ABSTRACT
A print head is disclosed for use with an additive manufacturing system. The print head may include a nozzle having an internal passage and at least one ellipsoidal orifice. The print head may also include a fiber guide disposed at least partially inside the nozzle and dividing the internal passage into a plurality of channels. A length of each of the plurality of channels extends in an axial direction of the nozzle.
PRINTHEAD FOR ADDITIVE MANUFACTURING SYSTEM

RELATED APPLICATIONS

[0001] This application is based on and claims the benefit of priority from U.S. Provisional Application No. 62/526, 448 that was filed on Jun. 29, 2017, the contents of which are expressly incorporated herein by reference.

TECHNICAL FIELD

[0002] The present disclosure relates generally to a print head and, more particularly, to a print head for use in an additive manufacturing system.

BACKGROUND

[0003] Continuous fiber 3D printing (a.k.a., CF3D™) involves the use of continuous fibers (e.g., carbon fibers, glass fibers, optical tubes, wires, etc.) embedded within a matrix discharging from a moveable print head. The matrix can be a traditional thermoplastic, a powdered metal, a liquid resin (e.g., a UV curable and/or two-part resin), or a combination of any of these and other known matrices. Upon exiting the print head, a cure enhancer (e.g., a UV light, an ultrasonic emitter, a heat source, a catalyst supply, etc.) is activated to initiate and/or complete curing of the matrix. This curing occurs almost immediately, allowing for unsupported structures to be fabricated in free space. When fibers, particularly continuous fibers, are embedded within the structure, a strength of the structure may be multiplied beyond the matrix-dependent strength. An example of this technology is disclosed in U.S. Pat. No. 9,511,543 that issued to Tyler on Dec. 6, 2016 (“the ’543 patent”).

[0004] Although CF3D™ provides for increased strength, compared to manufacturing processes that do not utilize continuous fibers, it may be difficult to maintain a desired spatial and/or orientational relationship between adjacent fibers during multi-fiber printing. For example, when printing a structure made up of carbon fibers that are simultaneously deposited adjacent to metallic wires, that are simultaneously deposited adjacent to optical tubes, it can be difficult to prevent the carbon fibers, wires, and tubes from overlapping, twisting, or otherwise moving away from a desired state during trajectory changes (e.g., cornering) of the print head. The disclosed print head is uniquely configured to address this and/or other issues of the prior art.

SUMMARY

[0005] In one aspect, the present disclosure is directed to a print head for an additive manufacturing system. The print head may include a nozzle having an internal passage and at least one elliptoidal orifice. The print head may also include a fiber guide disposed at least partially inside the nozzle and dividing the internal passage into a plurality of channels. A length of each of the plurality of channels extends in an axial direction of the nozzle.

[0006] In another aspect, the present disclosure is directed to another print head for an additive manufacturing system. This print head may include a matrix reservoir, and a nozzle in fluid communication with the matrix reservoir. The nozzle may have an internal passage and at least one elliptoidal orifice located at an end of the internal passage opposite the matrix reservoir. The print head may also include a plurality of radially oriented dividers disposed at least partially inside the nozzle and dividing the internal passage into a plurality of channels. A length of each of the plurality of channels extends in an axial direction of the nozzle.

[0007] In yet another aspect, the present disclosure is directed to a method of additively manufacturing a composite structure. The method may include wetting a plurality of separate reinforcements with a matrix, and directing the wetted plurality of separate reinforcements through a fiber guide inside a nozzle of a print head. The method may also include discharging the wetted plurality of separate reinforcements through an orifice of the nozzle, and moving the print head during discharging to create a three-dimensional trajectory in the wetted plurality of separate reinforcements. The method may further include exposing the wetted plurality of separate reinforcements to a cure energy after discharge from the nozzle, and selectively rotating the fiber guide while moving the print head to maintain an orientational relationship between the plurality of separate reinforcements.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 is a diagrammatic illustration of an exemplary disclosed additive manufacturing system; and

[0009] FIGS. 2 and 3 are cross-sectional illustrations of an exemplary disclosed print head that may be utilized with the additive manufacturing system of FIG. 1.

