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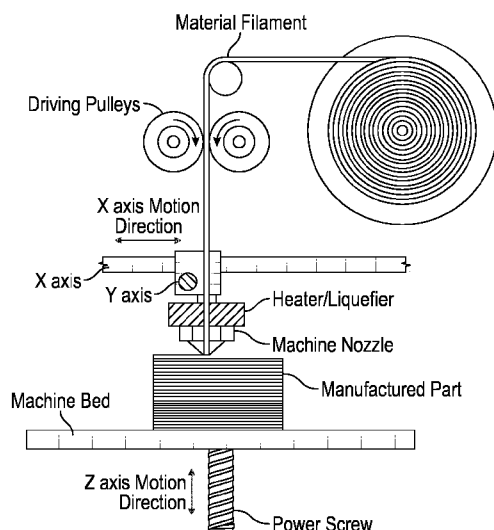


FIG. 1

(57) Abstract: A fused filament fabrication 3D printing method for fabricating an optical article includes applying a surface treatment (1710) to a building plate; heating the building plate to a predetermined plate temperature (1720); dispensing a thermoplastic through a nozzle set at a predetermined nozzle temperature onto the building plate (1730) while translating the nozzle or the building plate according to a first predetermined pattern at a predetermined printing speed to form a first layer; and solidifying the first layer, wherein a range of the predetermined plate temperature is between 30°C lower than a glass transition temperature of the thermoplastic and 20°C higher than the glass transition temperature of the thermoplastic, and a range of the predetermined nozzle temperature is at least 100 °C higher than the glass transition temperature of the thermoplastic, and at least 50 °C lower than a degradation temperature of the thermoplastic.

MANUFACTURING OF HIGH TRANSPARENT ARTICLES USING FDM 3D PRINTING

FIELD

[0001] The present disclosure relates to a method for fabricating a transparent article using Fused Deposition Modeling 3D printing and post processing.

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BACKGROUND

[0002] The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent the work is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

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[0003] FDM (Fused Deposition Modeling), also called FFF (Fused Filament Fabrication), is an additive manufacturing technology that produces an object by extruding polymer in an amorphous state through nozzle(s) to form layers as the polymer material hardens after extrusion.

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[0004] Aspects of the disclosure may address some of the above-described shortcomings in the art, particularly with the solutions set forth in the claims.

SUMMARY

[0005] The present disclosure relates to a fused filament fabrication 3D printing method for fabricating an optical article, including applying a surface treatment to a building plate; heating the building plate to a predetermined plate temperature; dispensing a thermoplastic through a nozzle set at a predetermined nozzle temperature onto the building plate while translating the nozzle or the building plate according to a first predetermined pattern at a predetermined printing speed to form a first layer; and solidifying the first layer, wherein a range of the predetermined plate temperature is between 30°C lower than a glass transition temperature of the thermoplastic and 20°C higher than the glass transition temperature of the thermoplastic, and a range of the predetermined nozzle temperature is at least 100 °C higher than the glass transition temperature of the thermoplastic, and at least 50 °C lower than a degradation temperature of the thermoplastic.

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[0006] Note that this summary section does not specify every feature and/or incrementally novel aspect of the present disclosure or claimed invention. Instead, this summary only provides a

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preliminary discussion of different embodiments and corresponding points of novelty. For additional details and/or possible perspectives of the embodiments, the reader is directed to the Detailed Description section and corresponding figures of the present disclosure as further discussed below.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Various embodiments of this disclosure that are proposed as examples will be described in detail with reference to the following figures, wherein:

10 [0008] FIG. 1 is a schematic of fused deposition modeling (FDM), also called fused filament fabrication (FFF).

[0009] FIG. 2 is a schematic of a temperature gradient during a FDM 3D printing process, within the scope of the present disclosure.

[0010] FIG. 3A and FIG. 3B are schematics of different optical wafers, within the scope of the present disclosure.

15 [0011] FIG. 4 is a schematic of an FDM 3D printing process for an optical wafer, within the scope of the present disclosure.

[0012] FIG. 5 is a schematic of issues that can occur during printing of the optical wafer, within the scope of the present disclosure.

