

WIRE EMBEDDING METHOD FOR 3D PRINTING

The present application claims priority to the Singapore patent application no. 10202105811Y, the entire disclosure of which is incorporated herein by reference.

TECHNICAL FIELD

[0001] The present disclosure relates to the field of additive manufacturing, and more particularly to a wire embedding method for 3D printing.

BACKGROUND

[0002] It has been a challenge to manufacture 3D-printed articles in which the structural components and the electronic circuits are simultaneously formed, especially in the case of circuits with high-current loading requirements. While direct embedding of conductive wires has been attempted experimentally, wide-spread adoption by the industry in actual manufacturing is unlikely to happen unless the wiring can be formed with a precision and quality comparable to the conventionally fabricated printed circuit board.

SUMMARY

[0003] In one aspect, the present application discloses a method of embedding a wire in a substrate in a 3D-printing process, the method comprising: extruding the wire in an extrusion direction via a nozzle towards a substrate surface of the substrate; concurrently with the extruding of the wire, displacing the nozzle in a pull-away direction away from the substrate surface to form an exposed length of the wire between the substrate surface and the nozzle, wherein the exposed length of the wire is formed without the exposed length of the wire contacting the substrate surface; providing a cooling phase; and forming a surface embedded length of the wire using the exposed length of the wire in a surface embedding phase.

[0004] The method may further comprise displacing the nozzle to a next nozzle retracting point and towards the substrate surface, such that the exposed length of the wire is angularly displaced until the exposed length of the wire comes into contact with the substrate surface, and such that the exposed length of wire forms the surface embedded length of the wire.

The method may further comprise upon the nozzle being proximal to the substrate surface at the next nozzle retracting point, displacing the nozzle in the pull-away direction.

[0005] Optionally, the surface embedded length of the wire may be joined to the substrate such that the surface embedded length of the wire is substantially disposed in one embedment layer of the substrate. Optionally, the surface embedded length of the wire may be joined to the substrate such that the surface embedded length of the wire is substantially parallel to the substrate surface. Optionally, the surface embedded length of the wire may comprise at least one partially surface embedded part. Optionally, the surface embedded length of the wire may comprise at least one fully surface embedded part.

[0006] The exposed length of the wire may be exposed to air on all sides immediately before the forming of the surface embedded length of the wire. Each of the wire and the substrate may undergo unaided cooling in the cooling phase. The method further comprising providing a pre-heating effect on the wire.

[0007] The method may be configured such that the cooling phase follows the surface embedding phase. The cooling phase may comprise a dwelling cooling phase, and in which the nozzle is spaced apart from the substrate throughout the dwelling cooling phase.

[0008] The method may further comprise changing a direction of travel of the nozzle to form a turning point between a first section of a printing path and a second section of the printing path, wherein the first section of the printing path and the second section of the printing path are contiguous and non-parallel to one another. The method may be configured such that no more than two cooling phases immediately following the turning point comprises a dwelling cooling phase.

[0009] The method may further comprise at least one non-dwell cooling phase, wherein the nozzle is not spaced apart from the substrate at a substantially constant nozzle-substrate spacing in the non-dwell cooling phase.

[0010] The method may further comprise extruding the wire at a non-zero extrusion speed if a nozzle-substrate spacing is concurrently increasing; and not extruding the wire if the nozzle-substrate spacing is not increasing, wherein the nozzle-substrate spacing corresponds

to a spacing between a tip of the nozzle and the substrate surface.

[0011] The method may further comprise forming an initial anchor by concurrently extruding a terminal end of the wire into the substrate and displacing the nozzle in the pull-away direction away from the substrate, wherein the extrusion direction is an angle between 45 degrees and 90 degrees relative to the substrate surface.

BRIEF DESCRIPTION OF DRAWINGS

[0012] Fig. 1 is a schematic block diagram of a system for use with a method of wire embedding according to one embodiment of the present disclosure.

[0013] Fig. 2A is a partial cross-section view of a print head.

[0014] Fig. 2B illustrates a printing path on a substrate as viewed from the print head of Fig. 2A.

[0015] Fig. 3 is a schematic flow chart of a method of embedding a wire according to an embodiment of the present disclosure.

[0016] Fig. 4 shows plots of nozzle displacement and extrusion speed according to one example of the method of Fig. 3.

[0017] Fig. 5 shows plots of nozzle displacement and extrusion speed according to another example of the method of Fig. 3.

[0018] Figs. 6A to 6C illustrate one method of forming an initial anchor.

[0019] Figs. 7A to 7C illustrate one method of surface embedding according to embodiments of the present disclosure.

[0020] Figs. 8A to 8C illustrate one example of the method with an angled initial anchor.

[0021] Figs. 9A to 9G are schematic cross-sectional views of a surface embedded wire according to embodiments of the present disclosure.

[0022] Figs. 10A to 10C are images of a wire embedded in a straight printing path using a

method of Fig. 3.

[0023] Figs. 11A and 11B are images of a wire embedded with a corner using a method of Fig. 3.

[0024] Fig. 12 is an image of wires in a substrate deposited using a conventional method.

DETAILED DESCRIPTION

[0025] Reference throughout this specification to “one embodiment”, “another embodiment” or “an embodiment” (or the like) means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” or the like in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided to give a thorough understanding of embodiments. One skilled in the relevant art will recognize, that the various embodiments be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, some or all known structures, materials, or operations may not be shown or described in detail to avoid obfuscation.

