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(54) Title: ADDITIVE MANUFACTURING SYSTEM

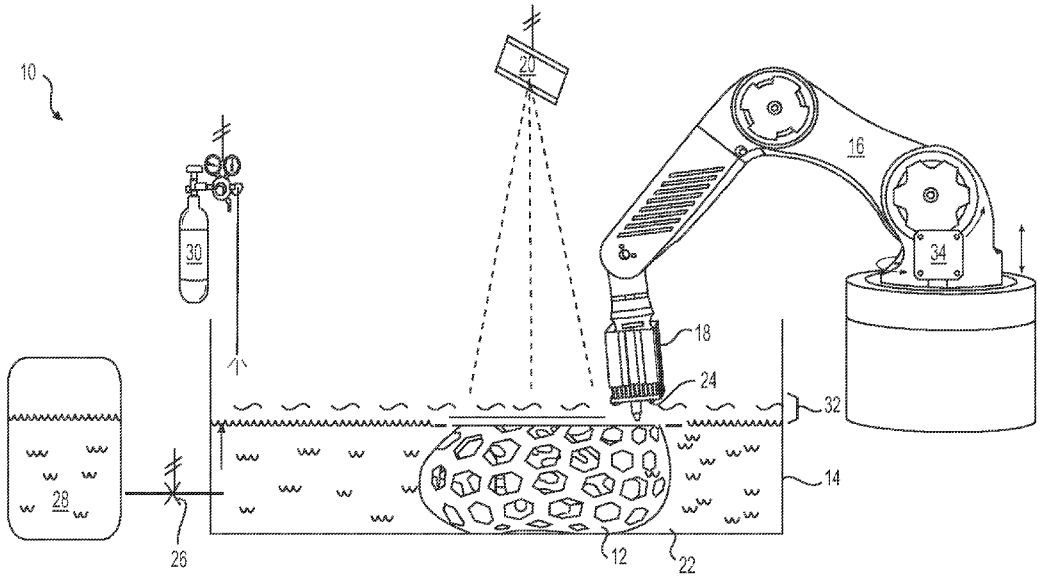


FIG. 1

(57) Abstract: A system for additively manufacturing a composite part is disclosed. The system may include a vat configured to hold a supply of resin, and a build surface disposed inside the vat. The system may also include a print head configured to discharge a matrix-coated continuous reinforcement onto the build surface, and an energy source configured to expose resin on a surface of the matrix-coated continuous reinforcement to a cure energy.

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[Continued on next page]

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

Description

ADDITIVE MANUFACTURING SYSTEM

Related Applications

[0001] This application is based on and claims the benefit of priority from United States Provisional Application No. 62/449,899 that was filed on January 24, 2017, the contents of which are expressly incorporated herein by reference.

Technical Field

[0002] The present disclosure relates generally to a manufacturing system and, more particularly, to a system for additively manufacturing a composite structure.

Background

[0003] Many different processes of additive manufacturing are commonly used to produce machine components. These processes may include, among others, Continuous Fiber 3D Printing (CF3D™) and Stereolithography (SLA).

[0004] CF3D™ involves the use of continuous fibers embedded within material discharging from a moveable print head. A matrix is supplied to the print head and discharged (e.g., extruded and/or pultruded) along with one or more continuous fibers also passing through the same head at the same time. 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 matrixes. 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. And 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. Patent 9,511,543 that issued to Tyler on December 6, 2016 ("the '543 patent").

[0005] SLA also involves the use of a light-emitting device (e.g., a UV light projector, an electron beam emitter, or a laser). The light-emitting device is computer controlled to selectively

energize a layer of resin within a vat in a particular pattern corresponding to an outline of a part. The resin (e.g., a liquid photo-polymerizing resin) solidifies upon being energized, and a subsequent layer of resin within the tank is them energized in a new pattern. This may continue, with the part being incrementally raised out of or lowered further into the vat, until all layers of the component have been fabricated. Parts produced via SLA may have high-resolution surface finishes.

[0006] Although parts fabricated via CF3D™ and SLA may have some desired characteristics (e.g., high-strength and high-resolution, respectively), neither process alone may be able to provide all desired characteristics of both processes. The disclosed system is directed at addressing one or more of the problems set forth above and/or other problems of the prior art.

