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(54) **Title**: METHODS AND APPARATUSES FOR PROCESSING ADDITIVE MANUFACTURED OBJECTS

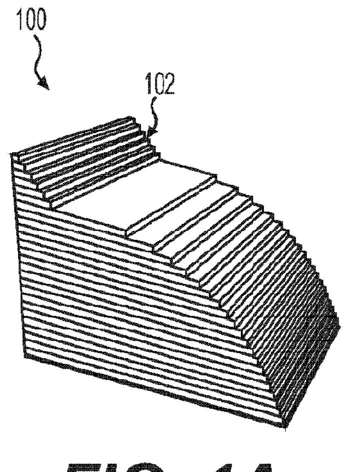

FIG. 1A

(57) **Abstract**: Disclosed herein are methods for processing objects made using additive manufacturing methods, comprising placing the object made by an additive manufacturing process using at least one thermoplastic polymer in an enclosed chamber, generating a mist of a liquid in the enclosed chamber, and exposing the object to the mist of the liquid for a predetermined period of time.

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specification

METHODS AND APPARATUSES FOR PROCESSING ADDITIVE MANUFACTURED OBJECTS

Technical Field

[0001] The present disclosure relates to additive manufacturing in general, and more particularly, methods and apparatuses for processing objects created using additive manufacturing processes.

Background

[0002] Additive manufacturing is a manufacturing technique that builds objects in an additive, usually layer-by-layer, fashion. One example of the additive manufacturing method, which has become more common over the past five plus years, is fused deposition modeling (FDM). This method is also sometimes called fused filament fabrication (FFF).

[0003] This additive manufacturing technology generally involves feeding a thermoplastic polymer in the form of a continuous filament into a heated nozzle, where the thermoplastic filament becomes a viscous melt and can therefore be extruded. The three-dimensional motion of the nozzle or the extruder assembly is precisely controlled by step motors and computer aided manufacturing (CAM) software. The first layer of the object is deposited on a build substrate, whereas additional layers are sequentially deposited and fused (or partially fused) to the previous layer by solidification due to a drop in temperature. The process continues until a three-dimensional part is fully constructed. The process may also involve a temporary support material that provides support to the part being built and is subsequently removed from the finished part by mechanical means or dissolution in a suitable liquid medium. This technology was disclosed in, for example, U. S. Patent No. 5,121,329.

[0004] Using the additive manufacturing method set forth above, a part created will have a series of ridges or edges along the surface where the thermoplastic filament is sequentially deposited and fused (or partially fused) to the previous layer. This may result in a surface that has a rougher finish than what could be achieved using other manufacturing methods. The rougher finish has several drawbacks. First, the objects created using FDM or FFF processes can be less aesthetically appealing compared to those prepared using other manufacturing methods (such as injection molding). Second, a rougher surface finish can make it difficult to apply additional surface finishing techniques such as painting or electroplating. Third, the grooves on the surface of the object may serve as stress concentrators that can lead to reduced mechanical properties of the object.

[0005] Methods of reducing the roughness of the finish on an object made using additive manufacturing processes include, for example, sanding or other techniques using abrasive materials to remove some of the thermoplastic filament. Many of the materials used in FDM and FFF additive manufacturing processes have relatively low softening temperatures. Thus, sanding can have a detrimental effect on the shape or features of the part created because of the significant amounts of heat generated by friction. Sanding also requires extensive skills, labor and time to be effective. Another method to reduce the roughness of the finish on an object is shot peening or shot blasting with some media. As with sanding, shot blasting requires extensive skills, labor and time to be effective. Other existing technologies involve exposing a part created by additive manufacturing of polymers to a solvent vapor generated by heating a reservoir of solvent. However, the heated solvent is often highly flammable and often has negative health effects related to human exposure. Additionally, the heated solvent vapor can lead to macroscopic deformation of the object being processed.

[0006] Thus, there is a need to develop a method and apparatus to easily process objects created using additive manufacturing of a thermoplastic that is safer, quicker and requires less skill and labor.

Summary of the Disclosure

[0007] Disclosed herein are methods and apparatuses for processing additive manufactured objects. Embodiments of the methods comprise: placing an object manufactured using additive manufacturing processes being placed inside an enclosed chamber, generating a mist that consists of micron-sized liquid droplets, from a liquid source, either inside or outside of the enclosed chamber, and exposing the object to the mist for a predetermined period of time. Embodiments of the methods further comprise generating the mist with a nebulizer.

[0008] In one embodiment of the present disclosure, the apparatus comprises a controller, a nebulizer, and an enclosed chamber, wherein the enclosed chamber comprises a reservoir and wherein the object to be placed in the enclosed chamber is made by an additive manufacturing process. In one embodiment, the reservoir is inside of the enclosed chamber. In another embodiment, the enclosed chamber has a reservoir attached to it. When the apparatus operates, the nebulizer receives a signal from the controller and starts to generate a mist of the liquid; the controller also sends a signal to the nebulizer after a predetermined period of time to stop generating the mist of the liquid.

The liquid droplets that constitute the mist have diameters that are typically less than 100 um, and are preferably to be less than 10 um.

[0009] Objects that are suitable for this method are additively manufactured with primarily thermoplastic polymers, including composite materials with thermoplastic matrices. Suitable additive manufacturing techniques including, but are not limited to, material extrusion based techniques such as fused deposition modeling (FDM) and fused filament fabrication (FFF), power bed fusion such as selective laser sintering (SLS), sheet lamination, binder jetting and material jetting. Embodiments of suitable additive manufacturing techniques further include those developed in the future that fall into the scope of the term “additive manufacturing” known in the art.

[0010] There are advantages with some embodiments of the present disclosure over previous methods. Heating of the liquid is not required to generate a vapor. The liquids used in the methods disclosed herein are often fairly benign in terms of toxicity (e.g. alcohols), which reduces the risk to anyone involved in the methods disclosed herein. Unlike vapor, micro-droplets of mist are much easier to observe so that detecting a leak in the enclosed chamber can be much easier. Another advantage may be that the efficiency of the methods allows the processing time of parts to be in the range of 10-40 minutes (with the possibility of doing one or many parts at the same time). Another advantage may be better dimensional stability for the part during and after processing. Unlike heated vapor, the micro-droplet mist is generated without heating and therefore is approximately at room temperature. This may allow the processing to occur only at the surface of the object while the bulk of the object remains unchanged. Finally, the methods disclosed herein may be low cost compared to other methods. The processes disclosed herein may consume minimal amounts of liquid.

[0011] The details of one or more variations of the subject matter disclosed herein are set forth below and the accompanying drawings. Other features and advantages of the subject matter disclosed herein will be apparent from the detailed description below and drawings, and from the claims.

