(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 May 2017 (26.05.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/087572 A1

(51) International Patent Classification:
B22F 3/00 (2006.01) *B29C 67/02* (2017.01)
B22F 7/04 (2006.01) *B29C 67/24* (2006.01)
B29C 67/00 (2017.01)

(21) International Application Number: PCT/US2016/062356

(22) International Filing Date: 16 November 2016 (16.11.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/256,436 17 November 2015 (17.11.2015) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

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

(54) Title: APPARATUS AND PROCESS FOR PRODUCING ADDITIVE MANUFACTURED METAL MATRIX COMPOSITES AND ARTICLE OF MANUFACTURE THEREOF

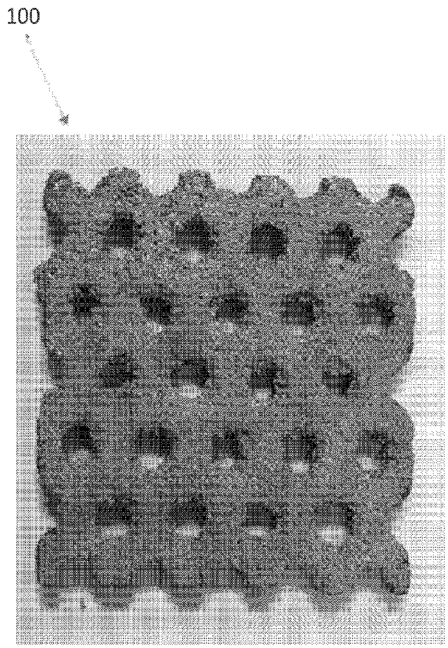

FIG. 1

(57) Abstract: A method, product, apparatus, and article of manufacture for the application of the Composite Based Additive Manufacturing (CBAM) method to produce objects in metal, and in metal fiber hybrids or composites. The approach has many advantages, including the ability to produce more complex geometries than conventional methods such as milling and casting, improved material properties, higher production rates and the elimination of complex fixturing, complex tool paths and tool changes and, for casting, the need for patterns and tools. The approach works by slicing a 3D model, selectively printing a fluid onto a sheet of substrate material for each layer based on the model, flooding onto the substrate a powdered metal to which the fluid adheres in printed areas, clamping and aligning a stack of coated sheets, heating the stacked sheets to melt the powdered metal and fuse the layers of substrate, and removing excess powder and unfused substrate.

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APPARATUS AND PROCESS FOR PRODUCING ADDITIVE MANUFACTURED METAL MATRIX COMPOSITES AND ARTICLE OF MANUFACTURE THEREOF

This application claims the benefit of U.S. Provisional Application No. 62/256,436, filed November 17, 2015. This application incorporates the following applications by reference (including their drawing figures): Application Nos. US 61/528,537; PCT/US12/52946; US 13/582,939; EP20120828967; US 61/769,724; PCT/US14/18806; US 14/835,685; US 14/835,690; US 14/835,697; US 14/703,372; US 62/243,590; US 61/773,810; US 14/199,603; US 61/914,613; and US 14/566,661.

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to three-dimensional fabrication.

BACKGROUND OF THE INVENTION

International Publication No. WO 2014/134224 A2 (corresponding to Application No. PCT/US14/18806) entitled “Methods and Apparatus for Three-Dimensional Composites” (as well as Application Nos. US 61/528,537; PCT/US12/52946; US 13/582,939; EP20120828967; US 61/769,724; US 14/835,685; US 14/835,690; US

14/835,697; US 14/703,372; US 62/243,590) describes a "layered" method and apparatus for producing three dimensional objects called "Composite Based Additive Manufacturing" or CBAM that produces a three-dimensional object using generally substrates, typically fibrous substrates and polymers. The present invention references International Publication No. WO 2014/134224 A2, and describes use of the technique described in the International Publication with metals.

SUMMARY OF THE INVENTION

The CBAM method described in International Publication No. WO 2014/134224 A2 extends the range of materials that can be used with 3D printing to create three-dimensional objects. Until recently, work on this technique has concentrated on using various substrates, including carbon fiber, polymer based material and natural fibers among others and various polymers as bonding agents. This application describes the application of the CBAM method and apparatus to produce objects in metal, and in metal fiber hybrids or composites. This application also describes an article of manufacture thereof.

This approach has a number of advantages including: the ability to produce more complex geometries than conventional methods such as milling and casting; improved material properties over conventional metals; higher production rates; the elimination of complex fixturing, complex tool paths and tool changes; and, in the case of casting, the need for patterns and tools.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a metal piece made by the method described in this application.

FIG. 2 is a flowchart illustrating the steps to produce a 3D metal object in accordance with the teachings of the present invention.

FIG. 3 shows an apparatus used to selectively deposit liquid (to which powder adheres), in an illustrative implementation of this invention.

FIG. 4 is a high-level block diagram of processors, in an illustrative implementation of this invention

FIG. 5 shows a compressive device, after a number of substrate tiles (layers) have been placed in it, one on top of the other in a compressive device. The tiles are aligned by inserting registration pins of the compressive device into the registration holes of each tile, respectively.

FIG. 6 shows a compressive device, after substrate layers with all of the “slices” of a ring torus have been inserted into it. Springs in the compressive device press the substrate layers together.

FIG. 7 is a block diagram that shows a processor that controls multiple components of an apparatus for fabricating a 3D object.