Summary

[0007] In one aspect, the present disclosure is directed to an additive manufacturing system. The additive manufacturing system may include a vat configured to hold a supply of resin, and a build surface disposed inside the vat. The system may also include a print head configured to discharge a matrix-coated continuous reinforcement onto the build surface, and an energy source configured to expose resin on a surface of the matrix-coated continuous reinforcement to a cure energy.

[0008] In another aspect, the present disclosure is directed to a method of additively manufacturing a composite structure. The method may include discharging from a print head a matrix-coated continuous reinforcement onto a build surface, and submerging the matrix-coated continuous reinforcement in resin. The method may also include exposing resin at a surface of the matrix-coated continuous reinforcement to a cure energy.

Brief Description of the Drawings

[0009] Fig. 1 is a diagrammatic illustration of an exemplary disclosed additive manufacturing system; and

[0010] Fig. 2 is a diagrammatic illustration of another exemplary disclosed additive manufacturing system.

Detailed Description

[0011] 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, polygonal, etc.). System 10 may include at least a vat 14, a support 16, a head 18, and an energy source 20. Vat 14 may be a vessel that is configured to hold a supply of resin (e.g., a photopolymer resin), from which at least a portion (e.g., a surface coating) of structure 12 is to be fabricated. Head 18 may be coupled to and moved by support 16 to fabricate at least a portion (e.g., an internal skeleton) of structure 12 within vat 14. In the disclosed embodiment of Fig. 1, support 16 is a robotic arm capable of moving head 18 in multiple directions during fabrication of structure 12. Energy source 20 may be configured to selectively expose resin in vat 14 that coats the structural skeleton fabricated by head 18, thereby causing the resin to cure and form a hardened coating on the skeleton.

[0012] Head 18, itself, 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 matrixes include thermosets, single- or multi-part epoxy resins, polyester resins, cationic epoxies, acrylated epoxies, urethanes, esters, thermoplastics, photopolymers, polyepoxides, thiols, alkenes, thiol-enes, and more. In one embodiment, the matrix inside head 18 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 18 via a corresponding conduit (not shown). In another embodiment, however, the matrix pressure may be generated completely inside of head 18 by a similar type of device. In yet other embodiments, the matrix may be gravity-fed through and/or mixed within head 18. In some instances, the matrix inside head 18 may need to be kept cool and/or dark to inhibit premature curing; while in other instances, the matrix may need to be kept warm for the same reason. In either situation, head 18 may be specially configured (e.g., insulated, chilled, and/or warmed) to provide for these needs.

[0013] The matrix may be used to coat, encase, or otherwise at least partially surround any number of continuous reinforcements (e.g., separate fibers, tows, rovings, ribbons, and/or sheets of material) and, together with the reinforcements, make up at least a portion (e.g., a wall) of composite structure 12. The reinforcements may be stored within (e.g., on separate internal

spools - not shown) or otherwise passed through head 18 (e.g., fed from external spools). When multiple reinforcements are simultaneously used, the reinforcements may be of the same type and have the same diameter and cross-sectional shape (e.g., circular, square, flat, etc.), or of a different type with different diameters and/or cross-sectional shapes. The reinforcements may include, for example, carbon fibers, vegetable fibers, wood fibers, mineral fibers, glass fibers, metallic wires, optical tubes, etc. It should be noted that the term "reinforcement" is meant to encompass both structural and non-structural types of continuous materials that can be at least partially encased in the matrix discharging from head 18.

[0014] The reinforcements may be exposed to (e.g., coated with) the matrix while the reinforcements are inside head 18, while the reinforcements are being passed to head 18 (e.g., as a prepreg material), and/or while the reinforcements are discharging from head 18, as desired. The matrix, dry reinforcements, and/or reinforcements that are already exposed to the matrix (e.g., wetted reinforcements) may be transported into head 18 in any manner apparent to one skilled in the art.

[0015] The matrix and reinforcement may be discharged from head 18 via at least two different modes of operation. In a first mode of operation, the matrix and reinforcement are extruded (e.g., pushed under pressure and/or mechanical force) from head 18, as head 18 is moved by support 16 to create the 3-dimensional shape of structure 12. In a second mode of operation, at least the reinforcement is pulled from head 18, such that a tensile stress is created in the reinforcement during discharge. In this mode of operation, the matrix may cling to the reinforcement and thereby also be pulled from head 18 along with the reinforcement, and/or the matrix may be discharged from head 18 under pressure along with the pulled reinforcement. In the second mode of operation, where the matrix is being pulled from head 18, the resulting tension in the reinforcement may increase a strength of structure 12, while also allowing for a greater length of unsupported material to have a straighter trajectory (i.e., the tension may act against the force of gravity to provide free-standing support for structure 12).