[0026] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. As used herein, the singular ‘a’ and ‘an’ may be construed as including the plural “one or more” unless apparent from the context to be otherwise.

[0027] Terms such as “first” and “second” are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context. The terms “about” and “approximately” as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms “generally” and “substantially” are to be understood in a similar manner, unless otherwise specified.

[0028] Various diameters or gauges of wires may be embedded in a substrate using a method and apparatus of the present embodiment. Examples of wires that may be used include but are not limited to conductive wires such as copper wires. Examples of materials which may form the substrate include but are not limited to electrical insulating materials such as polylactic acid (PLA). The substrate may be separately formed from additive or substrative manufacturing methods.

[0029] Fig. 1 is a schematic diagram of a 3D printing system 100 configured to perform a method 500 of embedding a wire 200 (also referred to as a wire embedding method) in a substrate 300, according to one embodiment of the present disclosure. The system 100 may include one or more print heads 110 configured to extrude material on a printing platform 102 or on previously printed material (also referred to as the substrate 300 disposed on the printing platform 102. The system 100 may provide for the use of more than one nozzle 120, e.g., a first nozzle to extrude a metal wire and a second nozzle to extrude a filament of a substrate material. In some examples, the system 100 may include a third nozzle to extrude a filament of a supporting material. In some examples, one nozzle 120 may be configured to concurrently extrude more than one wire 200 or filament through respective nozzle holes 122. To aid understanding and not to be limiting, the present disclosure will describe the system of Fig. 1 with reference to one print head 110, in which the print head 110 includes a nozzle 120, a heating device 130, and an extruder 140. The extruder 140, the heating device 130, and the nozzle 120 may be coupled such that a wire 200 provided by the extruder 140 can be heated before the wire 200 is extruded from a nozzle tip 124 of the nozzle 122.

[0030] A controller 160 is in operable communication with the extruder 140 to control a wire extrusion speed independently of a nozzle speed. The nozzle speed refers to the speed at which the nozzle 120 traverses the printing path 400, powered by the actuating system 150. The actuating system 150 is also configured to displace the nozzle 120 away from the substrate in a pull-away direction 125 that is substantially opposite an extrusion direction 123. The wire extrusion speed refers to the speed at which the wire 200 is extended in the extrusion direction 123. The extruder 140 may be configured to receive a continuous length of wire 200 from a suitable source, such as a spool of wire 142. The extruder 140 may be configured with a motor and wire/filament gripping elements such that both the amount of the wire 200 that can be extruded, and such that the extrusion speed may be controllable by

the controller 160. The extruder 140 is configured to control an exposed length 220 of the wire 200. The exposed length 220 refers to the length of the wire 200 that is extended and exposed beyond the nozzle tip 124. The extruder 140 is optionally further configured to stop further extrusion of the wire 200 (extrusion speed set to about zero) or to prevent the exposed length 220 of the wire 200 from being easily lengthened by an external force (i.e., a force external to the extruder) pulling on the extruded wire 200. In some embodiments, the system 100 includes a wire cutting mechanism 144 operable by the controller 160. The controller 160 may be further configured to operate a wire cutting mechanism 144 to cut the wire 200, e.g., in response to completing a wire embedding process. In other embodiments, the wire 200 may be cut manually.

[0031] In some embodiments, the heating device 130 is part of the extruder 140 such that the heating device 110 and the extruder 140 is collectively referred to as a hot end. In some other embodiments, the term hot end refers to the heating device 130 which is spaced apart from the driving mechanism of the extruder 140. According to embodiments of the present disclosure, in operation, the heating device 130 may be powered on at the beginning of the printing process, and the heating device 130 may be set to a predefined temperature throughout the entire process of embedding a wire 200. In some examples, the heating device 130 is not repeatedly powered on and off throughout a process of embedding a length of the wire 200. In some examples, the heating device 130 is preferably set to one predefined temperature, and the predefined temperature is maintained relatively constant throughout the process of embedding a length of the wire 200. Alternatively, the heating device 130 may be set to one or more predefined temperature selected from a working temperature range. The working temperature range is dependent on the materials selection of the wire 200 and the substrate 300. The system 100 and the method 500 proposed herein have been found to perform well with copper wires. In an example where the wire 200 is a copper wire and the substrate 300 includes polylactic acid (PLA), the predefined temperature may be selected from a working temperature range from about 200 degrees Celsius to about 260 °C (degrees Celsius). In another example where the wire 200 is essentially formed of copper and the substrate 300 is mostly formed of PLA, the heating device 130 is set to the predefined temperature of 240 °C.

[0032] Preferably, the present method 500 is conducted without directing a flow of air or

other coolants at the print head 110. As illustrated in Fig. 1, the system 100 is preferably configured without a fan operating to cool the print head 110, the wire 200, and/or the substrate 300. Preferably, the wire 200 is not forcibly cooled by air or coolant throughout its length, including from the length of the wire from the nozzle tip 120 to the spool of wire 142. In other words, heat is allowed to transfer along the wire 200 towards the spool of wire 142. The method 500 may include providing a pre-heating effect on the wire 200, before the wire passes through the heating device 130, such that the wire 200 is characterized by gradual temperature changes along the length of the wire. The part of the wire directly subjected to the heating device 130 may have the highest temperature, and the temperature of the wire may gradually decrease with increasing distance from the heating device 130.