20 [0013] FIG. 6 is a schematic of the relationships between various wafer fabrication challenges, useful within the scope of the present disclosure.

[0014] FIG. 7 is a snapshot of printing parameters for adjusting quality results, useful within the scope of the present disclosure.

[0015] FIG. 8 is a schematic of the wafer print profile design, useful within the scope of the present disclosure.

25 [0016] FIG. 9A is a printed wafer with a straight or parallel line pattern, useful within the scope of the present disclosure.

[0017] FIG. 9B is a printed wafer with a grid pattern, useful within the scope of the present disclosure.

30 [0018] FIG. 9C is a printed wafer with a spiral pattern, useful within the scope of the present disclosure.

[0019] FIG. 10 is an optical image of printing defects, useful within the scope of the present disclosure.

[0020] FIG. 11 is a cross-sectional microscopy image of printing defects, useful within the scope of the present disclosure.

5 [0021] FIG. 12 is a schematic of void formation inside the wafer and surface printing lines, useful within the scope of the present disclosure.

[0022] FIG. 13A is an optical image of an optical wafer printed using optimized printing parameters, useful within the scope of the present disclosure.

10 [0023] FIG. 13B is an optical image of an optical wafer cross-section printed using optimized printing parameters, useful within the scope of the present disclosure.

[0024] FIG. 14A is an optical image of a printed optical wafer's top layer or surface, useful within the scope of the present disclosure.

[0025] FIG. 14B is an optical image of a printed optical wafer's bottom layer or surface, useful within the scope of the present disclosure.

15 [0026] FIG. 15A is an optical image of a printed wafer with a coating, useful within the scope of the present disclosure.

[0027] FIG. 15B is an optical image of printed wafer without a coating, useful within the scope of the present disclosure.

20 [0028] FIG. 16 is a microscopy image and cross-sectional profile of a printed optical wafer, useful within the scope of the present disclosure.

[0029] FIG. 17 is an exemplary flow chart for a method of forming a lens, useful within the scope of the present disclosure.

DETAILED DESCRIPTION

25 [0030] The following disclosure provides many different variations, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting nor inoperable together in any permutation. Unless indicated otherwise, the features and embodiments described herein are operable together
30 in any permutation. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are

formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact.

[0031] In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Further, spatially relative terms, such as “top,” “bottom,” “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature’s relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. Inventive apparatuses may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

[0032] The order of discussion of the different steps as described herein has been presented for clarity sake. In general, these steps can be performed in any suitable order. Additionally, although each of the different features, techniques, configurations, etc. herein may be discussed in different places of this disclosure, it is intended that each of the concepts can be executed independently of each other or in combination with each other. Accordingly, the present disclosure can be embodied and viewed in many different ways.

[0033] FIG. 1 is a schematic of fused deposition modeling (FDM), also called fused filament fabrication (FFF). As illustrated in Fig.1, one or more polymer filaments, such as thermoplastic filaments, can be pulled by driving pulleys and fed into a heated nozzle heated to a predetermined nozzle temperature, inside which the polymer is melted and extruded onto a building plate at a predetermined location to form strands on the building plate. For example, the thermoplastic can be polycarbonate (PC), alicyclic polycarbonate copolymer, poly(methyl methacrylate) (PMMA), poly(methyl methacrylimide) (PMMI), polyamide (PA), polyester, copolyester, polysulfone (PSU), cellulose triacetate (TAC), thermoplastic polyurethane (TPU), or cyclic olefin copolymer (COC), among others.

[0034] The nozzle can include a heating element to melt the polymer, or the nozzle can be heated itself. The nozzle can then be translated in the same plane (a first base layer), or through multiple planes (a second layer, a third layer, etc.), along an X-Y axis direction or plane that is parallel to a

plane of the building plate. The nozzle can be translated at a predetermined printing speed. The heated strands of the polymer can be deposited side by side at specified layer thickness. A material of the building plate can be glass or metal, and the building plate can be heated to a predetermined plate temperature.