[0016] The reinforcement may be pulled from head 18 as a result of head 18 moving away from a build surface 22. In particular, at the start of structure-formation, a length of matrix-impregnated reinforcement may be pulled and/or pushed from head 18, deposited onto a build surface 22 within vat 14, and cured, such that the discharged material adheres to build surface 22. Thereafter, head 18 may be moved away from build surface 22, and the relative movement may

cause the reinforcement to be pulled from head 18. It should be noted that the movement of the reinforcement through head 18 could be assisted (e.g., via internal feed mechanisms), if desired. However, the discharge rate of the reinforcement from head 18 may primarily be the result of relative movement between head 18 and build surface 22, such that tension is created within the reinforcement. It is contemplated that build surface 22 could be moved away from head 18 instead of or in addition to head 18 being moved away from build surface 22.

[0017] One or more cure enhancers (e.g., one or more light sources, an ultrasonic emitter, a laser, a heater, a catalyst dispenser, a microwave generator, etc.) 24 may be mounted proximate (e.g., on and/or trailing from) head 18 and configured to enhance a cure rate and/or quality of the matrix as it is discharged from head 18. Cure enhancer 24 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 head 18.

[0018] During the fabrication of structure 12 by head 18, the internal skeleton may be incrementally submerged within the resin of vat 14. For example, after fabrication of each horizontal layer of structure 12, the level of the resin in vat 14 may be raised by a height of the new layer. The level of resin in vat 14 may be regulated by selectively allowing (e.g., by opening and closing a valve 26) additional resin to enter vat 14 from a supply 28.

[0019] After the raising of the resin level within vat 14, energy source 20 may be selectively regulated to cause curing of the resin that coats the new layer of structure 12. Energy source 20 may be, for example, a UV light projector, a laser, an electron beam emitter, and/or another source that is controlled to expose select surfaces of only the new layer of structure 12 that was just fabricated by head 18.

[0020] It should be noted that energy source 20 and cure enhancer(s) 24 may produce the same type and magnitude of cure energy, or different types and magnitudes of cure energy, as desired. In one exemplary embodiment, energy source 20 is an array of lasers (e.g., at least three different blue lasers) that focus light energy having a wavelength of about 430-470nm together at particular points within vat 14 to cause nearly instantaneous solidification and curing of the resin within vat 14. In this same embodiment, one or more UV lights may function as cure enhancers

24, to expose the matrix to light having a wavelength of about 365-405nm. In other embodiments, combinations of acoustic energy, heat, and/or light may be used together, if desired.

[0021] In some applications, care should be taken to avoid oxygen-exposure of the matrix inside the composite material of structure 12, prior to coating of the new layer with cured resin from vat 14. In these applications, a shield gas (e.g., an inert gas such as argon, helium, nitrogen, etc.) may be directed from a gas supply 30 into vat 14, in an amount sufficient to create a barrier 32 over structure 12.

[0022] A controller 34 may be provided and communicatively coupled with support 16, head 18, energy source 20, cure enhancers 24, valve 26, and/or gas supply 30. Controller 34 may embody a single processor or multiple processors that include a means for controlling an operation of system 10. Controller 34 may include one or more general- or special-purpose processors or microprocessors. Controller 34 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 34, including power supply circuitry, signal-conditioning circuitry, solenoid/motor driver circuitry, communication circuitry, and other appropriate circuitry. Moreover, controller 34 may be capable of communicating with other components of system 10 via wired and/or wireless transmission.

[0023] One or more maps may be stored in the memory of controller 34 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 34 to determine desired characteristics of energy source 20, cure enhancers 24, the associated matrix and resin, 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, matrix, and/or resin to be discharged at a particular location within structure 12; an amount, intensity, shape, and/or location of desired curing; and/or a location and thickness of any surface coatings to be generated by energy source 20. Controller 34 may then correlate operation of support 16 (e.g., the location and/or orientation of head 18), the discharge of material from head 18 (a type of material, desired performance of the material,

cross-linking requirements of the material, a discharge rate, etc.), the operation of energy source 20, the operation of cure enhancers 24, and/or the operation of valve 26, such that structure 12 is produced in a desired manner.