DETAILED DESCRIPTION

[0010] FIG. 1 illustrates an exemplary system 10, which may be used to continuously manufacture a composite structure 12 having any desired cross-sectional shape (e.g., circular, ellipsoidal, polygonal, etc.). System 10 may include at least a support 14 and a print head (“head”) 16. Head 16 may be coupled to and moved by support 14. In the disclosed embodiment of FIG. 1, support 14 is a robotic arm capable of moving head 16 in multiple directions during fabrication of structure 12, such that a resulting longitudinal axis of structure 12 is three-dimensional. It is contemplated, however, that support 14 could alternatively be an overhead gantry or a hybrid gantry/arm also capable of moving head 16 in multiple directions during fabrication of structure 12. Although support 14 is shown as capable of multi-axis movements, it is contemplated that any other type of support 14 capable of moving head 16 in the same or in a different manner could also be utilized, if desired. In some embodiments, a drive may mechanically couple head 16 to support 14 and may include components that cooperate to move and/or supply power or materials to head 16.

[0011] Head 16 may be configured to receive or otherwise contain a matrix. The matrix may include any type of material (e.g., a liquid resin, such as a zero-volatile organic compound resin; a powdered metal; etc.) that is curable. Exemplary matrices include thermosets, single- or multi-part epoxy resins, polyester resins, cationic epoxies, acrylated epoxies, urethanes, esters, thermoplastics, photopolymers, polyepoxides, thiols, alkenes, thiol-enes, reversible resins (e.g., Triazolinedione, a covalent-adaptable network, a spatiotemporal reversible resin, etc.) and more. In one embodiment, the matrix inside head 16 may be pressurized, for example by an external device (e.g., an extruder or another type of pump—not shown) that is fluidly connected to head 16 via a corresponding conduit (not shown). In another embodiment, however, the matrix pressure may be
anchor point 20, and the relative movement may cause additional reinforcement to be pulled from nozzle 18. It should be noted that the movement of the reinforcement through head 16 could be assisted (e.g., via internal feed mechanisms), if desired. However, the discharge rate of the reinforcement from nozzle 18 may primarily be the result of relative movement between head 16 and anchor point 20, such that tension is created within the reinforcement.

Nozzle 18 may be fluidly connected to a matrix reservoir 22. Although matrix reservoir 22 is shown as being at least partially inside of head 16, it should be noted that matrix reservoir 22 could alternatively be located separately upstream of head 16. As shown in FIG. 2, nozzle 18 may have a generally cylindrical outer wall 24, with an upstream or base end 26 in fluid communication with matrix reservoir 22, a downstream or tip end 28, and one or more generally-axially oriented internal passages 30 that extend from base end 26 to tip end 28.

Any number of reinforcements (represented as R in FIG. 2) may be passed axially through reservoir 22 where at least some matrix-wetting occurs (matrix represented as M in FIG. 2), and discharged from head 16 via nozzle 18. One or more orifices 32 may be located at tip end 28 of nozzle 18 to accommodate passage of the matrix-wetted reinforcements. In the disclosed embodiment, a single generally ellipsoidal (e.g., circular or oval) orifice 32 is shown. It is contemplated, however, that multiple orifices 32 could be used. In addition, orifices 32 of another shape may allow for printing of bundles having different cross-sectional shapes. In the embodiment of FIG. 2, the single orifice 32 is substantially aligned (e.g., aligned within engineering tolerances) with a central axis of nozzle 18.

Returning to FIG. 1, one or more cure enhancers (e.g., one or more light sources, ultrasonic emitters, lasers, heaters, catalyst dispensers, microwave generators, etc.) 34 may be mounted proximate head 16 (e.g., at a trailing side of nozzle 18) and configured to enhance a cure rate and/or quality of the matrix as it is discharged from nozzle 18. Cure enhancer 34 may be controlled to selectively expose internal and/or external surfaces of structure 12 to energy (e.g., light energy, electromagnetic radiation, vibrations, heat, a chemical catalyst or hardener, etc.) during the formation of structure 12. The energy may increase a rate of chemical reaction occurring within the matrix, sinter the material, harden the material, or otherwise cause the material to cure as it discharges from nozzle 18.