5 [0035] Once a first layer of the strands is deposited and completed, the building plate can be lowered (or the nozzle can be raised) along a Z axis direction (or the nozzle is raised along the Z axis direction) and 2nd layer is then deposited. These steps can be repeated until a part is finished. The heated strands can be fused or welded together when the strands are still in an amorphous or tacky state at or above a glass transition temperature of the polymer, and then cooled below the
10 glass transition temperature to form a solid. Printing can be performed on an open platform or inside an enclosed chamber or partially enclosed shroud, which can be heated to a predetermined temperature. The additional heating from the chamber or shroud can help maintain a desired temperature while printing, especially as the part increases in layers away from the heated building plate. After printing is completed, parts can be cooled down under ambient condition and removed
15 from building plate.

[0036] FIG. 2 is a schematic of a temperature gradient during a FDM 3D printing process, useful within the scope of the present disclosure. In a useful scope, the FDM 3D printing process may be non-isothermal, as it may be performed in an open environment and with poor temperature control. Temperature gradients exist in many locations, such as: 1) from nozzle to building plate; 2) from
20 extruded amorphous/molten filament to solidified filaments/layers; 3) from an interior of the fabricated part to an exterior of the part; and 4) from the part to its surround area, among others. The part can also receive low force/pressure during printing, which can be generated by the nozzle that is being pushed against the building plate, in order to reach a target layer thickness. Upon exiting the nozzle, the polymer melt can meet the previously deposited layer and immediately
25 begin to cool and solidify. As previously described, a heated chamber or shroud can help improve temperature control around the part and reduce the temperature gradient intensity.

[0037] Notably, the rapid cooling can prevent the layers from fully fusing, which often leads to voids, poor dimension accuracy, and weak mechanical strength. Parts can be weaker in the vertical, z-direction due to a weak interlayer bond strength, resulting in an anisotropic property, which can
30 cause part warpage. Part surface quality can also be poor, with defects such as layer seams, blobs, printing lines, etc.

[0038] Described herein, a method to fabricate lenses via FDM provides a solution to known lens defects, including: 1) internal defects such as voids, printing lines, blobs, black specks; 2) poor dimension accuracy, and poor dimension stability such as warpage; 3) rough surface topology.

5 [0039] Due to the above issues, it may be a challenge to manufacture an optical article, which requires 1) high clarity, as indicated by: low haze, high visible light transmission, neutral color, minimal black speck, high surface smoothness; 2) accurate dimension of thickness, diameter, radius and minimal warpage; and 3) minimal surface roughness.

[0040] FIG. 3A and FIG. 3B are schematics of different optical wafers, useful within the scope
10 of the present disclosure. An optical wafer can be defined as a thin and round part with high clarity. It can be curved (FIG. 3A) or flat (FIG. 3B). A thin and flat wafer was used as an example in the present disclosure, but it may be appreciated that a curved wafer can be fabricated similarly. The wafer described herein can have a 75 mm diameter and 1.0 mm thickness. Wafers having different diameters, thicknesses, and optics powers can also be produced using the same processes and
15 methods.

[0041] FIG. 4 is a schematic of an FDM 3D printing process for an optical wafer, useful within the scope of the present disclosure. In a useful scope, the printing can start from a first (base) layer adjacent to the substrate, and printed line by line and layer by layer. The nozzle can be heated to melt the filament and can have a predetermined diameter to control a thickness of each layer. The
20 building plate can be heated to promote a certain adhesion force between the building plate and the first layer of the wafer to avoid wafer movement during printing. Thus, the fabricated wafer can be divided into 3 parts: the first (base or bottom) layer, internal layers, and a final (top) layer.

[0042] FIG. 5 is a schematic of issues that can occur during printing of the optical wafer, useful within the scope of the present disclosure. In a useful scope, the printed wafer can include defects,
25 such as a rough surface, distinct printing lines, poor dimensional accuracy, warpage, and internal defects. The internal defects can include voids, blobs, and ocular occlusions, such as opaque specks, dust, and shards.