DETAILED DESCRIPTION OF INVENTION

Output of the Technique

FIG. 1 is a metal piece 100 made by the method described in this application. The method of making this metal piece is described in detail below.

Description of the Technique

FIG. 2 is a flowchart illustrating the steps to produce a 3D metal object in accordance with the teachings of the present invention:

1. Generate a CAD model (Step 102) which is sliced into layers (Step 104) by using a slicer program like Netfabb as described in (International Publication No. WO 2014/134224 A2, ¶0055; see also US Application Nos. US 61/528,537 and US 61/769,724). Each slice also includes registration holes, which will be used to orient each printed layer of substrate within the finished object exactly (International Publication No. WO 2014/134224 A2, ¶00121).

2. The output of the slicer, which for example may be a bitmap file, is sent to an inkjet printer (Step 106). For each layer, the printer selectively prints a fluid onto a sheet of substrate material (Step 108) (International Publication No. WO 2014/134224 A2, ¶00113). The fluid may either be the bonding agent itself in liquid form; or it may be a liquid to which a powdered bonding agent adheres. Substrates can include fiberglass, high temperature glass fibers, boron fibers, or carbon fibers.

3. If powdered bonding agent is being used, it is flooded onto the printed substrate (International Publication No. WO 2014/134224 A2, ¶0059). The powder adheres to the printed areas. Excess powder is removed, either by a stream of air, vacuum, vibration, or other mechanical means.

4. The coated sheets of substrate are stacked in press or clamp (Step 110) (International Publication No. WO 2014/134224 A2, ¶00124), using the registration holes of each layer to align the printed portions of each sheet within the stack (International Publication No. WO 2014/134224 A2, ¶00106).

5. The assembled sheets are then heated and possibly compressed in an oven, to melt the bonding material and fusing the layers of substrate to form the 3D object (Step 112) (International Publication No. WO 2014/134224 A2, ¶00149).

6. The unfused substrate around the 3D object is then removed (Step 114), usually by abrasive blasting material or chemical means (International Publication No. WO 2014/134224 A2, ¶0081).

Issues in Using Metals with the Technique

It has been discovered that metals can be used with this technique. In one example the substrate used is a non-woven carbon fiber veil such as available from Hollingsworth and Vose. Veils that have been metal coated can also be used. The veil or substrate is printed as described above on an inkjet printer using, for example, a HP45 thermal inkjet head with a solution primarily of de-ionized water, pyrrolidone and alcohol. The solution may have an anti-evaporant including glycols and pyrrolidones. This fluid is printed on the area of the substrate that would be part of the object, i.e., the printed area corresponds to a layer shape for the object . This is done for each layer as described in the previous applications. Each layer is flooded with a metal powder for example a solder powder. The excess powder is removed by mechanical, vacuum, vibration or compressed air or a combination of such methods. This leaves the solder powder selectively deposited. One of the problems with using a metal powder in a process of this kind is that the powder oxidizes so that that when heated to its melting point the particles of the powder will not fuse together well. There are a number of solutions to this problem, one such solution is to mix the metal powder with a powder flux such as rosin which acts as a reducing agent. A typical flux to metal powder ratio is about 50/50. Another method is to melt the powders in a reducing, vacuum and/or inert atmosphere oven. In this way other metals or alloys can be used, such as aluminum, steel, stainless steel, copper, brass, and titanium among others. In addition liquid flux may be used as or in combination with the printing fluid, through selective deposition methods such as inkjet printing.

As an example the metal powder can be mixed with a powder flux before it is deposited on the substrate. Then all the layers of the object are printed and stacked in register as described in the earlier applications. They are compressed and heated as described in the earlier applications. The heating temperature is raised to the melting point of the powder. The layers fuse together and produce a build block. After the build block is removed from the compression jig the build block is abrasively blasted and the areas where no powder adhered, that is the portions of the object that were not coated with metal, are abrasive blasted off, the uncoated carbon fiber being very fragile. What is left is a three dimensional carbon fiber metal composite of the part that was represented by the CAD model.

FIG. 3 shows an apparatus used to selectively deposit liquid (to which powder adheres), in an illustrative implementation of this invention. Registration guide pins 501 are inserted through a substrate layer 503 in order to properly align the substrate layer 503. A solenoid valve, or inkjet head or heads 505 are used to selectively dispense liquid from a liquid reservoir 507 though a nozzle 509 unto the substrate layer 503. The nozzle 509 is rastered in a 2D plane 510 that is parallel to, and above, the substrate layer 503, so that the liquid is selectively deposited at desired x, y coordinates of the substrate layer 503, and not deposited in other areas of the substrate layer 503. To achieve this rastering, a stepper motor 511 actuates two belts (not shown) that causes a support member (not shown) to move along two rails (not shown) in a direction parallel to the x axis. A second stepper motor (not shown) and third belt (not shown) are mounted on the support member, and are used to move a nozzle support (not shown) in a direction parallel to the y axis. The nozzle 509 is attached to the nozzle support. Together, the two stepper motors can move the nozzle 509 to any desired x, y coordinate above the substrate layer. A page wide head may also be used. A microprocessor 513 controls the stepper motors and the solenoid valve or inkjet head, thereby controlling when and where liquid is dispensed on the substrate layer 503. Alternately, rather than rastering in a line-by-line pattern, the stepper motors may cause the nozzle or nozzles 509 to move in other 2D patterns in the 2D plane to cause the liquid to be deposited at certain x, y coordinates. FIG. 2 does not show an apparatus for heating and pressing multiple layers of substrate, or for removing excess substrate. In some implementations, the substrate layer is moved to a different position before those steps occur.