[0033] The nozzle 120 may be an interchangeable part that can be coupled to the hot end or to the rest of the print head 110. More specifically, the nozzle tip 124 defines a nozzle hole 122 for the wire 200 to extend out beyond the nozzle tip 124. The nozzle hole 122 is characterized by a nozzle diameter. Embodiments of the present disclosure enables a selection of nozzle sizes (diameter of the nozzle hole) that may be significantly larger than the wire diameter or gauge. For example, a nozzle 120 of nozzle size 0.6 mm or 0.8 mm may be selected for use with wires of various wire diameters ranging from 0.2 mm to 0.6 mm. For example, a nozzle 120 of nozzle size 0.6 mm may be selected even if the wire 200 has a wire diameter of 0.4 mm. The nozzle size of 0.8 mm may be selected for use with a wire 200 having a wire diameter of 0.6 mm. Optionally, the wire diameter may be in a range of about 0.2 mm smaller than the diameter of the nozzle hole 122. According to embodiments of the present disclosure, it is not necessary for the nozzle hole diameter to be as small as possible in order to produce printed parts of good quality.

[0034] Fig. 2A schematically illustrates the nozzle 120 spaced apart from the substrate surface 302 by a nozzle-substrate spacing 430. For the sake of brevity and ease of reference, the term “nozzle-substrate spacing” 430 is used in the present disclosure in referring to a spacing (a shortest distance or a separation) between the nozzle tip 124 and the substrate surface 302. That is, the nozzle-substrate spacing corresponds to a spacing between a tip of the nozzle 120 and the substrate surface 302. The nozzle-substrate spacing 430 may be measured along the pull-away direction 125 or with respect to the Z-axis. In the present document, the term “substrate surface” 302 refers to a local region of a surface facing the

nozzle 120, in which the surface is one intended to receive material extruded from the nozzle 120. An X-Y plane may be defined by the substrate or more specifically by a surface 302 of the substrate 300. A normal of the X-Y plane may define a Z-axis that is substantially parallel to the X-Y direction or a built direction. In some examples, a first axis 121 of the nozzle 120 may be substantially parallel with the Z-axis. In other examples, the first axis 121 of the nozzle 120 may be oriented at a non-zero angle relative to the Z-axis. In actual application, the substrate surface 302 may or may not be a planar surface parallel to the printing platform 102. The substrate surface 302 is shown in the appended figures as a substantially flat surface simply for the purpose of illustration and is not intended to be limiting; references to the X-Y plane, X-axis, Y-axis, or Z-axis are to be understood in the same manner. The present method 500 may be used with 3D printers using any coordinate system or reference system. Merely to aid understanding and not to be limiting, the description herein is based on a gantry-type 3D printer configured to control relative motion between the printhead and the substrate. It will also be understood that the present method 500 may be used with various types of 3D printers, including but not limited to cartesian 3D printers, delta 3D printers, polar 3D printers, robotic arm 3D printers, gantry-type 3D printers, etc.

[0035] As schematically illustrated in Fig. 2A, according to embodiment of the present disclosure, a length of wire 200 can be surfaced embedded 250 at the substrate surface 302 of a substrate 300. The surface embedded length 250 of the wire 200 is joined to the substrate 300 with the wire 200 disposed substantially parallel to the substrate surface 302. Where the substrate 300 is formed of layers 303 (e.g., via 3D printing), the surface embedded length of the wire 200 is joined or fixed to the substrate such that the surface embedded 250 length of the wire 200 is substantially disposed in one embedment layer 313 of the substrate 300. The beginning of the wire 200 is used to form an initial anchor 241 at an initial anchoring location 441. One or more notches 242 may be formed intermittently on the unbroken or continuous wire 200 as it is surface embedded along the printing path 400. The method 500 may include forming an alternating series of notches 242 and surface embedded lengths 250 of the same continuous length of the wire 200. A surface embedded length 250 of the wire may be formed between two notches 242. A notch 243 may be formed between two surface embedded 250 lengths of the wire 200.

[0036] Fig. 2B schematically illustrates a non-limiting example of a printing path 400 as viewed from the nozzle 120. The one or more print heads 110 may be supported by an actuating system 150 controllable by a controller 160, such that the nozzle 120 may traverse over the printing path 400 over the printing platform 102 or over previously printed material 300. The controller 160 may be configured to cause the nozzle 120 to be displaced in a selected nozzle displacement direction 127 at a selected nozzle speed. Alternatively, the controller 160 may be configured to cause the nozzle 120 to be stationary at a selected position, i.e., the nozzle 120 may be configured to dwell or pause for a dwelling time, the dwelling time being between two time periods of nozzle displacement.

[0037] The present method 500 is able to embed a contiguous length of wire 200 even when there is a change in the orientation of the printing path 400. The method 500 may include changing a direction of travel of the nozzle 120 at a turning point 443 in the printing path 400. As illustrated in the non-limiting example of Fig. 2B, the printing path 400 may include a first section in a first orientation and a second section in a second orientation, in which the second orientation is different from the first orientation. The first section of the printing path 400 and the second section of the printing path 400 are contiguous and join one another at the turning point 443 at an angle, i.e., they are not parallel (non-parallel) to one another. For the sake of convenience and not to be limiting, the first orientation in this example is defined to be parallel to an X-axis, and the second orientation is defined to be parallel to a Y-axis or orthogonal to the first orientation. Similarly, for the sake of illustration and not to be limiting, the first section of the printing path 400 is defined to be three units in length and the second section of the printing path 400 is defined to be four units in length.