[0043] FIG. 6 is a schematic of the relationships between various wafer fabrication challenges, useful within the scope of the present disclosure. In a useful scope, the structure of the optical
30 wafer includes the 3 parts, each of which include respective challenges or issues during fabrication and affect the resulting wafer properties. For example, surface roughness in the top layer and/or

the bottom layer can cause optical clarity issues for the resulting optical wafer. For example, the internal defects occurring in the internal layers can cause i) optical clarity issues, ii) dimensional accuracy, and iii) mechanical degradation for the resulting optical wafer. For example, non-uniform layer thickness occurring in the internal layers can cause mechanical degradation for the resulting optical wafer. For example, poor adhesion between the bottom layer and the building plate can cause i) optical clarity issues and ii) warpage for the resulting optical wafer.

[0044] In a useful scope, the part can be fabricated layer by layer via the FDM 3D printing process using a 3D model. To produce 3D models, a computer-aided design (CAD) file can be used to plot the drawing of the part. This CAD file can then be converted into the standard triangulation language (STL) format, which is then sliced into thin vertical layers. Detailed printing parameters can be set up after on how to print each layer, such as pattern, speed, line width, layer thickness, etc. Depending on the 3D printing machine and the software used, some can have hundreds of parameters.

[0045] Thus, it can be important to specify optimal printing profiles for optical wafers as the first step to best actualize potential 3D printing advantages and avoid any possible issues due to poor printing design. After a printing profile design is specified, more printing parameters can be added and evaluated.

[0046] In a useful scope, the adhesion between the building plate and the wafer can be optimized. A level of adhesion between the building plate and wafer can be important for reducing printing issues. If adhesion is too weak, the part can move during printing, or the part can warp if there is not enough force to hold the part to the building plate due to temperature gradient inside the part, especially along the Z-direction. Conversely, if adhesion is too strong, the part may not be easily removed from the building plate after printing, or the bottom layer adjacent to the building plate can peel off during removal and thus deteriorate the bottom surface. This is important as a very thin bottom layer may be needed to achieve high surface quality. This thin layer can be easily peeled off if adhesion is too strong. Adhesion can be affected by many factors, such as 1) plate material; 2) filament material; 3) plate temperature; and 4) filament temperature, among others.

[0047] Some solutions are available for maintain strong adhesion between the building plate and the part, such as: 1) adhesive paper, which can be glued on the building plate and has good adhesion with a 3D printed part. However, the adhesion level may be too strong for optical wafers, which might peel off the bottom layers, or the high adhesion may leave some undesirable textures on the

bottom layer of the wafer due to its rough surface. 2) The adhesive can also be applied on the building plate to increase adhesion. However, the adhesive may smudge the building plate surface, and thus leave marks and/or stains on the wafer surface. This is especially an issue for optical surfaces.

5 [0048] Described herein, several solvents were screened, and acetone was determined to be the optimal solvent for promoting adhesion of the wafer to the building plate. The screening included a method including wiping the building plate surface for a predetermined length of time to reach an optimal adhesion level so the wafer can be fixed during printing and removed after part is cooled down, without peeling the bottom layer off. Other surface treatments, such as plasma, corona, can
10 also be used.

[0049] In a useful scope, parameters of the 3D printing process can be optimized. As previously described, fabrication of a part or wafer can result in: 1) poor bottom surface quality, 2) internal defects, such as voids, blobs, printing lines, black specks, etc., and 3) dimension accuracy and dimension stability such as warpage. The detailed results are described herein. For example, it was
15 determined that bottom layer thickness can affect bottom surface quality. Various layer thicknesses were evaluated, and it was determined that a very thin layer thickness, such as 0.04 mm to 0.06 mm, is needed to achieve a high glossy surface due to minimal visible printing lines produced by very thin layers. However, to print very thin layers, other factors, such as nozzle diameter, line width, nozzle temperature and plate temperature also needed to be evaluated, as they can determine
20 how the thin layers can be printed.