A controller 36 may be provided and communicatively coupled with support 14, head 16, and any number and type of cure enhancers 34. Controller 36 may embody a single processor or multiple processors that include a means for controlling an operation of system 10. Controller 36 may include one or more general- or special-purpose processors or microprocessors. Controller 36 may further include or be associated with a memory for storing data such as, for example, design limits, performance characteristics, operational instructions, matrix characteristics, reinforcement characteristics, characteristics of structure 12, and corresponding parameters of each component of system 10. Various other known circuits may be associated with controller 36, including power supply circuitry, signal-conditioning circuitry, solenoid/motor driver circuitry, communication circuitry, and other appropriate circuitry. Moreover,
controller 36 may be capable of communicating with other components of system 10 via wired and/or wireless transmission.

One or more maps may be stored in the memory of controller 36 and used during fabrication of structure 12. Each of these maps may include a collection of data in the form of models, lookup tables, graphs, and/or equations. In the disclosed embodiment, the maps are used by controller 36 to determine desired characteristics of cure enhancements 34, the associated matrix, and/or the associated reinforcements at different locations within structure 12. The characteristics may include, among others, a type, quantity, and/or configuration of reinforcement and/or matrix to be discharged at a particular location within structure 12, and/or an amount, intensity, shape, and/or location of desired curing. Controller 36 may then correlate operation of support 14 (e.g., the location and/or orientation of head 16) and/or the discharge of material from head 16 (a type of material, desired performance of the material, cross-linking requirements of the material, a discharge rate, etc.) with the operation of cure enhancements 34, such that structure 12 is produced in a desired manner.

In some instances, when multiple reinforcements are being discharged through nozzle 18 at the same time, it may be beneficial to maintain a desired spatial and/or orientational relationship between the reinforcements. For example, it may be important to avoid overlapping, twisting, and/or reordering of the different reinforcements for purposes of performance (e.g., electrical conductivity, strength, flexibility, noise interference, etc.) and/or appearance. For this purpose, a fiber guide 38 may be placed inside of head 16 (e.g., inside of nozzle 18).

An exemplary fiber guide 38 is illustrated in FIGS. 2 and 3. Fiber guide 38 may extend along an entire length of nozzle 18 or only a fraction of the length of nozzle 18. For example, fiber guide 38 may start at base end 26 (or at a point between base end 26 and tip end 28), and terminate short of orifice 32. A longer fiber guide 38 may reduce a likelihood of entanglements within nozzle 18, while terminating short of orifice 32 may allow the separate fibers to coalesce into a cohesive bundle prior to discharge from nozzle 18. In one embodiment, a length of fiber guide 38 is about 10-95% of the axial length of nozzle 18.

Fiber guide 38 may include a plurality of dividers 40 that segment passage 30 into one or more elongated channels 42. A length of each channel 42 may be oriented in the same general direction as the axis of nozzle 18. Each channel 42 may be configured to independently receive a particular reinforcement or grouping of reinforcements and to maintain separation of these reinforcement(s) from other reinforcement(s) simultaneously discharging from nozzle 18. In the embodiment of FIGS. 2 and 3, five different channels 42 are created by a general cross-shape. The cross shape may be formed by four radially oriented planar dividers 40 that are joined to each other at their inner edges. Channels 42 may include four peripheral channels 42a, and a center channel 42b. It is contemplated however, that dividers 40 could alternatively segment passage 30 into only peripheral channels (e.g., quarter- or half-moon shaped channels) 42a, into a single center channel 42b and a single annular-shaped peripheral channel (not shown), or into any other number of center and/or peripheral channels 42. Lower and/or upper ends of dividers 40 may be rounded to avoid damaging the reinforcements during discharge.

It should be noted that, while the disclosed dividers 40 are generally planar and divide nozzle 18 into open-sided channels 42 (i.e., channels without an outer radial wall), other configurations of dividers 40 and channels 42 may also be possible. For example, channels 42 could be completely enclosed by the extension of dividers 40 radially outward to the annular wall of passage 30 or by additional divider walls that extend obliquely between adjacent dividers 40. Alternatively, channels 42 could be formed by separate axial tubes that are arranged adjacent each other. In addition, while channels 42a are shown as each having a greater axial cross-sectional area (see FIG. 3) than channel 42b, it is contemplated that the opposite may be true in some embodiments. The cross-sectional area of each of channels 42a may be the same (shown in FIG. 3) or different. Finally, it is contemplated that fiber guide 38 may be removably installed within nozzle 18, and selectively swapped out for a fiber guide 38 having a different configuration. This may be accomplished, for example, by the removal of nozzle 18 from the remainder of head 16, the withdrawing of the first fiber guide 38, the insertion of the second fiber guide 38, and the reassembly of nozzle 18.