[0038] Fig. 3 is a schematic flowchart illustrating one aspect of a method 500 of embedding a wire 200 according to one embodiment of the present disclosure. The method 500 includes concurrently extruding the wire 200 into the substrate 300 (520) and retracting the nozzle 120 away from the substrate surface 302 in a pull-away direction 125 (530), in which the pull-away direction 125 is substantially opposite to the wire extrusion direction 123. For ease of reference, a “nozzle retracting point” refers to an instance, location, and/or phase at which the nozzle 120 is moved away from the substrate surface 302.

[0039] If the wire embedding process is completed, the wire 200 may be cut (540, 550).

Otherwise, in some embodiments, the method 500 optionally includes configuring the nozzle 120 to dwell spaced apart from the most recently formed surface embedded part of the wire (540, 560). This dwelling time contributes to an exposure time (580) during which the exposed length 220 of the wire 200 may cool down relatively gradually, i.e., preferably without air or other coolant being blown or forced to flow past the wire 200. After the dwelling time, the nozzle 120 is laterally displaced or displaced with a lateral displacement component (570). This displacement (570) may further contribute to the exposure time (580) during which the exposed length 220 of the wire 200 may cool down relatively gradually, i.e., preferably without air or other coolant being blown or forced to flow past the wire 200.

[0040] In alternative embodiments, the method 500 may include laterally displacing the nozzle 120 without first providing a dwelling time (540, 570). The nozzle 120 is displaced 127 laterally relative to the pull-away direction 125 and axially opposite the pull-away direction 125. This displacement (570) provides the exposure time (580) during which the exposed length 220 of the wire 200 may cool down relatively gradually, i.e., preferably without air or other coolant being blown or forced to flow past the wire 200.

[0041] Upon reaching a proximal position near the next nozzle retracting point 442, the nozzle 120 may be configured to immediately displace away from the substrate surface 302 in the pull-away direction 125, without dwelling in proximity of the next nozzle retracting point 442 (510). That is, upon the nozzle 120 being proximal to the substrate surface 302 at the next nozzle retracting point 442/440, the nozzle may be instantaneously displaced in the pull-away direction 125 such that the nozzle 120 does not dwell proximal to the substrate surface 302. Concurrent with the pulling away of the nozzle 120 (530), the wire 200 is extruded in the extrusion direction 123 (530). A notch 242 may be observed at/near the nozzle retracting point 442.

[0042] If a change in an orientation of the printing path 400 is desired, at least one nozzle retracting point 440 is provided near or at the turning point (or corner) 443 in the printing path. To terminate the process 500 of embedding the wire 200, the wire 200 may be cut.

[0043] Fig. 4 schematically illustrates plots of the nozzle displacement 127 over time. The nozzle displacement 127 is shown in three components, namely, the Z-component plot 712, the X-component plot 714, and the Y-component plot 716. Fig. 4 also shows the extrusion

speed 718 of the wire 200 over time. The method 500 may be described as beginning with an initial anchoring phase 701. Fig. 4 also shows a cooling phase 706 immediately following the initial anchoring phase 701.

[0044] The present method 500 of embedding a wire 200 may be described in terms of an alternating series of a cooling phase 706 and a surface embedding phase 704. A nozzle retracting phase 703 may occur concurrently with or at least partially overlap the cooling phase 706. The nozzle retracting phase 702 may be immediately followed by a dwelling phase 702. The wire 200 may undergo relatively gradual and unaided cooling as a result of the exposed length 220 being spaced apart or angularly displaced from the substrate 300. The Z-component plot 712 shows that the nozzle 120 is spaced apart from the substrate surface in the course of the cooling phase 706. In other words, for at least a part of the cooling phase 706, the nozzle 120 is spaced apart from the most recently disposed surface embedded 250 length of the wire 200.

[0045] Fig. 4 also shows an example in which there is a substantially instantaneous change in the nozzle-substrate spacing 430/712 at a transition 722 from the surface embedding phase 704 to the cooling phase 706. In other words, in a preferred embodiment, the nozzle 120 does not dwell when the nozzle 120 is proximal to the substrate surface 302 (Z-component is small or about zero). In other embodiments, the nozzle 120 may be configured to dwell proximal to the substrate surface 302 if the cooling phase 706 is extended over a longer period of time.

[0046] Fig. 5 schematically illustrates plots of the nozzle displacement 127 over time for another embodiment of the method 500. The nozzle displacement 127 is shown in three components, namely, the Z-component plot 742, the X-component plot 744, and the Y-component plot 746. Fig. 5 shows the extrusion speed 748 of the wire 200 over time. Fig. 5 further shows a plot of nozzle temperature (or temperature of the hot-end) 749 over time. Similar to the embodiment of Fig. 4, the temperature of the nozzle 120 or of the hot-end is held relatively constant throughout the method 500. The method 500 may be described as beginning with an initial anchoring phase 701.