[0050] In a useful scope, treatment of the wafer surface can be optimized. The top surface quality can be poor due to some defects from FDM 3D printing, such as printing lines, blobs, etc. These defects can be difficult to be remove by FDM 3D printing only, such as via printing with a thin line width to produce a thin layer. Therefore, a surface treatment, such as a coating, or surfacing,
25 can be applied to improve surface smoothness. A refractive index of the coating can be the same as the polymer for the part. For example, a refractive index of 1.59 can be used if polycarbonate (PC) is used as the polymer. The bottom surface quality can be mainly affected by the building plate surface quality and the bottom layer thickness. A high glossy surface can be achieved using a high glossy building plate, such as a glass plate, nickel plated stainless steel plate, or chrome
30 plated plate, and printing with a thin layer thickness.

[0051] In a useful scope, one layer in the part can be printed using a first predetermined pattern, then the subsequent printed layer can be printed using a second predetermined pattern. The first predetermined pattern can be printed using the predetermined printing speed. Notably, the second predetermined pattern can be printed using the predetermined printing speed or a second, different predetermined printing speed. Similarly, the predetermined plate temperature can be adjusted or kept the same between printed layers.

[0052] EXAMPLES

[0053] Example 1 – Experimental setup for FDM 3D printing

[0054] 3D filament preparation: an optical grade PC resin was used as raw material for the 3D filament, which was extruded using a Filabot Ex6 extruder having a diameter of 2.85 mm with tolerance of 0.05 mm. The extruded filament was inspected under microscopy and no defects and contamination was observed, such as shark skin, black speck, dust, or white swirls.

[0055] FDM 3D printer: an Ultimaker S5 3D printer was used. Its major specifications are listed in Table 1. Ultimaker Cura software was used to prepare the 3D printing. The software has 392 parameters under 12 settings, as shown in Table 2.

[0056] FIG. 7 is a snapshot of printing parameters for adjusting quality results, useful within the scope of the present disclosure. As shown, some parameters include layer height/thickness, first layer height/thickness, and line width, among others. It may be appreciated that other 3D printers can also be used, such as a Lulzbot TAZ6, PartPro300 Xt, Markforged Mark 2, Rize one, Stratasys F series, or Fusion3 F410.

Parameter	Value
Nozzle diameter	0.25 mm, 0.4 mm, 0.6 mm, 0.8 mm
Nozzle temperature	180-280 °C
Layer resolution	0.25 mm nozzle: 60-150 µm; 0.4 mm nozzle: 20-200 µm; 0.6 mm nozzle: 20-300 µm; 0.8 mm nozzle: 20-600 µm
Building plate	Glass build plate
Build plate temperature	20-140 °C
Build speed	< 24 mm ³ /s

Table 1 - Main specifications of Ultimaker S5

Quality	Speed	Material	Shell
15*: Layer height, Line width,..	60*: Print speed/acceleration	43*: Printing temp., Plate temp.	53*: Wall/Top/Bottom thickness, pattern
Travel	Dual extrusion	Infill	Build plate adh.
24*: Retraction distance/speed	15*: Prime tower, Ooze shield	33*: Density, Pattern,...	43*: Skirt, Brim, Raft...
Mesh Fixes	Support	Cooling	Special modes
11*: Stitching, Removal.	70*: Structure, Pattern, Density.	11*: Fan speed, ...	14*: Mesh, Mold

Table 2 – List of settings and parameters in Ultimaker Cura

[0057] Example 2 – Specification of printing profile design

[0058] As previously described, an initial step of 3D printing is to design the printing profile.

- 5 The printing profile refers to how the part will be placed on building plate, the printing path and pattern, etc. Table 3 lists the main design elements that can be considered.

Design	Value
Wafer placement orientation	Vertical, Horizontal
Printing pattern	Straight line, Circle, Zig Zag
Print line orientation between layers	Parallel, Perpendicular, Tilt

Table 3 – Printing profile design

- [0059] Wafer placement orientation: the optical wafer can be laid either horizontally with its flat surface on the building plate, or vertically with its thin edge on the building plate. The former option is used for optical wafer printing, as the part is more stable, there is less warpage, and there is less surface roughness due to layer seams, also called Z-seams.

- [0060] Printing pattern: the printing pattern can be determined by how filament strands are laid. A straight line pattern was chosen, as it will generate the least surface texture and roughness compared to circle and zig-zag patterns. A wall was thus also designed, which can hold the wafer during printing to prevent wafer delamination from the building plate, as the straight line pattern can create an asymmetric pattern.