[0012] Further modifications and alternative embodiments will be apparent to those of ordinary skill in the art in view of the disclosure herein. For example, the systems and the methods may include additional components or steps that are omitted from the diagrams and description for clarity of operation. Accordingly, the detailed description below is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the present disclosures. It is to be understood that the various embodiments disclosed herein are to be taken as exemplary. Elements and materials, and arrangements of those elements and materials, may be substituted for those illustrated and disclosed herein, parts and processes may be reversed, and certain features of the present teachings may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of the disclosure herein. Changes may be made in the elements disclosed herein without departing from the spirit and scope of the present teachings and following claims.

[0013] An exemplary method in accordance with the present disclosure comprises:

placing an object in an enclosed chamber, wherein the object is made by an additive manufacturing process using at least one thermoplastic polymer;

generating a mist of a liquid in the enclosed chamber; and

exposing the object to the mist of the liquid for a predetermined period of time.

[0014] An exemplary apparatus for processing an object in accordance with the present disclosure comprises a controller, a nebulizer, and an enclosed chamber, wherein the enclosed chamber comprises a reservoir; further wherein the object is made by an additive manufacturing process. In one embodiment, the reservoir is inside of the enclosed chamber. In another embodiment, the enclosed chamber has a reservoir attached to it. Another exemplary method in accordance with the present disclosure comprises placing an object in an enclosed container, wherein the object is made by an additive manufacturing process, using at least one poly (vinyl butyral) thermoplastic polymer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a schematic showing an exemplary method in accordance with the present disclosure.

[0016] FIG. 1A is a schematic showing a cross-sectional view of the surface of an object made using additive manufacturing before processing with an exemplary method in accordance with the present disclosure.

[0017] FIG. 1B is a schematic showing micro-droplets of mist from a liquid adjacent to the surface of the object made using additive manufacturing.

[0018] FIG. 1C is a schematic showing the object after exposure to the micro-droplets of mist from the liquid.

[0019] FIG. 1D is a schematic showing a cross-sectional view of the surface of the object after processing with an exemplary method in accordance with the present disclosure.

[0020] FIG. 2 is a schematic showing an exemplary apparatus in accordance with the present disclosure.

[0021] FIG. 3A is a schematic of an exemplary membrane nebulizer in accordance with the present disclosure.

[0022] FIG. 3B is a schematic of an exemplary ultrasonic nebulizer in accordance with the present disclosure.

[0023] FIG. 3C is a schematic of an exemplary jet nebulizer in accordance with the present disclosure.

[0024] FIG. 4 is a diagram showing a chemical structure of an exemplary polymer in accordance with the present disclosure.

DETAILED DESCRIPTION

[0025] This description and the accompanying drawings that illustrate exemplary embodiments should not be taken as limiting. Various mechanical, compositional, structural, electrical, and operational changes may be made without departing from the scope of this description and the claims, including equivalents. In some instances, well-known structures and techniques have not been shown or described in detail so as not to obscure the disclosure. Similar reference numbers in two or more figures represent the same or similar elements. Furthermore, elements and their associated features that are disclosed in detail with reference to one embodiment may, whenever practical, be included in other embodiments in which they are not specifically shown or described. For example, if an element is described in detail with reference to one embodiment and is not described with reference to a second embodiment, the element may nevertheless be claimed as included in the second embodiment.

[0026] For the purposes of this specification and appended claims, unless otherwise indicated, all numbers expressing quantities, percentages, or proportions, and other numerical values used in the specification and claims, are to be understood as being modified in all instances by the term “about,” to the extent they are not already so modified. Accordingly, unless indicated to the contrary, the numerical parameters set forth in the following specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

[0027] It is noted that, as used in this specification and the appended claims, the singular forms “a,” “an,” and “the,” and any singular use of any word, include plural referents unless expressly and unequivocally limited to one referent. As used herein, the term “include” and its grammatical variants are intended to be non-limiting, such that recitation of items in a list is not to the exclusion of other like items that can be substituted or added to the listed items.

[0028] Further, this description’s terminology is not intended to limit the invention. For example, spatially relative terms—such as “beneath”, “below”, “lower”, “above”, “upper”, “proximal”, “distal”, and the like—may be used to describe one element’s or feature’s relationship to another element or feature as illustrated in the figures. These spatially relative terms are intended to encompass different positions (i.e., locations) and orientations (i.e., rotational placements) of a device in use or operation in addition to the position and orientation shown in the figures. For example, if a device in the figures is turned over, elements described as “below” or “beneath” other elements or features would then be “above” or “over” the other elements or features. Thus, the exemplary term “below” can encompass both positions and orientations of above and below. A device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0029] Disclosed herein is a method for processing objects made using additive manufacturing, comprising processing the object using a mist generated from a liquid. The mist of the liquid interacts with the object and reduces the roughness of the surface of the object. This reduction in roughness may be referred to as “finishing” the object and may create, after processing using the methods disclosed herein, a surface that is shiny (reflects more light) compared to the surface prior to processing. The process does not necessarily need to produce a shiny surface after processing. It may be desirable to have a specific amount of roughness on the object to allow for specific types of finishing (painting, electroplating or other techniques that require a particular texture to maximize desired attributes).

[0030] **FIG. 1** is a schematic of an exemplary method in accordance with the present disclosure. **FIG. 1A** is a schematic showing a cross-sectional view of a surface 102 of an object 100 made using additive manufacturing before processing with an exemplary method in accordance with the present disclosure. **FIG. 1B** is a schematic showing micro-droplets of a mist 104 from a liquid adjacent to the surface 102 of the object

100 made using additive manufacturing. **FIG. 1C** is a schematic showing the object 100 after exposure to the micro-droplets of mist 104 from the liquid. **FIG. 1D** is a schematic showing a cross-sectional view of the surface 102 of the object 100 after processing with an exemplary method in accordance with the present disclosure.

[0031] Object 100 may be manufactured using additive manufacturing processes like FDM and FFF. Object 100 may consist of any material suitable for FDM or FFF manufacturing processes. Examples include, but are not limited to, vinyl acetal polymers, acrylonitril-butadiene-styrene (ABS), poly(lactic acid) (PLA), polycarbonate (PC), polystyrene (PS), high impact polystyrene (HIPS), polycaprolactone (PCL), polyamide and polyamide copolymers, and cellulose based polymers. In some embodiments, Object 100 is made of at least one thermoplastic polymer selected from vinyl acetal polymers, polyamide and polyamide copolymers, and cellulose based polymers. For example, the vinyl acetal polymers are selected from poly (vinyl butyral). In one embodiment, the poly (vinyl butyral) comprises vinyl acetate, vinyl alcohol, and vinyl butyral monomeric units. In some embodiments, the poly (vinyl butyral) comprises vinyl acetate monomeric units in an amount ranging from about 0 to about 5%, such as from about 0 to about 4%, by weight, vinyl alcohol monomeric units in an amount ranging from about 10% to about 30%, such as from about 15% to about 25%, by weight, and vinyl butyral monomeric units in an amount ranging from about 65% to about 90%, such as from about 71% to about 85%, by weight.