FIG. 4 is a high-level block diagram of processors, in an illustrative implementation of this invention. A CAD model of a desired 3D object in STL file format is created using a remote processor 601. This processor 601 employs software (such as Netfabb.RTM. Studio software) to create a machine-specific build file. The machine-specific build file is exported to a second processor 603. Depending on the particular implementation, this second processor controls the operation, including movements, of: (1) an inkjet head or other device that selectively deposits liquid, (2) a vibrating trough (and/or compressed air) that spreads out the powder on the substrate and then removes the excess powder. Alternately, this invention may be implemented with other arrangements of processors. For example, more than one remote processor and more than one onboard processor may be employed, and any of the above tasks may be handled by one or more of these different processors.

FIG. 5 shows a compressive device 803, after a number of substrate layers (e.g., 801) have been placed in it, one on top of the other in order.

FIG. 6 shows substrate layers being compressed in the compressive device 903. Screws 905, 907, 909, 911, plates 913, 915 and a spring 917 in the compressive device are used to exert pressure.

FIG. 7 is a high-level block diagram of some hardware that may be used in this invention. One or more processors 1301 control an applicator 1303, a heating element 1305, an actuator 1307, an artificial pressure source 1309, and a stirrer in a container of liquid 1311. The applicator 1303 deposits powder in positive regions, but not in negative regions, of substrate layers. The heating element 1305 transforms the powder into matter that flows and then hardens. The resulting hardened material is disposed in a spatial pattern that infiltrates the substrate layers. The artificial pressure source 1309 may comprise a press, clamp, spring, elastic element, or other device for compressing the substrate layers. The stirrer may be used to stir a liquid that is used for removing excess substrate.

CLAIMS

What is claimed is:

1. A method for producing an object, comprising:

taking a file of layers of a 3D object;

for each layer, printing a fluid selectively onto a sheet of substrate material;

flooding onto the substrate a powdered metal which adheres to the selectively printed fluid;

removing excess powder; and

heating and compressing a plurality of sheets in stacked registration to melt the powdered metal and fuse the layers of substrate.

2. The method of claim 1, further comprising removing unfused material of the substrate sheets.

3. The method of claim 1, wherein registration holes are used to stack the sheets in registration.

4. The method of claim 1, wherein the substrate material comprises fiberglass, high temperature glass fibers, boron fibers, or carbon fibers.

5. The method of claim 1, wherein the powdered metal is a solder powder.

6. The method of claim 1, wherein the powdered metal is aluminum, steel copper brass titanium or other metal or alloy.

7. The method of claim 1, wherein the excess powder is removed by a stream of air, vacuum, vibration, or other mechanical means.

8. The method of claim 1, wherein the powdered metal is mixed with a powder flux acting as a reducing agent.

9. The method of claim 1, wherein the powdered metal is melted in a reducing atmosphere, vacuum, or inert atmosphere oven.

10. The method of claim 1, wherein the heating temperature is raised to the melting point of the powder.

11. The method of claim 2, wherein unfused substrate is removed by air-blasting with an abrasive material or chemical means.

12. The method of claim 1, wherein the substrate material is a non-woven carbon fiber veil.

13. The method of claim 1, wherein the substrate material is a metal coated veil.

14. The method of claim 1, wherein the printing is done using an inkjet head with a solution primarily of de-ionized water, pyrrolidone, and alcohol.

15. The method of claim 14, wherein the solution has an anti-evaporant chosen from the group consisting of glycols and pyrrolidones.

16. A product produced by a process comprising:

taking a file of layers of a 3D object;

for each layer, printing a fluid selectively onto a sheet of substrate material;

flooding onto the substrate a powdered metal which adheres to the selectively printed fluid;

removing excess powder; and

heating and compressing the sheets in stacked registration to melt the powdered metal and fuse the layers of substrate.

17. The product of claim 16, wherein the process further comprises removing unfused material of the substrate sheets.

18. The product of claim 16, wherein registration holes are used to stack the sheets in registration.

19. The product of claim 16, wherein the substrate material comprises fiberglass, high temperature glass fibers, boron fibers, or carbon fibers.

20. The product of claim 16, wherein the powdered metal is a solder powder.

21. The product of claim 16, wherein the powdered metal is aluminum, steel copper brass titanium or other metal or alloy.

22. The product of claim 16, wherein the excess powder is removed by a stream of air, vacuum, vibration, or other mechanical means.

23. The product of claim 16, wherein the powdered metal is mixed with a powder flux acting as a reducing agent.

24. The product of claim 16, wherein the powdered metal is melted in a reducing atmosphere, vacuum, or inert atmosphere oven.

25. The product of claim 16, wherein the heating temperature is raised to the melting point of the powder.

26. The product of claim 16, wherein unfused substrate is removed by air-blasting with an abrasive material or chemical means.

27. The product of claim 16, wherein the substrate material is a non-woven carbon fiber veil.

28. The product of claim 16, wherein the substrate material is a metal coated veil.

29. The product of claim 16, wherein the printing is done using an inkjet head with a solution primarily of de-ionized water, pyrrolidone, and alcohol.

30. The product of claim 29, wherein the solution has an anti-evaporant chosen from the group consisting of glycols and pyrrolidones.