[0047] The printing path 400 of the example in Fig. 5 includes a change in direction, i.e., a turning point 443. After the turning point 443, the two cooling phases 706 to immediately

follow the turning point 443 are configured as dwell cooling phases 726. A dwell cooling phase 726 refers to a cooling phase 706 that includes a period of time when the nozzle 120 is held spaced apart from the substrate 300 at a substantially constant nozzle-substrate spacing 430. A non-dwell cooling phase 736 refers to a cooling phase 706 in which the nozzle 120 is not held spaced apart from the substrate 300 at a substantially constant nozzle-substrate spacing 430. After the first two dwell cooling phases 726 to immediately follow a turning point 443, subsequent cooling phases may be non-dwell cooling phases 736. Prior to a turning point 443, the subsequent cooling phases 706 may be at least one selected from the following: non-dwell cooling phase, dwell cooling phase, or any combination thereof. After the first two cooling phases to follow a turning point 443, the subsequent cooling phases 706 may be at least one selected from the following: non-dwell cooling phase, dwell cooling phase, or any combination thereof.

[0048] Referring to Fig. 4 and Fig. 5, the method 500 may be alternatively described as a synchronized series of events or phases.

[0049] As shown in Fig. 4 and Fig. 5, in some embodiments, the nozzle 120 may be configured to have no lateral displacement (i.e., zero displacement or approximately zero displacement in an X-Y plane substantially parallel to the substrate surface 302) concurrent with the extrusion of the wire 200 (extrusion speed is non-zero).

[0050] Referring now to Figs. 6A to 6C, the method 500 of wire embedding will be described in greater detail. The system 100 is configured to bring the nozzle 120 into proximity with the substrate surface 302 (Fig. 6A). The system 100 is configured to perform initial anchoring 701 to anchor a terminal end (free end) of the wire 200 to the substrate 300. In this example, the terminal end of the wire 200 is anchored to the start of the first section of the printing path 400. Initial anchoring involves positioning the nozzle 120 in substantial alignment with a nozzle retracting point 440, which in this case coincides with the beginning of the first section of the printing path 400. The nozzle 120 is provided in proximity to the substrate surface 302 and the extruder 140 operates to extrude the wire 200 toward/into the substrate 300 (Fig. 6B). In some embodiments, the nozzle 120 is held at the proximal spacing 434 from the substrate surface 302 for a period of time (initial dwelling time).

[0051] Concurrent with the wire 200 being extruded from the nozzle 120 along the extrusion

direction 123 and the terminal end of the wire 200 extending deeper into the substrate 300, the nozzle 120 is displaced away from the substrate surface 302 along a pull-away direction 125 (Fig. 6C). This is also referred to as a nozzle retracting point 440. The pull-away direction 125 is configured to be substantially opposite to the extrusion direction 123. The extruder 140 may be configured to extrude the wire 200 as soon as the nozzle-substrate spacing 430 is at a desired or predetermined proximal spacing value 434. After the nozzle 120 has been retracted or pulled away from the substrate 300, the actuating system 150 may be configured to stop displacing the nozzle 120 away from the substrate 300 when the nozzle is spaced apart from the substrate surface by a predetermined distance (hereinafter referred to as the pull-away distance) 434. Alternatively, the movement of the nozzle 120 and the extrusion of the wire 200 may be preconfigured as a coordinated sequence of timed processes, phases, or events (as illustrated by Fig. 4 and Fig. 5).

[0052] In terms of the nozzle-substrate spacing 430, the initial anchoring process (Fig. 6C) may be described as extruding the wire 200 concurrently with initially holding the nozzle-substrate spacing at the proximal spacing 434, and then extruding the wire 200 concurrently with increasing the nozzle-substrate spacing 430 until the nozzle-substrate spacing reaches the pull-away distance 436.

[0053] In some examples, the wire extrusion begins before or after the nozzle-substrate spacing 430 is at a proximal spacing 434, in which the proximal spacing 434 is one selected from a range between about 0 mm and about 0.3 mm inclusive, and the pull-away distance 436 is selected from a range between about 3 mm and about 7 mm inclusive. In this non-limiting example, the extrusion begins before or when the nozzle-substrate spacing 430 is at the proximal spacing 434 of about 0 millimeters (mm), and the pull-away distance 436 is predetermined to be about 5 mm.

[0054] The terminal end of the wire 200 is driven by the extruder 140 towards or into the substrate 300 over a time period when the nozzle-substrate spacing 430 is about constant or increasing (Fig. 6C). The initial anchor 241 is provided by at least by extending the terminal end of the wire 200 in the extrusion direction 123 into the substrate 300 and concurrently moving the nozzle 120 in the pull-away direction 125 (substantially opposite to the extrusion direction). In some examples, the initial anchor 241 includes an unexposed length of the

wire 200 disposed in or surrounded by the substrate material, in which the unexposed length of the wire 200 is about the thickness of a layer 303 of the substrate 300.

[0055] The formation of a surface embedded length of the wire 200 and the formation of a notch 242 will be described with reference to Figs. 7A to 7C.

[0056] Fig. 7A shows a nozzle 120 at a spaced-apart position 810, with an exposed length 220 of the wire 200 between the nozzle 120 and a most proximal surface embedded part of the wire 200. The nozzle 120 is displaced to a proximal position 820. The nozzle-substrate spacing 430 decreases as a result of the diagonal displacement from the first position 810 to the second position 820 of the nozzle 120. As the nozzle-substrate spacing decreases, the exposed length 220 of the wire 200 is disposed on the substrate surface 302, thereby forming a surface embedded part 250 of the wire 200.