[0032] The processes disclosed herein may be applied to parts made with any suitable additive manufacturing process as long as the material used is a thermoplastic polymer (including composite materials with thermoplastic polymer matrices).

[0033] Additive manufacturing processes other than FDM and FFF may be used with the present disclosure. These additive processes include, for example, material extrusion, binder jetting, material jetting, sheet lamination and powder bed fusion.

[0034] **FIG. 2** is a schematic illustrating apparatus 200. Apparatus 200 includes an enclosed chamber 210 that provides an enclosed space for processing the object 214. Fig. 2 includes a nebulizer 212 that is used to generate micro-droplets of a mist, 217, from a liquid. A controller 211 is used to control the nebulizer 212. The object 214 being processed sits on a rotational platform 213 to ensure an even exposure to the mist 217. A porous membrane 215 allows the micro-droplets of the mist 217 to flow through into a reservoir 216. The porous membrane 215 may be made of any suitable material that allows the liquid that does not coat the object 214 to flow through into the reservoir 216. Fig. 2 only shows a single nebulizer 212, but more than one nebulizer may be included in the apparatus to increase the volume of the mist 217 generated. Fig. 2 shows the nebulizer 212 inside the enclosed chamber 210, but the nebulizer could also be configured outside the enclosed chamber 210. In this alternate location, the micro-droplets of the mist 217 could be transported from the external nebulizer 212 into the enclosed chamber 210 through an opening.

[0035] **FIG. 3A** is a schematic showing a nebulizer 300. The nebulizer 300 includes a container 324 for a liquid 322. A heating element 325 may be included to heat the liquid 322 in the container 324. An absorbent material 323 is placed between a membrane 320 and the container 324. The liquid 322 gets transported from the container 324 to the membrane 320 via wicking (e.g. capillary) action. The membrane 320 is vibrated and generates micro-droplets of the mist 217. Use of nebulizer 300 is often referred to as membrane nebulization. This technique is known as membrane nebulization, which involves the use of a porous, vibrating membrane to generate micro-droplets of the mist from the liquid. This is also widely known as vibrating mesh technology (VMT). The preferred nebulization method is membrane nebulization or VMT as it has the highest nebulization efficiency, consumes extremely low power and does not require a lot of equipment or hardware.

[0036] Other methods may be used to transport the liquid 322 from the container 324 to the membrane. Other suitable methods include, but are not limited to, a tube and a pump, a gravity feed from another container or other similar arrangements.

[0037] The mist 217 generated by the vibrating membrane 320 then covers the object 214 on the rotational platform 213 inside the enclosed chamber 210. The membrane 320 suitable to be used in this embodiment typically has several hundred to several thousand pores or holes with average diameters in the range of 1-10 microns. However, the membrane 320 may have any number of holes or pores sufficient to generate the desired size of micro-droplets of the mist 217.

[0038] Liquid 322 may be selected based on the material used to manufacture object 214. The liquid 322 must be able to dissolve or partially dissolve the material used to manufacture object 214. Here, a solvent is understood to be any substance that dissolves a solute (a chemically different liquid, solid or gas), resulting in a solution. Examples of suitable liquids include, but are not limited to the organic solvents: alcohols such as methanol, ethanol, isopropanol, n-propanol, isobutanol, butanol, neopentyl alcohol; ethers, such as diethyl either, dimethyl ether, tetrahyrdofuran, dioxane, propylene oxide; esters, such as methyl acetate, ethyl acetate, propyl acetate, isopropyl acetate, benzyl benzoate, butyl acetate, and isoamyl acetate; ketones, such as acetone, methyl butyl ketone, methyl ethyl ketone (MEK), cyclohexanone, isophorone, and methyl isobutyl ketone; diols and diol-derivatives, such as 2-methoxyethanol, 2-ethoxyethanol; acids such as formic acid and acetic acid; and hydrocarbon solvents such as alkanes, alkenes, and alkynes generally with 12 carbon units or less, benzene, methylbenzene, xylene, and terpenes such as limonene. Suitable liquids may also be mixtures of multiple liquids. The suitable liquid may also be mixed with the inorganic solvent water (including any combination of mixed liquids).

[0039] In some embodiments, the liquids include ethanol and/or isopropanol due to their wide availability and relatively low cost. Any one of these liquids may also be mixed with water or other miscible liquids to achieve desired characteristics.

[0040] In order for ethanol and/or isopropanol to be used as the organic liquids for polishing, the additive manufacturing material must be selected so it is soluble or partially soluble in ethanol and/or isopropanol. Examples of the additive manufacturing materials include: polyamide copolymers, cellulose based polymers such as nitrocellulose, cellulose acetate propionate (CAP), cellulose acetate butyrate (CAB), methyl cellulose and ethyl cellulose, and vinyl acetal polymers.

[0041] **FIG. 3B** is a schematic showing a nebulizer 301. Nebulizer 301 includes a container 324 for a liquid 322. A heating element 325 may be included to heat the liquid 322 in the container 324. An ultrasonic atomizer 336 is fully or partially immersed in the liquid 322. The ultrasonic atomizer 336 is typically in the shape of a disk. Power is applied to the ultrasonic atomizer 336 to vibrate the ultrasonic atomizer 336. This vibration agitates the liquid 322 and generates micro-droplets of the mist 217. The ultrasonic nebulizer 336 may include a piezoelectric element to generate the ultrasonic waves. The ultrasonic nebulizer 336 may include any appropriate device to generate ultrasonic waves. This technique is known as ultrasonic wave nebulization, which uses high frequency ultrasonic waves generated by a piezoelectric element to create micro-droplets of the mist from the liquid.

[0042] **FIG. 3C** is a schematic showing nebulizer 302. Nebulizer 302 includes a container 324 for a liquid 322. A heating element 325 may be included to heat the liquid 322 in the container 324. A nozzle 328 is configured to eject compressed gas 330. The nozzle mixes the liquid 322 with the gas 330 and sprays micro-droplets of the mist 317. This technique is known as jet nebulization, which uses a compressed gas passing through a liquid to generate micro-droplets of the mist from the liquid.

[0043] Although not necessary, the heating element may be used to heat the liquid in the container. This may be desirable to permit desired properties for the micro-droplets generated from the liquid. The temperature of the liquid cannot exceed the boiling point of the liquid. The temperature for heating the liquid may range, for example, from 25 to 60 ºC.

[0044] A heating element may also be included in the enclosed chamber to heat the atmosphere of the enclosed chamber to a predetermined temperature. The predetermined temperature will vary with the type of material used to manufacture the object and the liquid used to generate the micro-droplets of mist. Generally speaking, the higher the environmental temperature, the faster the polishing will be to reach a desired surface smoothness/roughness. However the temperature of the atmosphere in the enclosed chamber shall not exceed the glass transition temperature or the melting temperature of the material used to manufacture the object, whichever is lower, or the boiling temperature of the liquid. The predetermined temperature may range, for example, from 25 to 60 ºC, depending on the specific process.

