIG. 8A.

5 FIG. 8B show the results of the tensile tests for the respective sample parts 200. The sample part S10 has very similar tensile strength in vertical and horizontal directions at approximately 1009 MPa, suggesting that the microstructure is highly isotropic in nature, which typically may not occur for additively manufactured parts. The sample part S25 depicts a very anisotropic microstructure, with a tensile strength of 1049 MPa
10 in the vertical direction and a tensile strength of 987 MPa in the horizontal direction. The longer cooling time of the sample part S25 has apparently resulted in a more prominent directional cooling, resulting in the anisotropic properties.

The average tensile strengths of the sample parts S400, S500, S600, and S700 with
15 variable cooling times are better than the sample parts S10 and S25 with fixed cooling times. A possible hypothesis for this improvement is due to a more controlled rate of cooling, thus resulting in a more consistent microstructure formation. As the predefined temperature increases, the overall tensile strength of the sample parts 200 decreases, which suggests that larger crystals could be forming within the microstructures.
20 Additionally, all the samples parts 200 except S10 have higher tensile strength in the vertical direction than in the horizontal direction, but the results may differ if thicker walls were fabricated.

The elongation of the sample parts 200 was also measured. The elongation
25 differences are merely about 1.2% to 1.55% across all sample parts 200 in the vertical direction, and merely about 1% in the horizontal direction.

FIG. 9 shows the electron backscatter diffraction (EBSD) scans of the microstructure of the sample parts 200. The EBSD scans show that the sample parts 200 exhibit body
30 centred cubic (BCC) ferritic phase microstructure, which can be aged-hardened and which suggests possible martensitic and ferrite formation.

The thin walls of the sample parts 200 tend to be more anisotropic due to prominent directional cooling in the built-up axis. The anisotropy of the sample parts 200 can be determined by the multiple-of-uniform-density (MUD) value. Typically referred to as the 'texture strength', the MUD value describes the relative strength of a particular orientation in the sample part 200 with respect to other orientations.

FIG. 10A to FIG. 10F show the pole figures of the sample parts 200 obtained from the EBSD data, together with their respective MUD values. It can be seen that the sample parts 200 with shorter manufacturing times have lower MUD values. For example, the sample parts S10 and S25 have MUD values of 5.58 and 11.03, respectively, corresponding to their manufacturing time of about 1100 seconds and about 2000 seconds, respectively. This difference in MUD values suggests that the sample part S25 is more anisotropic than the sample part S10, which agrees with the tensile strength results in FIG. 8B. Likewise, the MUD values of the sample parts S400, S500, S600, and S700 are 9.92, 10.47, 7.94, and 7.87, respectively, generally agreeing with the correlation between the shorter manufacturing time and lower MUD value.

FIG. 11 shows the EBSD images in the IPF (inverse pole figure) X direction of the samples parts 200. It can be seen that all the sample parts 200 except S10 generally have their crystals growing vertically upwards from the bottom. This observation explains the consistent pattern of the tensile strength results in FIG. 8B, where the tensile strength in the vertical direction is higher than in the horizontal direction.

The results show that the properties of the sample parts 200 are affected by their cooling times. By increasing the cooling time, it is possible to manipulate the microstructure and modify the tensile strength of the sample part 200. However, the drawback comes with an increase in the overall manufacturing time and greater anisotropic properties, which may not be desired in certain applications. On the other hand, having a shorter cooling time can lead to a much more equal strength in both vertical and horizontal directions, but at the expense of a higher oxidization rate.

By using the temperature-based feedback loop in the apparatus 100 and method 300 to vary the cooling times for different parts 200, it is possible to achieve a gradient-like

material in the part 200 while striking a balance between manufacturing time and part quality. The apparatus 100 and method 300 can be used for DED manufacturing of parts 200 with changing cross-sectional areas from the bottom to the top of the part 200. These parts 200 may include, but are not limited to, ship propellers or tubings
5 that vary in dimensions and geometries. Further, the apparatus 100 and method 300 can be used to fabricate functionally graded material (FGM) parts 200 where the chemical composition and microstructure vary through the part 200. This results in varying mechanical properties, such as hardness and density, for environments that require a variance in properties.

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In the foregoing detailed description, embodiments of the present disclosure in relation to a directed energy deposition apparatus and method are described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the
15 present disclosure, but merely to illustrate non-limiting examples of the present disclosure. The present disclosure serves to address at least one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or
20 modifications can be made to the disclosed embodiments without departing from the scope of the present disclosure. Therefore, the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

Claims

1. A method for additively manufacturing a part using a directed energy deposition apparatus, the method comprising steps:
 - 5 (a) depositing a material onto a build platform of the directed energy deposition apparatus to form a current layer of the part;
 - (b) melting the material in the current layer;
 - (c) cooling the part comprising the current layer to thereby cure the melted material;
 - 10 (d) measuring a temperature of the part during said cooling;
 - (e) after the part has cooled to a predefined temperature, depositing the material onto the current layer to form a next layer of the part; and
 - (f) repeating steps (a) to (e) to thereby fabricate on the build platform the part comprising a plurality of successive layers.
- 15 2. The method according to claim 1, wherein the temperature of the part is measured using a thermal camera.
3. The method according to claim 1 or 2, wherein the predefined temperature is
20 dependent on the material.
4. The method according to any one of claims 1 to 3, wherein the predefined temperature is adjustable based on an ordinal number of the respective layer being formed.
- 25 5. A product comprising the part fabricated by the method according to any one of claims 1 to 4.
6. A directed energy deposition apparatus for additively manufacturing a part, the
30 apparatus comprising:
 - a build platform for fabricating the part thereon;
 - a supply chamber comprising a nozzle for depositing a material onto the build platform;

a heat source for melting the material;
a thermal device for measuring temperature of the part;
a controller configured for:

- 5 (a) depositing the material from the supply chamber onto the build platform to form a current layer of the part;
(b) activating the energy source to melt the material in the current layer;
(c) deactivating the energy source to cool the part comprising the current layer to thereby cure the melted material;
10 (d) measuring, using the thermal device, a temperature of the part during said cooling;
(e) after the part has cooled to a predefined temperature, depositing the material from the supply chamber onto the current layer to form a next layer of the part; and
15 (f) repeating steps (a) to (e) to thereby fabricate on the build platform the part comprising a plurality of successive layers.

7. The apparatus according to claim 6, wherein the thermal device comprises a thermal camera.
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8. The apparatus according to claim 6 or 7, wherein the predefined temperature is dependent on the material.
9. The apparatus according to any one of claims 6 to 8, wherein the predefined
25 temperature is adjustable based on an ordinal number of the respective layer being formed.

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