31. An apparatus for producing an object, comprising:

an inkjet printer for taking a file of layers of a 3D object and, for each layer, printing a fluid selectively onto a sheet of substrate material;

an applicator for flooding onto the substrate a powdered metal which adheres to the selectively printed fluid;

a removal device to remove excess powder; and

a heating and compressing apparatus to heat and compress the sheets in stacked registration to melt the powdered metal and fuse the layers of substrate.

32. The apparatus of claim 31, further comprising a removal device to remove unfused material of the substrate sheets.

33. The apparatus of claim 31, wherein the substrate material comprises fiberglass, high temperature glass fibers, boron fibers, or carbon fibers.

34. The apparatus of claim 31 wherein the powdered metal is a solder powder.

35. The apparatus of claim 31, wherein the powdered metal is aluminum, steel copper brass titanium or other metal or alloy.

36. The apparatus of claim 31, wherein the excess powder is removed by a stream of air, vacuum, vibration, or other mechanical means.

37. The apparatus of claim 31, wherein the powdered metal is mixed with a powder flux acting as a reducing agent.

38. The apparatus of claim 31, wherein the powdered metal is melted in a reducing atmosphere, vacuum, or inert atmosphere oven.

39. The apparatus of claim 31, wherein the heating temperature is raised to the melting point of the powder.

40. The apparatus of claim 31, wherein unfused substrate is removed by air-blasting with an abrasive material or chemical means.

41. The apparatus of claim 31, wherein the substrate material is a non-woven carbon fiber veil.

42. The apparatus of claim 31, wherein the substrate material is a metal coated veil.

43. The apparatus of claim 31, wherein the printing is done using an inkjet head with a solution primarily of de-ionized water, pyrrolidone, and alcohol.

44. The apparatus of claim 43, wherein the solution has an anti-evaporant chosen from the group consisting of glycols and pyrrolidones.

45. A three-dimensional article of manufacture comprising a plurality of substrate layers that are infiltrated or coated by, and bound together by, a hardened metal material, wherein each substrate layer is a sheet-like structure that is substantially planar or flat and is made from materials that can be abraded, abrasively blasted, or chemically removed, and wherein the substrate layer materials are selected from the group consisting of carbon fibers, ceramic fibers, polymer fibers, glass fibers, and metal fibers.

46. The article of manufacture of claim 45, wherein the hardened material exhibits a set of one or more characteristics, which set is sufficient for distinguishing the hardened material as having formed as a result of powder having been positioned on the substrate layers and then being at least partially softened followed by hardening.

47. The article of manufacture of claim 45, wherein the metal material is an alloy.

48. The article of manufacture of claim 45, wherein the metal material comprises ferrite or metal particles.

49. The three-dimensional article of manufacture of claim 45, wherein the article has multiple three-dimensional angles, curves, or planes in differing orientations.

50. A three-dimensional article of manufacture comprising a plurality of substrate layers that are infiltrated or coated by and bound together by a hardened metal material, wherein each substrate layer is a sheet-like structure that is substantially planar or flat and is made from materials that can be abraded, abrasively blasted, or chemically removed, and wherein the hardened material exhibits a set of one or more characteristics, which set is sufficient for distinguishing the hardened material as having formed as a result of powder having been positioned on the substrate layers and then being at least partially softened followed by hardening.

51. The three-dimensional article of manufacture of claim 50, wherein the article has multiple three-dimensional angles, curves, or planes in differing orientations.

52. The three-dimensional article of manufacture of claim 50, wherein the substrate layer materials are selected from the group consisting of carbon fibers, ceramic fibers, polymer fibers, glass fibers, and metal fibers.