[0057] Fig. 7B shows the nozzle 120 at the proximal position 820. The nozzle 120 is proximal to the substrate 300 and aligned with a next nozzle retracting point 440/442. The extruder 140 may be configured to extrude the wire 200 in response to the nozzle 120 reaching the proximal position 820. Alternatively, the extruder 140 may be configured to extrude the wire 200 as soon as the nozzle-substrate spacing 430 is approximately equal to a proximal spacing 434. In another embodiment, the nozzle movement 127 and the extrusion of the wire 200 are preconfigured as a coordinated sequence of timed processes (as illustrated in Fig. 4 and Fig. 5). Preferably, no dwelling time is provided between the nozzle 120 approaching the substrate surface 302 (Fig. 7A) and the nozzle 120 pulling away from the substrate surface 302 (Fig. 7C). That is, preferably, the nozzle 120 does not dwell or remain stationary for a period of time when the nozzle 120 is proximal to the substrate surface 302.

[0058] In some examples, the proximal spacing 434 may be preconfigured to be about 0 millimeters (mm). In some examples, the nozzle-substrate spacing is increased to a pull-away distance of about 5 mm. In some examples, the proximal spacing is selected from a range between about 0 mm and about 0.3 mm inclusive, and the pull-away distance is selected from a range between about 3 mm and about 7 mm inclusive.

[0059] At the nozzle retracting point or nozzle retracting phase, concurrent with the pulling-

away displacement of the nozzle 120 and at least over a time period when the nozzle-substrate spacing 430 is increasing, the wire 200 is extruded or driven by the extruder 140 towards the substrate 300.

[0060] The system 100 is configured to perform surface embedding of a length of wire 250 such that a length of the wire 200 is disposed substantially parallel to the substrate surface 302. In some examples, the surface embedded length 250 of the wire 200 may be performed between any two notches 242 or nozzle retracting points 440.

[0061] Fig. 7A shows the nozzle 120 is at a spaced-apart position 810 at the end of an anchoring process to form the most recent nozzle retracting point 440. An exposed length 220 of wire 200 extends between the nozzle 120 and the most recently formed anchor 240' (at the most recent nozzle retracting point 400').

[0062] Upon forming a predetermined exposed length 220 of the wire, or upon the nozzle-substrate spacing 430 being at its maximum value, the nozzle 120 may be held stationary relative to the substrate surface 302. In other words, the nozzle undergoes a period of dwelling or a dwelling time 702. The dwelling time 702 may be a few minutes, including but not limited to two or three minutes. In some examples, the dwelling time 702 may be around two to five minutes. In some examples, the dwelling time 702 is about three minutes. The nozzle 120 undergoes dwelling 702 after a period of wire extrusion 703 and pulling away. During the dwelling time 702, the exposed length 220 of the wire 200 between the nozzle tip 124 and the most recent nozzle retracting point 440 (on/in the substrate 300) preferably undergoes unaided cooling. That is, the exposed length 220 of the wire 200 is preferably permitted to dissipate some of its heat to the surrounding air without the aid of one or more fans blowing air or other coolant fluids across the nozzle-substrate spacing 430.

[0063] After the dwelling time 702, the nozzle 120 is moved such that a resultant displacement 127 of the nozzle 120 brings the nozzle 120 to a proximal position 820 that is proximal to a next nozzle retracting point. The next nozzle retracting point is further along the printing path 400. In some examples, the resultant displacement 127 of the nozzle 120 may be described as a diagonal displacement in which the nozzle-substrate spacing 430 decreases with a traverse displacement of the nozzle 120 in the direction of the printing path 400. In some examples, the Z-axis displacement of the nozzle 120 (towards the substrate

surface 302) and the displacement of the nozzle 120 parallel to the X-Y plane (along the printing path 400) are carried concurrently. In some examples, the Z-axis displacement and the displacement parallel to the X-Y plane are carried sequentially, one after another. For the sake of brevity, the resultant displacement 127 may be referred to as the “diagonal displacement” even if the actual path traced by the nozzle tip 124 may not be a straight diagonal path. In some examples, the diagonal displacement 127 may be described as arcuate. The diagonal displacement 127 corresponds to displacing the nozzle 120 to a next nozzle retracting point 440/442 and towards the substrate surface 302, such that the exposed length 220 of the wire 200 is angularly displaced about the (most recently formed) anchor 240 until the exposed length 220 of the wire 200 comes into contact with the substrate surface 302. The exposed length 220 of wire 220 thus forms the surface embedded 250 length of the wire 200 extending between two nozzle retracting points 440.

[0064] During the diagonal displacement 127 of the nozzle 120, there is an exposed length 220 of the wire 200 extending between the most recent nozzle retracting point 440' and the nozzle tip 124. In some examples, the extruder 140 is configured such that further extrusion does not occur during the diagonal displacement 127. In some examples, the extruder 140 is configured to enable a limited or a relatively small amount of extrusion during the diagonal displacement 127. The diagonal displacement 127 of the nozzle 120 disposes the exposed length 220 of the wire 200 along the printing path 400 on the substrate surface 302. The previously exposed length 220 of wire 200 is disposed such that it extends from the most recent nozzle retracting point 440' and the next nozzle retracting point 440.

[0065] In some embodiments, upon the completion of the anchoring process, i.e., upon the nozzle-substrate spacing 430 reaching the pull-away distance 436, the system 100 causes the nozzle 120 to immediately move towards yet another nozzle retracting point without first undergoing a dwelling time 702.

[0066] In some examples, as shown in Fig. 8A, the anchor 240 may be angularly displaced relative to the pull-away direction 125. In some examples, the wire 200 may be driven in an extrusion direction 123 that is at an angle θ between about 45 degrees and about 90 degrees relative to the substrate surface 302.