[0045] **FIG. 4** is a diagram showing a chemical structure of an exemplary polymer in accordance with the present disclosure. Vinyl acetal polymers are, for example, suitable for this disclosure due to their good solubility in alcohols such as ethanol and isopropanol, as well as good printability for FDM or FFF based additive manufacturing. Vinyl acetal polymers can be represented by the general structure shown in Fig. 4.

[0046] Vinyl acetal polymers are generally produced by a two-step chemical process: (1) hydrolysis of poly(vinyl acetate) to form poly(vinyl alcohol), and (2) reacting poly(vinyl alcohol) with an aldehyde or mixed aldehydes to form predominantly 1,3-dioxane rings. The reactions are generally incomplete; therefore acetal polymers are usually composed of a mixture of vinyl acetate units ("z" shown in the structure), vinyl alcohol units (y), and vinyl acetal units (x). The R group depends on the aldehyde and can be any hydrocarbon group. R groups may be chosen, for example, from: -H, $-CH_3$, $-C_2H_5$, $-C_3H_7$, and $-C_4H_9$. In one embodiment, R group is $–C_3H_7$, and the resulting polymer is commonly referred to as poly(vinyl butyral) or PVB.

[0047] Generally, PVB is composed of a mixture of vinyl acetate monomeric units, vinyl alcohol monomeric units and vinyl butyral monomeric units ($R = -C_3H_7$) on its polymer backbone. The composition (weight fractions of the components) can be adjusted to achieve desired properties. In some embodiments, the composition disclosed herein includes: vinyl acetate (0-5 wt%), vinyl alcohol (10-30 wt%), and vinyl butyral (65-90 wt%). In some embodiments, the composition disclosed herein includes: vinyl acetate (0-4 wt%), vinyl alcohol (15-25 wt%) and vinyl butyral (71-85 wt%).

[0048] The additive manufacturing material disclosed herein can further comprise at least one other ingredient, selected, for example, from colorants, pigments, fillers, fibers, plasticizers, nucleating agents, heat/UV stabilizers, process aids, impact modifiers, other polymers, and other additives. Additives can be incorporated by a variety of methods, such as melt compounding. In some embodiments, the main polymer is still forming the matrix or the continuous phase after the addition of the at least one other ingredient.

[0049] Most FDM/FFF printers require the materials to be in the form of a filament, usually with a circular cross-section. The filaments are produced commonly by a melt extrusion process. In the melt extrusion process, fully dried raw materials, along with other ingredients, are fed into a polymer extruder (either single-screw or twin-screw) with a cylindrical die and continuously extruded. The extrudate is subsequently quenched/cooled and pulled by a puller to give the desired physical dimensions before being collected. The process can also include equipment such as melt or gear pumps (to ensure a stable output), laser micrometers (on-line measurement of the physical dimensions) or other similar devices.

[0050] The filaments need to have an average diameter with small variations. The average diameter of the commonly used filaments for additive manufacturing processes ranges, for example, from 1.75 mm to 3 mm. The diameter variation is preferred to be as small as possible, such as ± 0.1 mm, further such as ± 0.05 mm.

[0051] The diameter of the heated nozzle and the thickness of the layer deposited by the additive manufacturing process are factors in the roughness of the surface of the object made using the additive manufacturing process. The larger the diameter of the heated nozzle and the thicker the layer, the larger the difference between high and low points on the surface of the part manufactured. The smaller the diameter of the heated nozzle and the thinner the layer, the smaller the difference between the high and low points on the surface. However, smaller diameters for the heated nozzle and thinner layers also require more passes by the additive manufacturing process that increases the manufacturing time.

[0052] The roughness of the surface of the object can be measured before and after the object is subjected to a process disclosed in the present disclosure. Profilometry or similar methods may be used to measure the degree of roughness of the surface of the object.

[0053] In an embodiment, the process for measuring the roughness of the surface is as follows:

The sample for the roughness testing has the following formulation:

	Content (phr*)
PVB (B05HX from Chang Chun Group)	100
Anti-Oxidant (B215 from BASF)	0.3
Nitrile Rubber (P35 from OMNOVA Solutions)	15

* “phr” means parts per hundreds of resin.

The sample was prepared by (1) manually mixing all of the ingredients in the formulation above, (2) melt compounding the ingredients using a 20 mm co-rotating twin-screw extruder under the conditions listed in Table 1, and (3) manufacturing the compounded material into a filament with an average diameter of 1.75 mm via single-screw extrusion, under the extrusion conditions listed in Table 2.

[0054] Table 1. Melt compounding conditions

	Feed Zone	2nd Zone	3rd Zone	4th Zone	Die	RPM
Temperature (ºC)	120	160	190	200	190	120

[0055] Table 2. Filament extrusion conditions

	Feed Zone	Compression Zone	Metering Zone	Die	RPM
Temperature (ºC)	90	170	200	190	30

[0056] The resulting filament was used to print 15 mm * 15 mm * 30 mm cuboids as test specimens (0.2 mm layer height, shell number = 2, 20% infill, printing temperature = 210 ºC). The test specimens were polished using a self-built polishing device that consists of a vibrating mesh nebulizer with an overall diameter of 20 mm, a vibrating frequency of 112 kHz, and 850 holes with a hole-diameter of 8 um. The device has an internal volume of about 3 L. The polishing time was 20 min.

[0057] As-printed and polished specimens were tested for surface roughness using a roughness tester (Mitutoyo Surftech SJ400). The scan direction was parallel to the "z" direction (perpendicular to the layers). The results are shown below:

	Ra (um)	Rz (um)
As printed	15.65	95.9
Polished (20 min)	2.61	9.1

[0058] Here Ra and Rz are commonly used surface roughness parameters and they are defined as:

Ra: the arithmetic average of the absolute values of the distances between the peaks - both positive peaks and negative peaks (valleys) - and the medium line.

Rz: the arithmetic mean value of the single roughness depths of consecutive sampling lengths.

*(More detailed explanations of the definitions can be seen at:

http://www.rubert.co.uk/faqs/roughness-parameters/

https://my.misumi-ec.com/pdf/tech/press/pr1167_1168.pdf)

[0059] The polished part exhibited dramatically improved surface smoothness (reduced surface roughness).

[0060] In some embodiments, the process comprises:

1. placing the object created using additive manufacturing into an enclosed chamber;
2. applying a sufficient amount of voltage to a nebulizing unit to generate micro-droplets of the mist from the liquid;
3. holding the object in the mist for a predetermined period of time; and
4. removing the object from the enclosed chamber.