53. The three-dimensional article of manufacture of claim 50, wherein the powder is made of one or more metals.

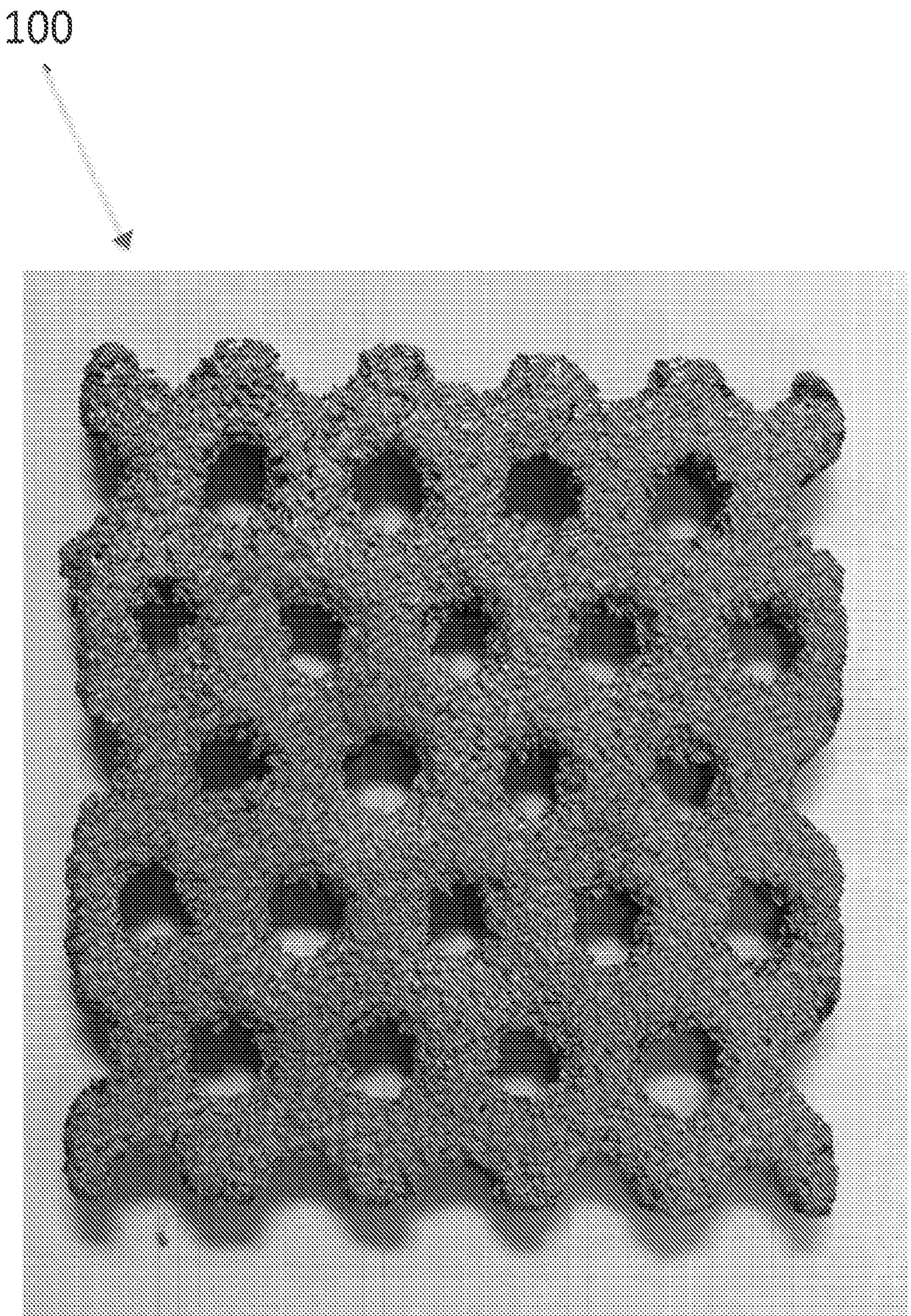

FIG. 1

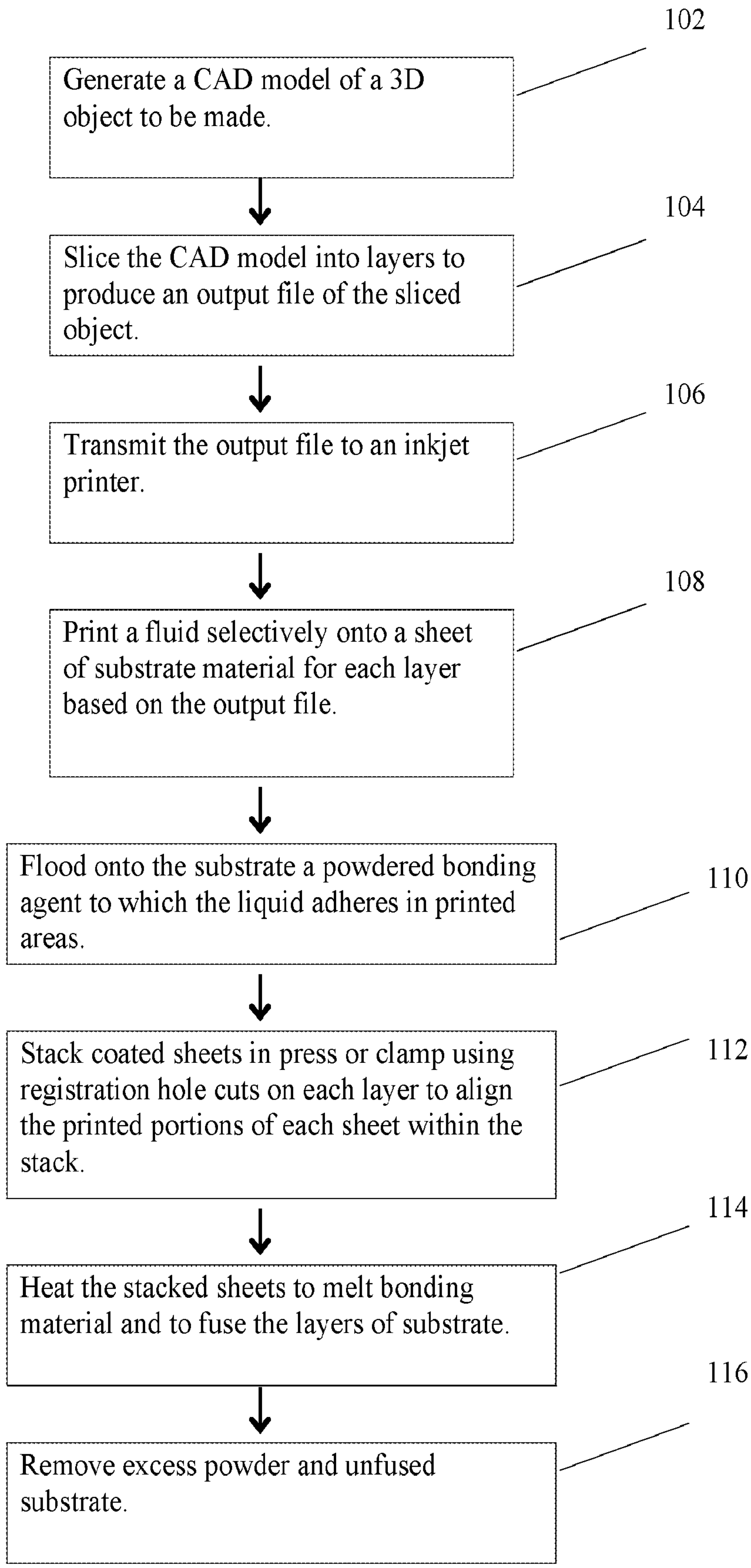
102
Generate a CAD model of a 3D object to be made.
104
Slice the CAD model into layers to produce an output file of the sliced object.
106
Transmit the output file to an inkjet printer.
108
Print a fluid selectively onto a sheet of substrate material for each layer based on the output file.
110
Flood onto the substrate a powdered bonding agent to which the liquid adheres in printed areas.
112
Stack coated sheets in press or clamp using registration hole cuts on each layer to align the printed portions of each sheet within the stack.
114
Heat the stacked sheets to melt bonding material and to fuse the layers of substrate.
116
Remove excess powder and unfused substrate.