[0061] Print line orientation between layers: the line direction between two adjacent layers can be parallel, perpendicular, or at an angle. FIG. 8 is a schematic of the wafer print profile design, useful within the scope of the present disclosure. The parallel orientation shown can be used, as it generates the least grids, and thus, the least haziness.

[0062] FIG. 9A is a printed wafer with a straight or parallel line pattern, useful within the scope of the present disclosure. FIG. 9B is a printed wafer with a grid pattern, useful within the scope of the present disclosure. FIG. 9C is a printed wafer with a spiral pattern, useful within the scope of the present disclosure. As shown, the straight line pattern (FIG. 9A) has much higher clarity than the grid pattern (FIG. 9B) or the spiral pattern (FIG. 9C).

[0063] Example 3 - Optimization of adhesion between building plate and wafer by surface treatment

[0064] As previously described, the building plate surface can be treated in order to achieve optimal adhesion strength with the part or wafer. Several solvents, such as isopropyl alcohol (IPA), acetone, methanol, methyl ethyl ketone, and A1100 were tested. The solvents were sprayed onto a cloth, which was then wiped against the building plate surface for less than 3 minutes. The wafer was printed after surface treatment. Results are shown in Table 4. It may be appreciated that other chemicals, and other surface treatment methods, such as plasma and corona, can also be tested for use with FDM 3D printing.

Solvent	Adhesion Strength	Results
IPA	Weaker	Wafer movable during printing
Acetone	Optimal	Wafer stable during printing, and removed with no layer peeling during part removal
Methanol	Weaker	Wafer movable during printing
A1100	Stronger	Bottom layer peeled off during part removal

Table 4 – Results of plate surface treatment

[0065] Several factors can contribute to adhesion strength between the building plate and the wafer: 1) building plate surface tension, 2) building plate surface polarity, 3) building plate

chemistry, i.e., glass, chrome, stainless steel, aluminum, etc., and 3) solvent compatibility with filament material, as there might be faint residue left on the building plate after wiping. In this case, the solvent should have good compatibility with the PC, and that is why acetone and A1100 can provide stronger adhesion than IPA and methanol.

5 [0066] Example 4 - Optimization of 3D printing process and parameters

[0067] As previously described, the 3D printing process and parameters can be optimized in order to produce an optical wafer with 1) high clarity, 2) high dimension accuracy and stability, and 3) high surface smoothness. Over 300 parameters as listed in the Cura software were screened, and major printing parameters were identified, which are listed in Table 4. These parameters were
10 further tested at different values, which generated numerous combinations of printing conditions. A general tendency of improving wafer quality by adjusting each parameter is summarized in Table 5.

Parameter	Value		
Nozzle diameter (mm)	0.25	0.4	0.8
Line width (mm)	0.22	0.35	0.7
Layer height (mm)	0.1, 0.04	0.2, 0.1, 0.04	0.4, 0.2
Printing temperature (°C)	240-285		
Plate temperature (°C)	100-140		
Printing speed (mm/s)	10-70		
Nozzle numbers	Single, Dual		

Table 4 – Major printing parameters for FDM 3D printing

Part structure	Defect/Issue	Reasons	Parameter adjustment to reduce defects/issues (↓: decrease; ↑: increase; ↔: minimal impact)					
			Layer height	Initial layer height	Line width	Melt temp.	Plate temp.	Printing speed
Internal layers	Blobs	Unstable flow, vary filament diameter, oozing	↓	NA	↓	↓	↓	↓
	Voids	Fila frozen too fast, poor inter layer adhesion	↓	NA	↑	↑	↑	↓
Top surface (layer)	Blobs	Unstable flow, vary filament diameter, oozing	↓	NA	↓	↓	NA	↓
	Print lines	Frozen filament	↓	NA	↑	↑	NA	↔
Bottom surface (layer)	Print lines	Frozen filament	NA	↓	↑	↑	↑	↔
	Surface peel	Adhesion to plate too strong	NA	↑	↑	↓	↓	↓

Table 5 - General tendency of improving wafer quality by adjusting each parameter

[0068] FIG. 10 is an optical image of printing defects, useful within the scope of the present disclosure. FIG. 11 is a cross-sectional microscopy image of printing defects, useful within the scope of the present disclosure. Some examples of impact from different line width settings on defects such as blobs and printing lines, and layer height on voids, are shown in FIG. 10 and FIG. 11. Black speck defects can be avoided if nozzle temperature is below a predetermined temperature, such as below 330°C.