The predetermined period of time necessary for the process can vary depending on the size of the part, the size of the enclosed chamber, the number of nebulizers used, the specification of the nebulizers, environmental temperature, the type of material used to manufacture the object to be processed, the level of roughness or size of the ridges along the surface of the object and the liquid used to generate the micro-droplets of the mist. In general, the period of time for exposure to the micro-droplets of mist ranges, for example, from 10 to 60 minutes. However, any suitable period of time may be used as the predetermined period of time for a specific process to run.

[0061] Example 1 – Preparation of a 3D printing material filament

[0062] Raw PVB resin (B05HX made by Chang Chun Group, in the form of a fine powder) was first dried in an oven at 60 °C for 4 h. It was then dry-blended with 0.03% of anti-oxidant (B215 from BASF) and 0.5% of titanium dioxide (R-902 from DuPont), and pelletized using a 20 mm twin-screw extruder.

[0063] The pellets were then dried at 60 °C for another 4 hours and gravity-fed to a 20 mm single-screw extruder to process it into a filament. The processing temperatures were as follows:

Feed zone	Compression zone	Metering zone	Die
90 °C	160 °C	220 °C	190 °C

[0064] The extrudate, pulled by a puller at a constant speed, was cooled in a water tank and collected on a spool. The puller speed was set to draw the filament to final diameter of about 1.75 mm. The spooled filament was then dried before printing.

[0065] Example 2 – Polishing of a 3D printed part

[0066] A polishing device prototype was produced following the schematics in Fig 2. The device consists of a rotational stage for placing the 3D printed part, a nebulizing unit with two vibrating membrane nebulizers, and all the electronics required to power the nebulizing unit as well as the structural components.

[0067] An owl model (about 12 cm tall) was printed on a FlashForge Creator Pro desktop 3D printer using the filament prepared as described in example 1, under the following printer settings:

[0068] Printing/nozzle temperature: 210 °C;

[0069] Build plate temperature: 60 °C;

[0070] Printing speed: 60 mm/s;

[0071] Layer height: 0.2 mm.

[0072] The printed owl model was polished in the prototype device for 40 min using isopropanol as the organic liquid. After polishing, the part was removed from the device and the surface dried off (natural evaporation of isopropanol) in several hours. The polished part exhibited a much smoother and shiny surface.

[0073] After the object has been processed by the micro-droplets of the mist, there may be some residual liquid remaining on the part. This liquid may be removed by evaporation, or by drying using radiant heat, forced air, by a vacuum or other suitable method.

[0074] It is to be understood that the particular examples and embodiments set forth herein are non-limiting, and modifications to structure, dimensions, materials, and methodologies may be made without departing from the scope of the present teachings.

[0075] It will be evident that various modifications and changes may be made without departing from the broader spirit and scope of the disclosure as set forth in the claims that follow. The specification and drawings are accordingly to be regarded as illustrative rather than restrictive.

claims

1. A method for processing an object comprises:

placing the object in an enclosed chamber, wherein the object is made by an additive manufacturing process using at least one thermoplastic polymer;

generating a mist of a liquid in the enclosed chamber; and

exposing the object to the mist of the liquid for a predetermined period of time.

2. The method of claim 1, wherein the additive manufacturing process is selected from a material extrusion process, a binder jetting process, a material jetting process, a sheet lamination process, and a powder bed fusion process.

3. The method of claim 2, wherein the material extrusion process is selected from fused deposition modeling and fused filament fabrication.

4. The method of claim 1, wherein the at least one thermoplastic polymer is selected from vinyl acetal polymers, acrylonitrile-butadiene-styrene, poly (lactic acid), polycarbonate, polystyrene, high impact polystyrene, polycaprolactone, polyamide and polyamide copolymers, and cellulose based polymers.

5. The method of claim 4, wherein the at least one thermoplastic polymer is selected from vinyl acetal polymers, polyamide and polyamide copolymers, and cellulose based polymers.

6. The method of claim 4 wherein the vinyl acetal polymers are selected from poly (vinyl butyral).

7. The method of claim 6, wherein the poly (vinyl butyral) comprises vinyl acetate, vinyl alcohol, and vinyl butyral monomeric units.

8. The method of claim 6, wherein the poly (vinyl butyral) comprises vinyl acetate monomeric units in an amount ranging from about 0 to about 5% by weight, vinyl alcohol monomeric units in an amount ranging from about 10% to about 30% by

weight and vinyl butyral monomeric units in an amount ranging from about 65% to about 90% by weight.

9. The method of claim 6, wherein the poly (vinyl butyral) comprises vinyl acetate monomeric units in an amount ranging from about 0 to about 4% by weight.
10. The method of claim 6, wherein the poly (vinyl butyral) comprises vinyl alcohol monomeric units in an amount ranging from about 15% to about 25% by weight.
11. The method of claim 6, wherein the poly (vinyl butyral) comprises vinyl butyral monomeric units in an amount ranging from about 71% to about 85% by weight.
12. The method of claim 1, wherein the object further comprises at least one component selected from colorants, pigments, fillers, fibers, plasticizers, nucleating agents, heat stabilizers, ultraviolet stabilizers, processing aids, and impact modifiers.
13. The method of claim 1, wherein the liquid comprises at least one solvent.
14. The method of claim 1, wherein the mist comprises micro-droplets.
15. The method of claim 14, wherein the micro-droplets are less than 100 micrometers in diameter.
16. The method of claim 14, wherein the micro-droplets are less than 10 micrometers in diameter.
17. The method of claim 1, wherein the mist is created by a nebulizer.
18. The method of claim 17, wherein the nebulizer is selected from a jet nebulizer, an ultrasonic wave nebulizer, and a membrane nebulizer.
19. The method of claim 13, wherein the at least one solvent is selected from alcohols, ethers, esters, and ketones.
20. The method of claim 19, wherein the alcohols are selected from methanol, ethanol, propanol, isopropanol.

21. The method of claim 19, wherein the alcohols are selected from diols and the derivatives thereof.
22. The method of claim 19, wherein the ethers are selected from diethyl ether and propylene oxide.
23. The method of claim 19, wherein the esters are selected from methyl acetate, ethyl acetate, and propyl acetate.
24. The method of claim 19, wherein the ketones are selected from acetone, methyl butyl ketone, and ethyl isobutyl ketone.
25. The method of claim 13, wherein the at least one solvent is water.
26. The method of claim 1, wherein the liquid is a mixture of at least one organic solvent.
27. The method of claim 26, wherein the mixture comprises at least two organic solvents.
28. The method of claim 26, wherein the mixture comprises water and at least one organic solvent.
29. The method of claim 1, wherein the enclosed chamber comprises a rotational platform for placement of the object.
30. The method of claim 1, further comprising circulating the mist inside the enclosed chamber.
31. The method of claim 1, further comprising heating the enclosed chamber to a predetermined temperature.
32. The method of claim 31, wherein the predetermined temperature does not exceed the glass transition temperature or melting point of the thermoplastic polymer, whichever is lower.
33. The method of claim 31, wherein the predetermined temperature does not exceed the boiling point of the liquid.