FIG. 2

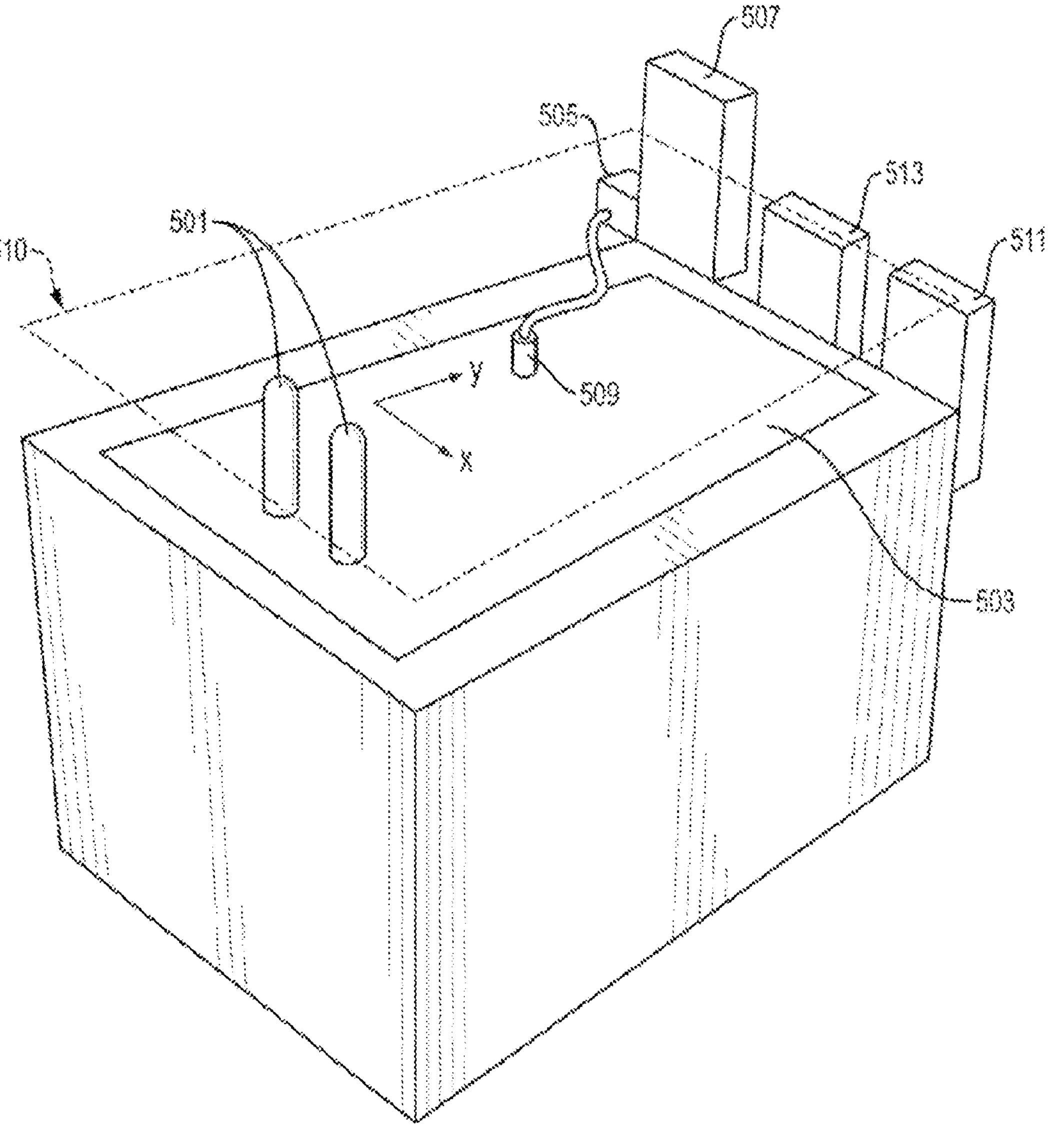

FIG. 3

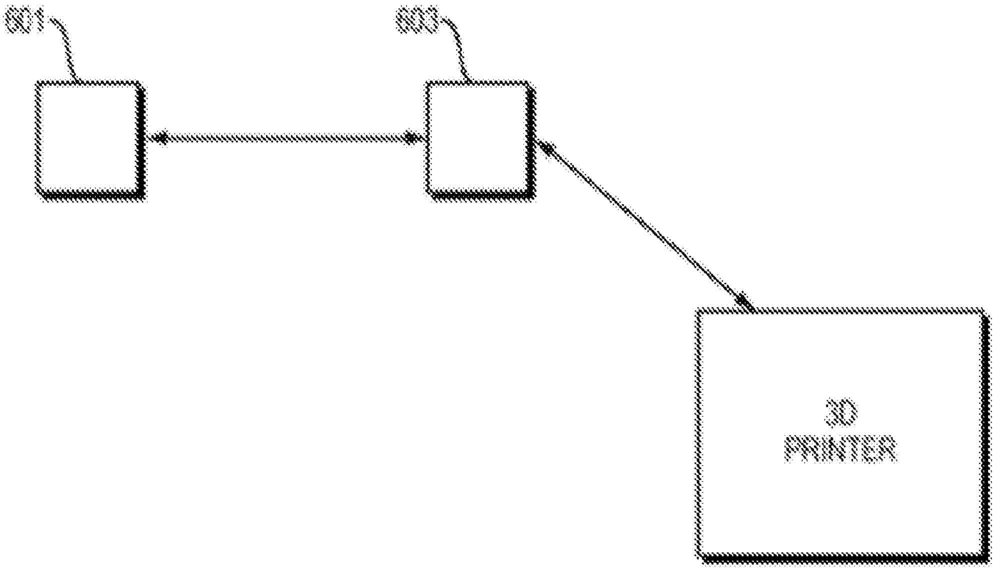

FIG. 4

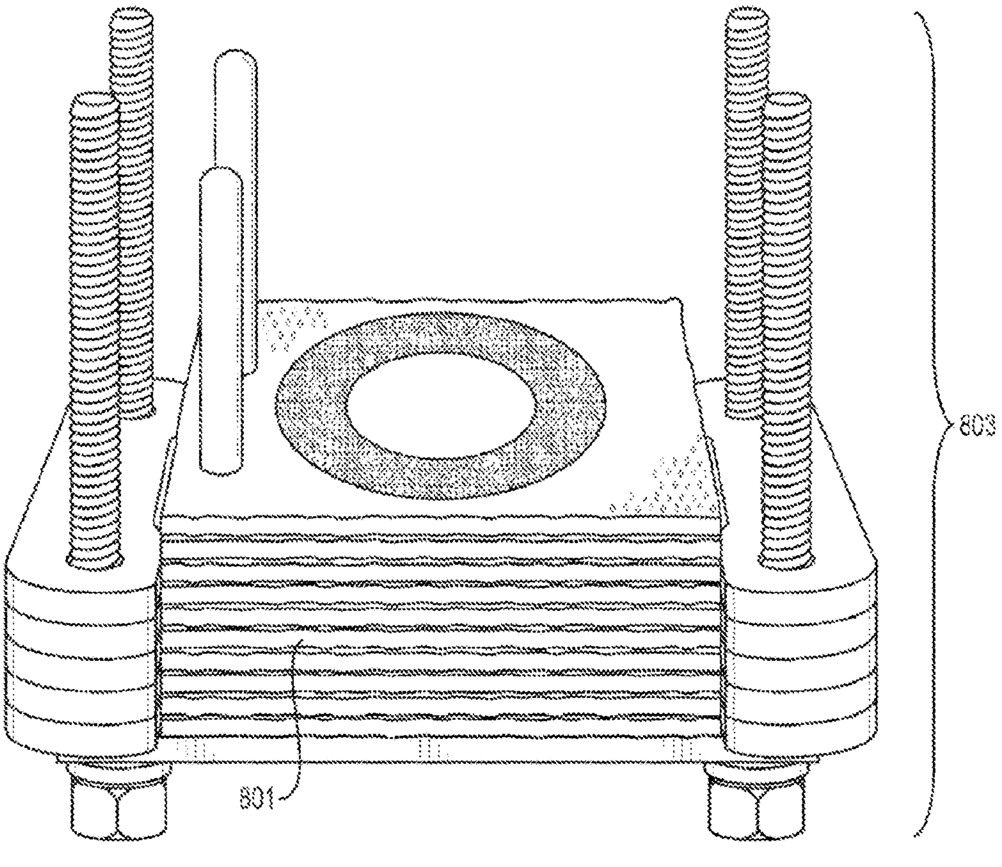

FIG. 5

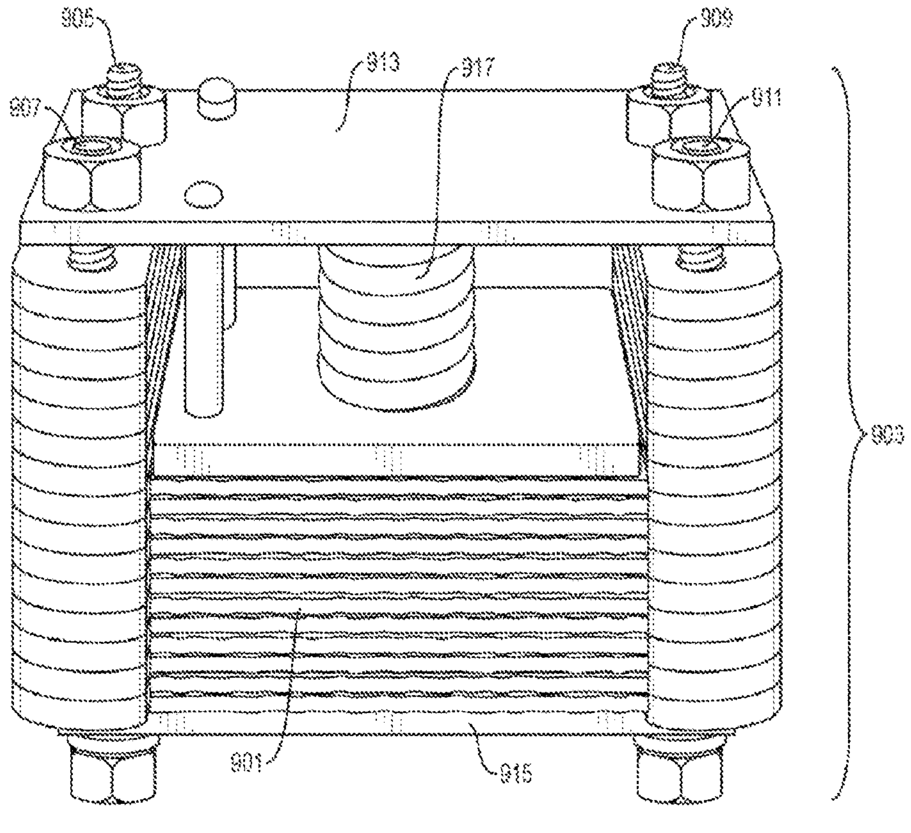

FIG. 6

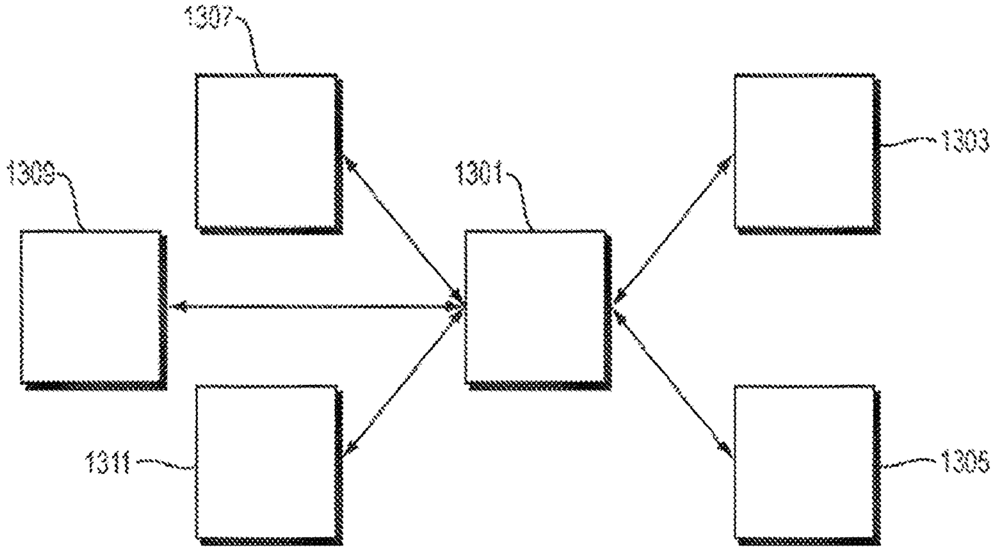

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/062356

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B22F 3/00; B22F 7/04; B29C 67/00; B29C 67/02; B29C 67/24 (2016.01)
CPC - B22F 3/008; B22F 2998/00; B29C 67/0074; B29C 67/0077; B29C 67/0081; B33Y 10/00 (2016.11)
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)
IPC - B22F 3/00; B22F 7/04; B29C 67/00; B29C 67/02; B29C 67/24