It is contemplated that fiber guide 38 could be driven to rotate in some applications. In particular, the continuous reinforcements discharging from nozzle 18 may need to have a particular orientation regardless of the movements imparted by support 14 on head 16 (e.g., regardless of cornering of head 16). It is contemplated that head 16 may be rotated independent of support 14, that nozzle 18 could be rotated independent of the rest of head 16 (e.g., of matrix reservoir 22), and/or that fiber guide 38 could be rotated independent of nozzle 18 to achieve the desired orientation of the associated reinforcements. For this purpose, a rotary actuator (e.g., a gear, a motor, etc.) 44 may be connected between support 14 and head 16 (shown in FIG. 1), between nozzle 18 and matrix reservoir 22 (not shown), and/or between fiber guide 38 and nozzle 18 (shown in FIG. 2), as desired.

It should be noted that fiber guide 38 could be rotated even when head 16 is not changing trajectory. In this situation, the rotation of fiber guide 38 would result in a controlled twisting and/or overlapping of the discharging reinforcements.

INDUSTRIAL APPLICABILITY

The disclosed system and print head may be used to continuously manufacture composite structures having any desired cross-sectional size, shape, length, density, and/or strength. The composite structures may include any number of different reinforcements of the same or different types, diameters, shapes, configurations, and consists, each coated with a common matrix. In addition, the disclosed print head may allow for multiple simultaneously discharging reinforcements to maintain a desired spatial and/or orientational arrangement, even when the orientation of the print head is changing (e.g., curing cornering). Operation of system 10 will now be described in detail.

At a start of a manufacturing event, information regarding a desired structure 12 may be loaded into system 10 (e.g., into controller 36 that is responsible for regulating operations of support 14 and/or head 16). This information may include, among other things, a size (e.g., diameter, wall thickness, length, etc.), a contour (e.g., a trajectory), surface features (e.g., ridge size, location, thickness, length, flange...
size, location, thickness, length; etc.) and finishes, connection geometry (e.g., locations and sizes of couplings, tees, splices, etc.), location-specific matrix stipulations, location-specific reinforcement stipulations, desired spatial and/or orientational relationships between adjacent reinforcements, primary load directions, etc. It should be noted that this information may alternatively or additionally be loaded into system 10 at different times and/or continuously during the manufacturing event, if desired. Based on the component information, one or more different reinforcements and/or matrices may be selectively installed and/or continuously supplied into system 10.

[0029] Installation of the reinforcements may be performed by passing individual reinforcements or groups of reinforcements down through matrix reservoir 22, and then threading the separate reinforcements through channels 42 inside of nozzle 18. Installation of the matrix may include filling reservoir 22 within head 16 and/or coupling of an extruder or external bath (not shown) to head 16. Head 16 may then be moved by support 14 under the regulation of controller 36 to cause matrix-coated reinforcements to be placed against or on a corresponding stationary anchor point 20. Cure enhancers 34 within head 16 may then be selectively activated to cause hardening of the matrix surrounding the reinforcements, thereby bonding the reinforcements to anchor point 20.

[0030] The component information may then be used to control operation of system 10. Specifically, the reinforcements may be pulled and/or pushed from nozzle 18 (along with the matrix), while support 14 selectively moves head 16 in a desired manner during curing, such that an axis of the resulting structure 12 follows a desired trajectory (e.g., a free-space, unsupported, 3-D trajectory). For example, support 14 may move head 16 in an X-, Y-, and/or Z-direction away from the anchor point 20, such that matrix-wetted reinforcements may be pulled separately through channels 42 and then allowed to coalesce just prior to discharge through orifice 32. The use of fiber guide 38 may inhibit a spatial relationship change between adjacent reinforcements during changes in the trajectory of head 16.

[0031] During the movement of head 16, even though the spatial relationships between adjacent reinforcements may be maintained via fiber guide 38, it may still be possible for the resulting structure to vary in orientation of its associated reinforcements, unless otherwise accounted for. For example, a change in the trajectory of head 16 from a purely Y-direction to a purely X-direction could cause the discharging bundle of the reinforcements to roll. For instance, a side-discharging reinforcement could become a top-discharging reinforcement during the trajectory change described above. This may be acceptable in some situations.