34. The method of claim 1, wherein the at least one thermoplastic polymer is a composite material with thermoplastic matrices.

35. The method of claim 1, further comprises drying the object after the object is exposed to the mist of the liquid for a predetermined period of time.

36. An apparatus for processing an object comprising:

a controller;

a nebulizer; and

an enclosed chamber, wherein the enclosed chamber comprises a reservoir;

wherein the object is made by an additive manufacturing process.

37. The apparatus of claim 36, wherein the nebulizer is selected from a jet nebulizer, an ultrasonic wave nebulizer, and a vibrating membrane nebulizer.

38. The apparatus of claim 36, wherein the enclosed chamber comprises a rotatable platform.

39. The apparatus of claim 36, further comprising a heat source.

40. A method for processing an object comprising:

placing the object in an enclosed chamber, wherein the object is made by an additive manufacturing process, using at least one vinyl acetal thermoplastic polymer;

generating a mist of a liquid comprising at least one solvent in the enclosed chamber;

exposing the object to the mist of the liquid for a predetermined period of time;

rotating the object on a rotational platform; and

drying the object.

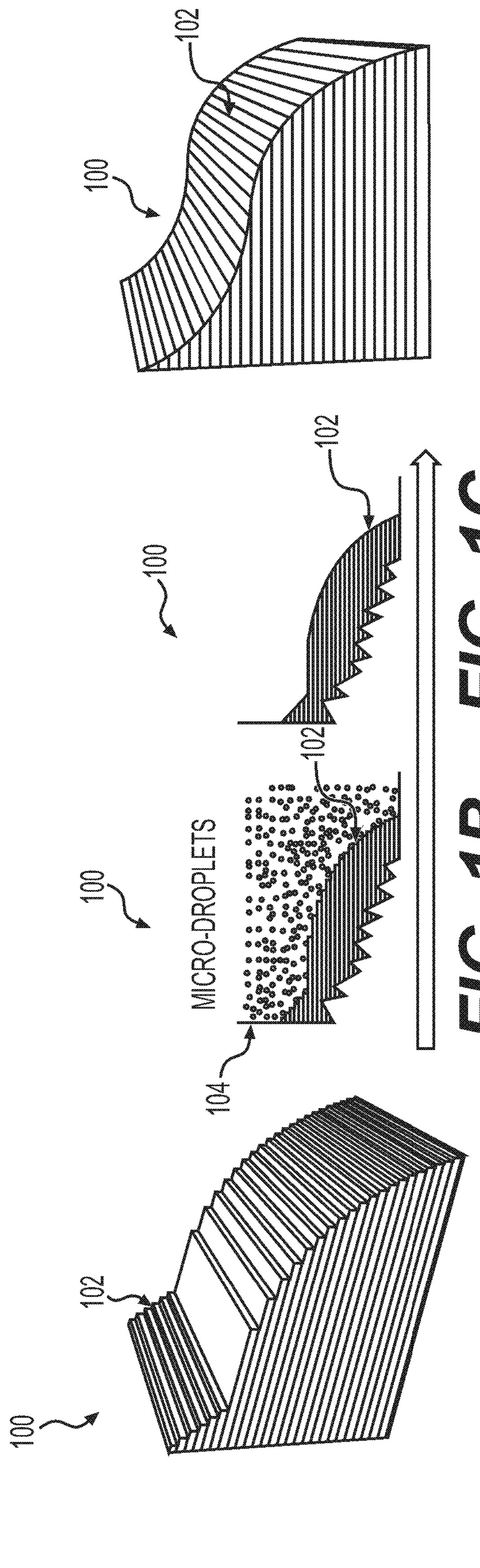

FIG. 1A

FIG. 1B

FIG. 1C

FIG. 1D

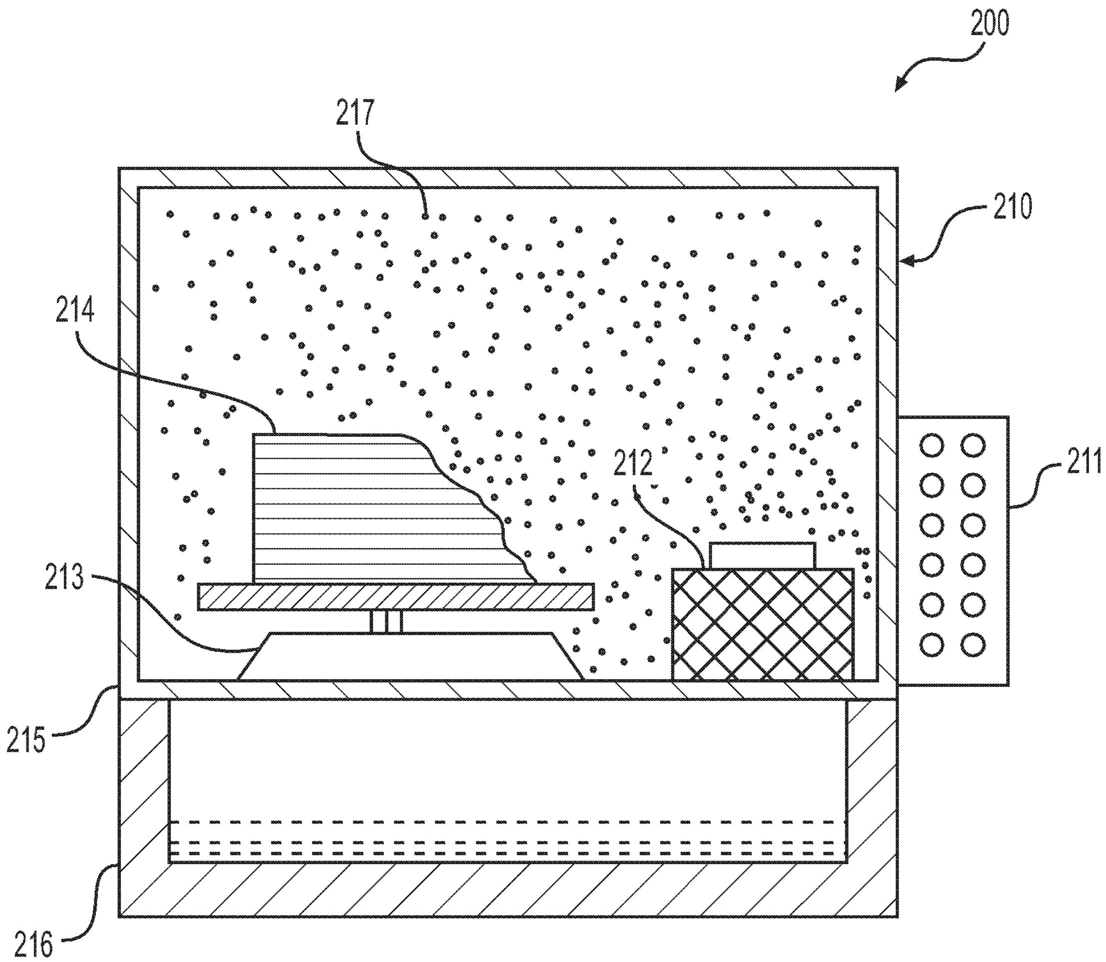

FIG. 2

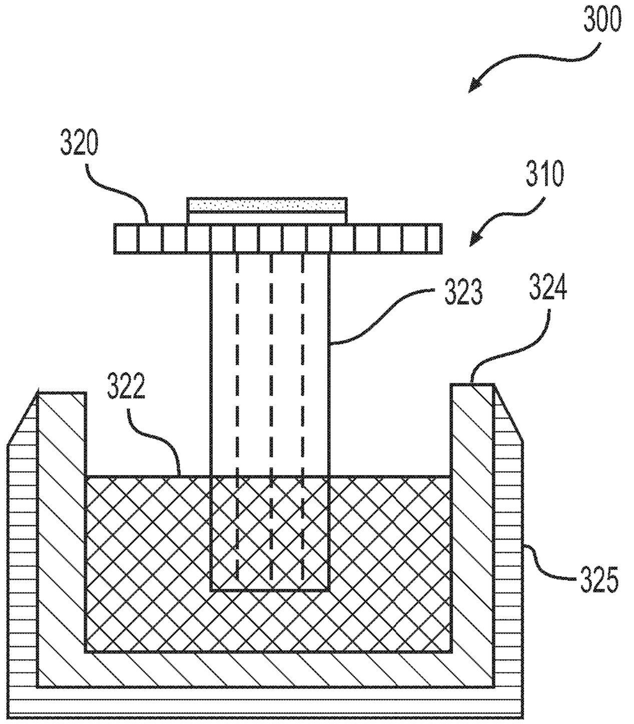

FIG. 3A

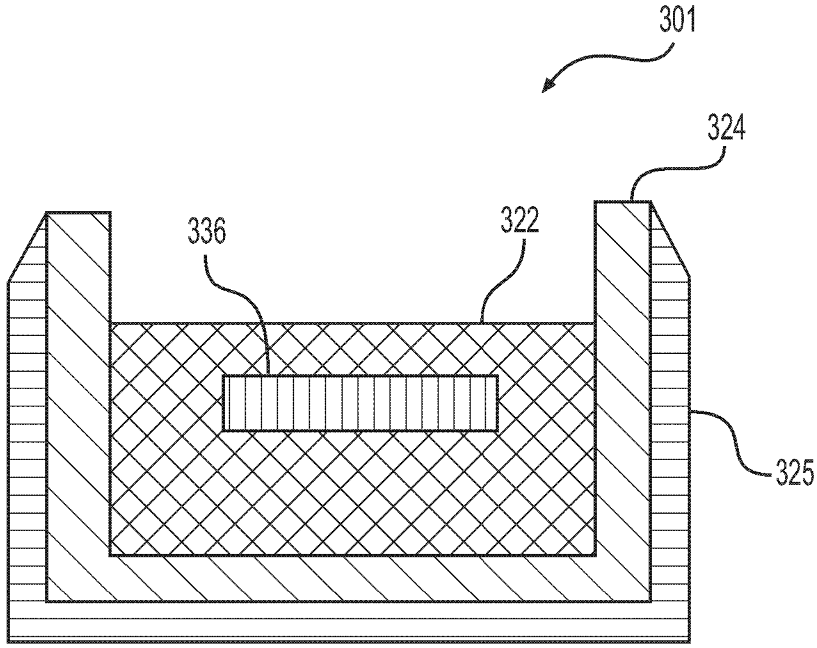

FIG. 3B

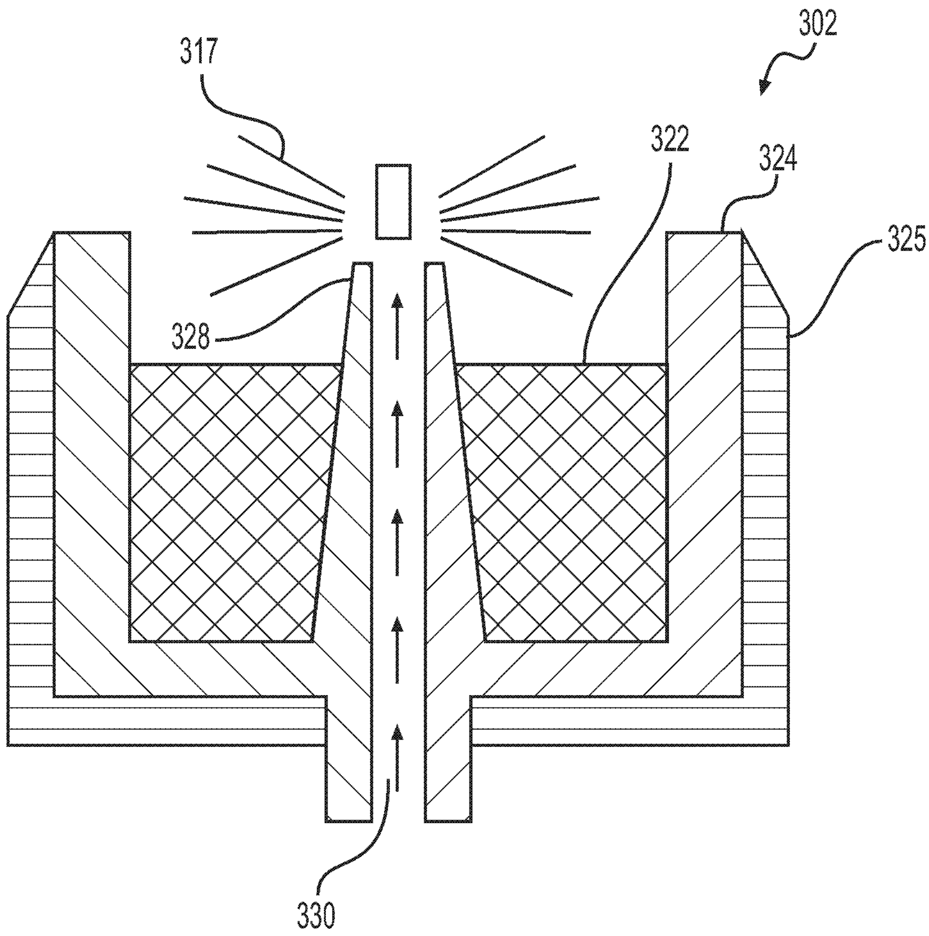

FIG. 3C

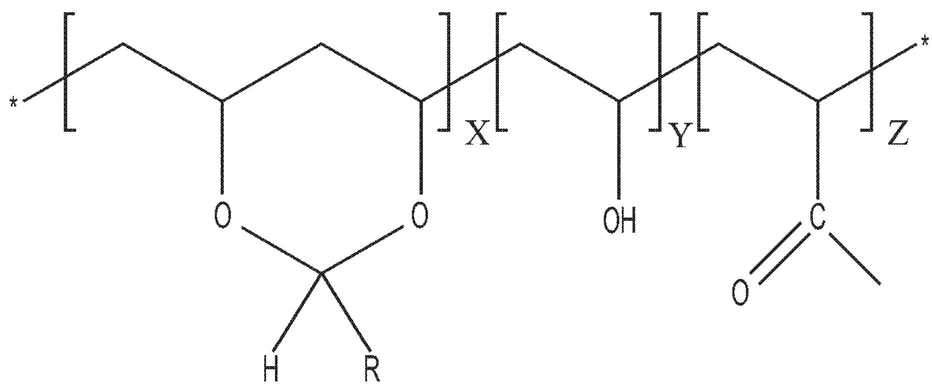

FIG. 4

国际检索报告

国际申请号
PCT/CN2015/081512

A. 主题的分类

B29C 71/00 (2006.01) i

按照国际专利分类表(IPC)或者同时按照国家分类和 IPC 两种分类

B. 检索领域

检索的最低限度文献（标明分类系统和分类号）

B29C-，G06F-，H01L-，B22F-

包含在检索领域中的除最低限度文献以外的检索文献

在国际检索时查阅的电子数据库（数据库的名称，和使用的检索词（如使用））