CPC - B22F 3/008; B22F 2998/00; B29C 67/0074; B29C 67/0077; B29C 67/0081; B33Y 10/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 156/58; 264/112; 428/188; 428/293.1; 428/546; 428/547; 428/548
ECLA - B22F 3/005; L22F 998/00 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google, Google Scholar, YouTube
Search terms used: 3D printing, carbon fiber, metal powder, solution, melt, harden, airblast

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2014/134224 A2 (IMPOSSIBLE OBJECTS LLC) 04 September 2014 (04.09.2014) entire document	1-7, 9-12, 14-22, 24-27, 29-36, 38-41, 43-53
Y	US 6,780,368 B2 (LIU et al) 24 August 2004 (24.08.2004) entire document	1-7, 9-12, 14-22, 24-27, 29-36, 38-41, 43-53
Y	US 8,377,547 B2 (NOGUCHI et al) 19 February 2013 (19.02.2013) entire document	9, 24, 38
Y	CN 104150915 A (XI'AN JIAOTONG UNIVERSITY) 19 November 2014 (19.11.2014) see machine translation	14, 15, 29, 30, 43, 44
A	US 5,637,175 A (FEYGIN et al) 10 June 1997 (10.06.1997) entire document	1-53
A	US 5,340,656 A (SACHS et al) 23 August 1994 (23.08.1994) entire document	1-53

☐ 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
"E" earlier application or patent but published on or after the international filing date
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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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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 January 2017	23 JAN 2017

Name and mailing address of the ISA/US	Authorized officer
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