[0024] Another embodiment of system 10 is disclosed in Fig. 2. Like the embodiment of Fig. 1, system 10 of Fig. 2 may also include vat 14, support 16, head 18, and energy source 20. However, in contrast to Fig. 1, system 10 of Fig. 2 may include an additional support 36 that is connected to move build surface 22. In this embodiment, the level of resin within vat 14 may remain substantially constant, and support 36 may be selectively activated by controller 34 to incrementally lower build surface 22 and structure 12 into the resin after fabrication of each new layer of structure 12 by head 18. Support 36 may take any form known the art, for example an elevator having an external motor 38 that is connected to the end of a lead screw 40, and one or more brackets 42 transforming a rotation of lead screw 40 into a lowering of build surface 22.

[0025] In one example, build surface 22 may be at least partially transparent and/or perforated. The partially transparent surface may allow for cure energy from a second energy source 20 (e.g., a source located below build surface 22) to pass through build surface 22 and expose a lower end of structure 12. The perforated nature of build surface 22 may allow for resin to flow from a lower section of vat 14 to an upper section, by way of build surface 22, during lowering of building surface 22.

[0026] Also in contrast to the embodiment of Fig. 1, support 16 may take a different form. For example, support 16 may embody a gantry that is located at an upper end of vat 14. In this embodiment, support 16 may function to only move head 18 transversely (e.g., in X- and Y-directions). It is contemplated, however, that support 16 could have another configuration (e.g., a hybrid gantry/arm configuration), if desired.

Industrial Applicability

[0027] The disclosed system may be used to continuously manufacture composite structures having any desired cross-sectional size, shape, length, density, strength and/or surface texture. 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 and/or resin. Operation of system 10 will now be described in detail.

[0028] At a start of a manufacturing event, information regarding a desired structure 12 may be loaded into system 10 (e.g., into controller 34 that is responsible for regulating operations of system 10). 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, 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 matrixes may be selectively installed and/or continuously supplied into head 18, and vat 14 may be filled with a specific amount and/or type of resin.

[0029] Installation of the reinforcement may be performed by passing the reinforcements down through print head 18. Installation of the matrix may include filling head 18 with matrix and/or coupling of an extruder (not shown) to head 18. Head 18 may then be moved by support 16 under the regulation of controller 34 to cause matrix-coated reinforcements to be placed against or on a corresponding build surface 22. Cure enhancers 24 within head 18 may then be selectively activated to cause hardening of the matrix surrounding the reinforcements, thereby bonding the reinforcements to build surface 22.

[0030] The component information may then be used to control operation of system 10. For example, the reinforcements may be pulled and/or pushed from head 18 (along with the matrix), while support 16 selectively moves head 18 in a desired manner during exposure of the matrix-coated reinforcement to cure energy, such that an axis of the resulting structure 12 follows a desired trajectory.

[0031] In some situations, an outer coating on structure 12 may be beneficial. The outer coating may provide, for example, a desired surface texture (e.g., smoothness), a desired property (e.g., hardness, conductivity, etc.), or a desired appearance (e.g., sheen) that cannot be created via the discharge of matrix-coated reinforcement from head 18 alone.

[0032] As each layer of matrix-coated reinforcement is deposited by head 18 and cured, controller 34 may cause the layer to be selectively coated with resin from vat 14 (e.g., by increasing the resin level or by lowering build surface 22 incrementally). Thereafter, one or more of energy sources 20 may be situated to flash a pattern onto the just-submersed layer of

structure 12 (e.g., from above, below, and/or a side of structure 12), thereby causing the resin in vat 14 to solidify at the surface of the submersed layer.

[0033] It is contemplated that, rather than the outer coating described above being applied layer-by-layer, as head 18 creates structure 12, the outer coating could be applied after all of structure 12 has been created. For example, the completed structure 12 may be lowered into vat 14 (e.g., all at once or one level at a time), and a desired pattern flashed on the completed outer surface of structure 12 to create the coating. The pattern may be flashed layer-by-layer onto the completed surface of structure 12, or flashed all at once, as desired. It should also be noted that the coating processes of Figs. 1 and 2 may be used for more than coating structure 12. That is, the processes may allow entirely new features to extend from and/or built on top of structure 12, albeit structures without fiber-reinforcement. In addition, it may be possible for layers of matrix-coated reinforcement to be interleaved with any number of adjacent layers of only cured resin, if desired. Once structure 12 has grown to a desired length, structure 12 may be disconnected (e.g., severed) from head 18 in any desired manner.