CNABS；SIPOABS；WPI；EPODOC；CNPAT：喷雾器，FFF，增材制造，聚合物，FDM，喷嘴，控制器，液体，雾，热塑性，室

C. 相关文件

类 型*	引用文件，必要时，指明相关段落	相关的权利要求
A	US 5121329 A（斯特拉塔西斯公司）1992 年 6 月 9 日（1992-6-9）说明书，第 5-6 栏	1-40
A	CN 104475736 A（湖南华曙高科技有限责任公司）2015 年 4 月 1 日（2015-4-1）说明书，第 0012-0018 段	1-40
A	CN 103192524 A（苏州华漫信息服务有限公司）2013 年 7 月 10 日（2013-7-10）说明书，第 0011 段	1-40
A	JP 2003-347266 A（芝浦制作所株式会社）2003 年 12 月 5 日（2003-12-5）说明书，第 0018-0024 段	1-40

☐ 其余文件在 C 栏的续页中列出。　　☒ 见同族专利附件。

* 引用文件的具体类型：
"A" 认为不特别相关的表示了现有技术一般状态的文件
"E" 在国际申请日的当天或之后公布的在先申请或专利
"L" 可能对优先权要求构成怀疑的文件，为确定另一篇引用文件的公布日而引用的或者因其他特殊理由而引用的文件
"O" 涉及口头公开、使用、展览或其他方式公开的文件
"P" 公布日先于国际申请日但迟于所要求的优先权日的文件
"T" 在申请日或优先权日之后公布，与申请不相抵触，但为了理解发明之理论或原理的在后文件
"X" 特别相关的文件，单独考虑该文件，认定要求保护的发明不是新颖的或不具有创造性
"Y" 特别相关的文件，当该文件与另一篇或者多篇该类文件结合并且这种结合对于本领域技术人员为显而易见时，要求保护的发明不具有创造性
"&" 同族专利的文件

国际检索实际完成的日期
2016 年 2 月 15 日（2016-2-15）

国际检索报告邮寄日期
2016 年 3 月 7 日（2016-3-7）

国际检索单位名称和邮寄地址
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国际检索报告

关于同族专利的信息

国际申请号

PCT/CN2015/081512

检索报告中引用的专利文件	公布日期	同族专利	公布日期
US 5121329 A	1992年6月9日	EP 0833237 A2	1998年4月1日
		DE 69033809 T2	2002年4月25日
		CA 2027731 C	1995年9月5日
		CA 2027731 A1	1991年5月1日
		EP 0833237 B1	2001年9月19日
		EP 0426363 A2	1991年5月8日
		EP 0426363 A3	1993年10月6日
		AT 205944 T	2001年10月15日
		JP H03158228 A	1991年7月8日
		JP H082598 B2	1996年1月17日
		DE 69033809 D1	2001年10月25日
		US 5340433 A	1994年8月23日
		EP 0833237 A3	1998年4月22日
CN 104475736 A	2015年4月1日	None	
CN 103192524 A	2013年7月10日	None	
JP 2003-347266 A	2003年12月15日	None	

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2015/081512

A. CLASSIFICATION OF SUBJECT MATTER

B29C 71/00(2006.01)i

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)

B29C-,G06F-, H01L-, B22F-,

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

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