[0067] In some examples, as shown in Fig. 8B, the anchor 240 may be angularly displaced

at an angle θ relative to the substrate surface 302, and the nozzle 120 may be pulled away in a corresponding direction 125' such that the anchor 240 and the exposed length 220 of the wire 200 is kept substantially straight. As shown in Fig. 8C, after a desired exposed length 220 of the wire 200 has been extruded or extended between the substrate surface 302 and the nozzle tip 124, the nozzle may be displaced 127' towards the substrate 300. The previously exposed length 220 of the wire 200 is disposed on the substrate surface 302 to form a surface embedded 250 length of the wire 200.

[0068] In the present disclosure, reference to a length of wire 200 being "embedded" or "surface embedded" may refer to any one or a combination of the examples shown in Figs. 9A to 9G. A surface embedded length 250 of wire 200 is disposed generally in a transverse plane or in a plane substantially parallel to the substrate surface 302. The surface embedded 250 length of the wire 200 may be joined to the substrate (upon the substrate reverting from a molten or softened state to a solidified state 343) such that there is an anchoring effect 243 around the sides of the wire 200 along substantially the whole length of the surface embedded wire 200, including and not limited to an anchoring effect at the notches 242. The surface embedded 250 length of the wire 200 is substantially disposed in one embedment layer 313 of the substrate 300. The surface embedded length 250 of the wire 200 is substantially near to or at the substrate surface 302, or substantially in a most recently deposited layer 303 of the substrate 300, as illustrated in Figs. 9A and 9B. Alternatively, the surface embedded length 250 of the wire 200 is not wholly but is at least substantially disposed in a top-most layer 303 of the substrate 300, as illustrated in Fig. 9E. In some examples, the surface embedded length 250 of the wire 200 may slightly protrude above or beyond the substrate surface 302, as illustrated in Fig. 9A. In other examples, an exposed side of the surface embedded length 250 of the wire 200 may be substantially aligned or substantially in plane with the substrate surface 302, as illustrated in Fig. 9B. In some examples, the surface embedded length 250 of the wire 200 may be fully or partially covered by the substrate material or other materials, as illustrated in Figs. 9C and 9D. In yet other examples, the surface embedded length 250 of the wire 200 may be disposed in an open channel, as illustrated in Figs. 9A, 9B, and 9E. In other words, the term "surface embedded" as used herein includes "partially surface embedded" (e.g., Fig. 9A) and "fully surface embedded" (e.g., Figs. 9B to 9E). For one surface embedded 250 length of the wire 200, it

may be partially surface embedded at one or more parts and fully surface embedded at one or more other parts. For example, one part of the wire 200 intended to be insulated all round may be fully surface embedded, and another part of the wire 200 may be partially surface embedded to serve as an electrical contact pad. The surface embedded 250 length of the wire 200 may include at least one partially surface embedded part. The surface embedded 250 length of the wire 200 may include at least one fully surface embedded part.

[0069] The above describes the method 500 of embedding a wire in a substrate in a 3D-printing process in which the method 500 includes extruding the wire in an extrusion direction via a nozzle towards a substrate surface of the substrate. The method 500 includes forming an anchor in the substrate concurrently with a displacement of the nozzle in a pull-away direction away from the substrate surface, in which the forming of the anchor is concurrent with a forming of an exposed length of the wire between the anchor and the nozzle. The exposed length of the wire is formed without contacting the substrate surface. The method includes forming a surface embedded length of the wire using the exposed length of the wire. The anchor may be formed by the extruding of the wire into the substrate concurrently with the displacement of the nozzle in the pull-away direction. The method 500 enables the formation of surface embedded lengths of the wire with a desired precision and quality as evidenced by the images of Figs. 10A to 10C and the images of Figs. 11A and 11B.

[0070] Figs. 10A to 10C are images of surface embedded lengths 250 of straight sections of a wire 200 formed by the method 500 of the present disclosure. The surface embedded length 250 is substantially transversely disposed near the substrate surface. The surface embedded length 250 is disposed in a channel having a width and depth substantially similar to the diameter of the wire 200, such that a side of the surface embedded length 250 of the wire 200 is approximately aligned with or in-plane with the substrate surface 302. The layer 303 of the substrate 300 with a surface embedded length 250 of the wire 200 embedded therein is referred to as the wire embedment layer 313. It has been experimentally verified that the wire embedment layer 313 need no more than two layers 303 underneath, in which each layer 303 of the substrate 300 (also known as a substrate print height or a substrate printing resolution) is as thin as 0.2 millimeters (mm). In some other examples, the substrate print height is about 0.6 mm. Preferably, the substrate print height is about 0.4 mm. The

density of the layers may be between 80% to 100%. In other words, the method 500 enables surface embedment of the wire 200 to be substantially disposed most if not all of the wire 200 in one wire embedment layer 313, causing relatively little interference with the other layers 303 of the substrate 300.

[0071] Figs. 11A and 11B are images of surface embedded lengths 250 of a wire embedded according to the method 500 of the present disclosure. Contiguous straight sections of a wire 200 are surface embedded at approximately ninety degrees to one another. Similar to the examples of Figs. 10A to 10C, the surface embedded lengths 250 of the wire 200 are substantially transversely disposed near the substrate surface. The surface embedded lengths 250 are each disposed in a respective channel having a width and depth substantially similar to the diameter of the wire 200, such that a side of each surface embedded length 250 of the wire 200 is approximately aligned with or in-plane with the substrate surface 302.