[0034] It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed additive manufacturing system. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed additive manufacturing system. 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.

Claims

What is claimed is:

1. An additive manufacturing system, comprising:

a vat configured to hold a supply of resin;

a build surface disposed inside the vat;

a print head configured to discharge a matrix-coated continuous reinforcement onto the build surface; and

an energy source configured to expose resin on a surface of the matrix-coated continuous reinforcement to a cure energy.

2. The additive manufacturing system of claim 1, further including a cure enhancer configured to at least partially cure a matrix in the matrix-coated continuous reinforcement prior to exposure of the resin.

3. The additive manufacturing system of claim 2, further including an elevator configured to incrementally lower the matrix-coated continuous reinforcement into the supply of resin.

4. The additive manufacturing system of claim 3, wherein the build surface is perforated to pass resin from a section of the vat below the build surface to a section of the vat above the build surface during incremental lowering of the matrix-coated continuous reinforcement.

5. The additive manufacturing system of claim 2, further including a valve moveable to incrementally raise a level of the supply of resin inside the vat after discharge of the matrix-coated continuous reinforcement.

6. The additive manufacturing system of claim 1, further including a support configured to move the print head inside the vat.

7. The additive manufacturing system of claim 6, further including a controller in communication with the print head, the energy source, and the

support, the controller being configured to cause cured layers of the matrix-coated continuous reinforcement to be interleaved with cured layers of the resin.

8. The additive manufacturing system of claim 6, further including a controller in communication with the print head, the energy source, and the support, the controller being configured to cause all layers of the matrix-coated continuous reinforcement to be cured prior to curing of the resin on the surface of the matrix-coated continuous reinforcement.

9. The additive manufacturing system of claim 1, wherein the energy source is at least one of an overhead UV projector, laser, and electron beam generator.

10. The additive manufacturing system of claim 9, wherein:
the build surface is at least partially transparent; and
the additive manufacturing system further includes a second energy source configured to expose resin on a surface of the matrix-coated continuous reinforcement to cure energy via the build surface.

11. The additive manufacturing system of claim 1, further including a gas supply configured to generate an oxygen inhibiting barrier at a surface of the resin inside of the vat.

12. A method of additively manufacturing a composite structure, comprising:
discharging from a print head a matrix-coated continuous reinforcement onto a build surface;
submerging the matrix-coated continuous reinforcement in resin; and
exposing resin at a surface of the matrix-coated continuous reinforcement to a cure energy.

13. The method of claim 12, further including exposing a matrix in the matrix-coated continuous reinforcement to cure energy to at least partially cure the matrix prior to submerging the matrix-coated continuous reinforcement in resin.

14. The method of claim 13, further including incrementally lowering the matrix-coated continuous reinforcement into the resin.

15. The method of claim 14, further including passing resin through the build surface during incremental lowering of the matrix-coated continuous reinforcement.

16. The method of claim 13, further including incrementally raising a level of resin inside a vat housing the build surface.

17. The method of claim 16, further including moving the print head inside the vat.

18. The method of claim 12, further including interleaving cured layers of the matrix-coated continuous reinforcement with cured layers of the resin.

19. The method of claim 12, further including at least partially curing all of the matrix-coated continuous reinforcement prior to curing of any resin on the surface of the matrix-coated continuous reinforcement.

20. The method of claim 12, wherein exposing resin at the surface of the matrix-coated continuous reinforcement to the cure energy includes directing the cure energy through the build surface.