CNABS;SIPOABS;WPI;EPODOC;CNPAT:nebulizer, FFF, additive manufacturing, polymer, FDM, nozzle, controller, liquid, mist, thermoplastic, chamber

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5121329 A (STRATASYS INC.) 09 June 1992 (1992-06-09) description,columns 5-6	1-40
A	CN 104475736 A (HUNAN FARSOON HIGH-TECHNOLOGY CO., LTD.) 01 April 2015 (2015-04-01) description, paragraphs 0012-0018	1-40
A	CN 103192524 A (SUZHOU WOMAN INFORMATION SERVICES CO., LTD.) 10 July 2013 (2013-07-10) description, paragraph 0011	1-40
A	JP 2003-347266 A (SHIBAURA SEISAKUSHO KK.) 05 December 2003 (2003-12-05) description, paragraphs 0018-0024	1-40

☐ 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
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "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
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 February 2016	**07 March 2016**

Name and mailing address of the ISA/CN	Authorized officer
STATE INTELLECTUAL PROPERTY OFFICE OF THE P.R.CHINA **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088, China**	**XIA,Ruilin**
Facsimile No. **(86-10)62019451**	Telephone No. **(86-10)62415353**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2015/081512

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	5121329	A	09 June 1992	EP	0833237	A2	01 April 1998
				DE	69033809	T2	25 April 2002
				CA	2027731	C	05 September 1995
				CA	2027731	A1	01 May 1991
				EP	0833237	B1	19 September 2001
				EP	0426363	A2	08 May 1991
				EP	0426363	A3	06 October 1993
				AT	205944	T	15 October 2001
				JP	H03158228	A	08 July 1991
				JP	H082598	B2	17 January 1996
				DE	69033809	D1	25 October 2001
				US	5340433	A	23 August 1994
				EP	0833237	A3	22 April 1998
CN	104475736	A	01 April 2015	None			
CN	103192524	A	10 July 2013	None			
JP	2003-347266	A	05 December 2003	None			