[0072] Images of a few attempts to embed a wire using a conventional method are shown in Fig. 12. The conventional method includes delivering a stream of air or other cooling fluid at a plastic substrate so that the plastic substrate will freeze or harden quickly enough and fix the wire in a hardened part of the plastic. It was observed that the wires in Fig. 12 were nonetheless too deeply sunken into the substrate. In fact, in the examples of Fig. 12, although the wires were originally deposited on substrate surface, the wires did not manage to fuse with the substrate near the substrate surface. Instead, each of the wires of Fig. 12 end up being in trenches that with various depths and widths that may be at least a few times the size of the wire diameter. In other words, the wires of Fig. 12 may excessively deform the substrate and interfere with other circuit elements in an underlying layer of the substrate, and/or adversely impact the structural integrity of the substrate. For practical applications, the wires of Fig. 12 would not be useful for forming operable circuit connections. In fact, the formation of the trenches of Fig. 12 may also result in the improper or faulty printing of subsequent layers over the trenches.

[0073] The conventional example of Fig. 12 presents a clear contrast to the examples of Figs. 10A to 10C, and the examples of Figs. 11A and 11B. The experimental results suggest that the method 500 of the present disclosure enables the substrate material around the most recently surface embedded 250 length of wire 200 to cool down such that a sufficient extent

of bonding (or adhesion or fusion) is formed between the most recently surface embedded 250 length of wire 200 and the substrate 300. The experimental results surprisingly show that that delivering a forced flow of air or coolant across the print head, the wire, and/or the substrate yield less preferred outcomes. The present system 100 may thus be characterized as providing a more gradual temperature gradient along the length of the wire 200, with the nozzle 120 being hotter than the part of the wire 200 at the extruder 140.

[0074] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not intended to be limiting or exhaustive. Various changes and modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. A method of embedding a wire in a substrate in a 3D-printing process, the method comprising:
 - extruding the wire in an extrusion direction via a nozzle towards a substrate surface of the substrate;
 - concurrently with the extruding of the wire, displacing the nozzle in a pull-away direction away from the substrate surface to form an exposed length of the wire between the substrate surface and the nozzle, wherein the exposed length of the wire is formed without the exposed length of the wire contacting the substrate surface;
 - providing a cooling phase; and
 - forming a surface embedded length of the wire using the exposed length of the wire in a surface embedding phase.
2. The method according to claim 1, comprising:
 - displacing the nozzle to a next nozzle retracting point and towards the substrate surface, such that the exposed length of the wire is angularly displaced until the exposed length of the wire comes into contact with the substrate surface, and such that the exposed length of wire forms the surface embedded length of the wire.
3. The method according to claim 1 or claim 2, further comprising:
 - upon the nozzle being proximal to the substrate surface at the next nozzle retracting point, displacing the nozzle in the pull-away direction.
4. The method according to any one of claims 1 to 3, wherein the surface embedded length of the wire is joined to the substrate such that the surface embedded length of the wire is substantially disposed in one embedment layer of the substrate.

5. The method according to any one of claims 1 to 4, wherein the surface embedded length of the wire is joined to the substrate such that the surface embedded length of the wire is substantially parallel to the substrate surface.
6. The method according to any one of claims 1 to 5, wherein the surface embedded length of the wire comprises at least one partially surface embedded part.
7. The method according to any one of claims 1 to 6, wherein the surface embedded length of the wire comprises at least one fully surface embedded part.
8. The method according to any one of claims 1 to 7, wherein the exposed length of the wire is exposed to air on all sides immediately before the forming of the surface embedded length of the wire.
9. The method according to any one of claims 1 to 8, wherein each of the wire and the substrate undergoes unaided cooling in the cooling phase.
10. The method according to claim 9, further comprising providing a pre-heating effect on the wire.
11. The method according to any one of claims 1 to 10, wherein the cooling phase follows the surface embedding phase.
12. The method according to any one of claims 1 to 11, wherein the cooling phase comprises a dwelling cooling phase, and in which the nozzle is spaced apart from the substrate throughout the dwelling cooling phase.
13. The method according to any one of claims 2 to 12, further comprising changing a direction of travel of the nozzle to form a turning point between a first section of a printing path and a second section of the printing path, wherein the first section of the printing path and the second section of the printing path are contiguous and non-parallel to one another.

14. The method according to claim 13, wherein no more than two cooling phases immediately following the turning point comprises a dwelling cooling phase.
15. The method according to any one of claims 1 to 14, further comprising at least one non-dwell cooling phase, wherein the nozzle is not spaced apart from the substrate at a substantially constant nozzle-substrate spacing in the non-dwell cooling phase.
16. The method according to any one of claims 1 to 15, further comprising:
 - extruding the wire at a non-zero extrusion speed if a nozzle-substrate spacing is concurrently increasing; and
 - not extruding the wire if the nozzle-substrate spacing is not increasing, wherein the nozzle-substrate spacing corresponds to a spacing between a tip of the nozzle and the substrate surface.
17. The method according to any one of claims 1 to 16, further comprising:
 - forming an initial anchor by concurrently extruding a terminal end of the wire into the substrate and displacing the nozzle in the pull-away direction away from the substrate, wherein the extrusion direction is an angle between 45 degrees and 90 degrees relative to the substrate surface.