21. The method of claim 12, further including generating an oxygen inhibiting barrier at a surface of the resin.

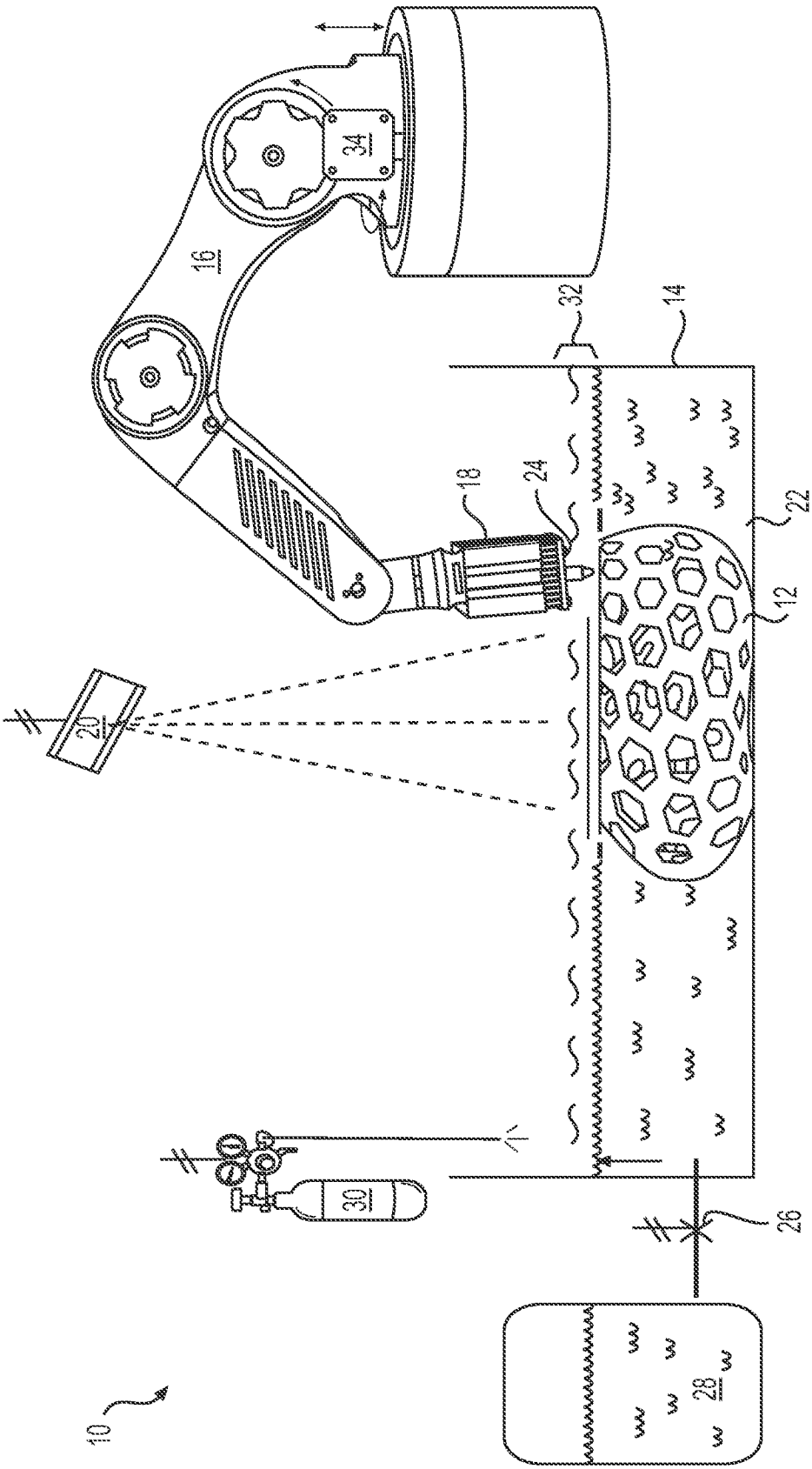


FIG. 1

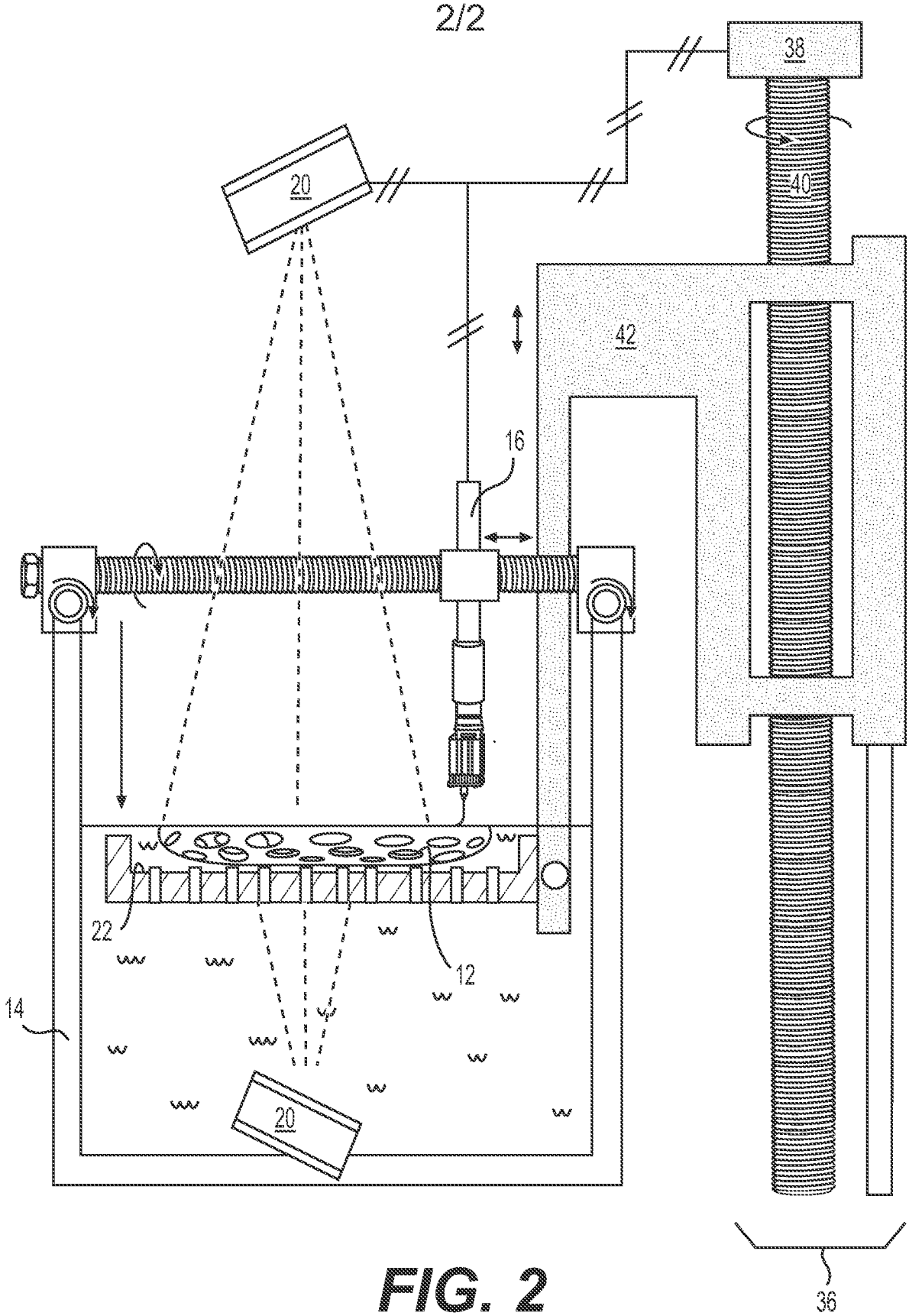


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 18/14483

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B29C 67/00 (2018.01)
CPC - B29B 15/122, B29C 2035/0827, B29C 35/0805

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,529,471 A (KHOSHEVIS) 25 June 1996 (25.06.1996) Abstract, Col 1 lines 44-47; Col 2 lines 29-34, 36-41; Col 4 lines 45-54; Col 5 lines 10-15, 20-24, 34-38; Col 8 lines 39-44; Col 9 lines 6-8, 22-25; Col 11 lines 1-2; Figure 1	1-21
A	US 2015/0102532 A1 (CARBON3D, INC.) 16 April 2015 (16.04.2015) Entire document, especially para[0009], [0172]	1-21
A	US 7,892,474 B2 (SHKOLNIK et al.) 22 February 2011 (22.02.2011) Entire document	1-21
A	US 5,236,637 A (HULL) 17 August 1993 (17.08.1993) Entire document	1-21
A	US 2013/0292862 A1 (JOYCE) 07 November 2013 (07.11.2013) Entire document	1-21
A	WO 2016/184997 A1 (ADDIFAB APS) 24 November 2016 (24.11.2016) Entire document	1-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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Date of the actual completion of the international search	Date of mailing of the international search report
24 April 2018	11 MAY 2018
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)