[0032] However, in other situations, it may be beneficial to cause fiber guide 38 to rotate during the trajectory change of head 16. In the example described above, fiber guide 38 may be rotated by about 90° during the trajectory change of head 16, such that the side-discharging reinforcement remains the side-discharging reinforcement after the change in trajectory. The rotation of fiber guide 38 may be accomplished, for example, by controller 36 selectively energizing rotary actuator 44. Controller 36 may coordinate operation of rotary actuator 44 with the motion of head 16 imparted by support 14, such that the individual fibers are maintained in a desired spatial and/or orientational relationship. Once structure 12 has grown to a desired size and/or length, structure 12 may be disconnected (e.g., severed) from head 16 in any desired manner.

[0033] It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed system and head. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed system and head. It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

What is claimed is:

1. A print head for an additive manufacturing system, comprising:
   a nozzle having an internal passage and at least one ellipsoidal orifice; and
   a fiber guide disposed at least partially inside the nozzle and dividing the internal passage into a plurality of channels,
   wherein a length of each of the plurality of channels extends in an axial direction of the nozzle.

2. The print head of claim 1, wherein the fiber guide includes a plurality of radially oriented dividers.

3. The print head of claim 2, wherein the plurality of radially oriented dividers are generally planar and have inner edges connected to each other.

4. The print head of claim 2, wherein the plurality of radially oriented dividers form a cross-shape.

5. The print head of claim 2, wherein the plurality of radially oriented dividers extend radially outward to an annular wall of the internal passage.

6. The print head of claim 1, wherein the plurality of channels includes a center channel and at least one peripheral channel.

7. The print head of claim 6, wherein the at least one peripheral channel includes a plurality of peripheral channels.

8. The print head of claim 1, wherein the plurality of channels are open at an outer radial side.

9. The print head of claim 1, further including a rotary actuator configured to rotate the fiber guide.

10. The print head of claim 1, wherein the fiber guide terminates short of the at least one ellipsoidal orifice.

11. The print head of claim 10, wherein ends of the fiber guide at the at least one ellipsoidal orifice are rounded.

12. The print head of claim 1, wherein the fiber guide is removably disposed inside of the nozzle.

13. The print head of claim 1, further including a matrix reservoir in fluid communication with the nozzle at an end opposite the at least one ellipsoidal orifice.

14. A print head, comprising:
   a matrix reservoir;
   a nozzle in fluid communication with the matrix reservoir and having an internal passage and at least one ellipsoidal orifice located at an end of the internal passage opposite the matrix reservoir; and
   a plurality of radially oriented dividers disposed at least partially inside the nozzle and dividing the internal passage into a plurality of channels,
   wherein a length of each of the plurality of channels extends in an axial direction of the nozzle.

15. The print head of claim 14, wherein the plurality of radially oriented dividers are generally planar and have inner edges connected to each other.
16. The print head of claim 15, wherein the plurality of radially oriented dividers form a cross-shape.

17. The print head of claim 14, wherein the plurality of channels includes a center channel and a plurality of peripheral channels.

18. The print head of claim 14, wherein:
the plurality of radially oriented dividers terminate short of the at least one ellipsoidal orifice; and
ends of the plurality of radially oriented dividers at the at least one ellipsoidal orifice are rounded.

19. A method of additively manufacturing a composite structure, comprising:
wetting a plurality of separate reinforcements with a matrix;
directing the wetted plurality of separate reinforcements through a fiber guide inside a nozzle of a print head;
discharging the wetted plurality of separate reinforcements through an orifice of the nozzle;
moving the print head during discharging to create a three-dimensional trajectory in the wetted plurality of separate reinforcements;
exposing the wetted plurality of separate reinforcements to a cure energy after discharge from the nozzle; and
selectively rotating the fiber guide while moving the print head to maintain an orientational relationship between the plurality of separate reinforcements.

20. The method of claim 19, further including coalescing the wetted plurality of separate reinforcements prior to discharging the wetted plurality of separate reinforcements through an orifice of the nozzle.

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