[0069] FIG. 12 is a schematic of void formation inside the wafer and surface printing lines, useful within the scope of the present disclosure. Generally, the filament was extruded and printed as overlapping between lines to increase adhesion between the layers. Voids will form if the layer height is above predetermined threshold, such as 0.2 mm if a 0.4 mm nozzle is used. Such voids will disappear if the layer height is less than 0.1 mm since gaps between two adjacent layers

become smaller. That is, the extruded strands on the new layer can more closely nestle into the depression between strands on the previous layer. The printing pressure also becomes higher because the nozzle is pushed more to achieve thin layer thicknesses.

[0070] FIG. 13A is an optical image of an optical wafer printed using optimized printing parameters, useful within the scope of the present disclosure. FIG. 13B is an optical image of an optical wafer cross-section printed using optimized printing parameters, useful within the scope of the present disclosure. The FDM 3D printing process was optimized and able to produce a wafer with 1) high glossy bottom surface, 2) minimal voids, blobs, printing lines, and black specks, and 3) high dimension accuracy with no warpage, as shown in FIG. 13A. A range for each parameter is also listed, considering PC with different melt flow indices (MFI) and different FDM 3D printers. Their impacts on wafer quality were also described in Table 6.

Processing parameter	Value	Range	Impact on wafer quality
Nozzle diameter	0.4 mm	0.2-0.6 mm	Too big: blobs, oozing, printing lines Too small: poor adhesion, surface scratching
Nozzle temperature	285 °C	260-310 °C	Too high: oozing, material degradation, black speck Too low: poor adhesion, unstable flow
Plate temperature	140 °C	100-160 °C	Too high: adhesion with plate too strong, wafer surface too soft Too low: adhesion with plate too weak, wafer warpage
Initial layer height	0.04 mm	0.02-0.1 mm	Too high: rough bottom surface Too low: poor adhesion with plate
Layer height	0.06 mm	0.04-0.1 mm	Too high: voids inside wafer Too low: poor adhesion between layers
Printing speed	10-30 mm/s	10-200 mm/s	Too high: blobs Too low: poor adhesion

Table 6 - Optimized FDM 3D printing processing parameters

[0071] As listed, a range of the nozzle diameter can be between 0.1 to 1.0 mm, or 0.3 to 0.6 mm, or 0.4 to 0.5 mm. A temperature range of the predetermined plate temperature of the building plate can be between 100°C to 160°C, or between 30°C lower than a glass transition temperature of the

thermoplastic and 20°C higher than the glass transition temperature of the thermoplastic. A temperature range of the predetermined nozzle temperature can be between 280°C to 290°C, or at least 100°C higher than the glass transition temperature of the thermoplastic, and at least 50°C lower than a degradation temperature (according to ASTM E2550-17) of the thermoplastic. A cross-sectional shape of the nozzle and thus the filament is circular, square, or rectangular. A range of the thickness of the first (initial) layer can be between 0.02 mm and 0.1 mm, or 0.04 mm to 0.06 mm. A range of the predetermined printing speed can be between 1 mm/s to 100 mm/s, or 5 mm/s to 30 mm/s. A range of the thickness of each additional layer on the base layer can be 0.04 mm to 0.2 mm, or 0.06 mm to 0.1 mm.

[0072] Example 5 – Wafer surface treatment

[0073] FIG. 14A is an optical image of a printed optical wafer's top layer or surface, useful within the scope of the present disclosure. FIG. 14B is an optical image of a printed optical wafer's bottom layer or surface, useful within the scope of the present disclosure.

[0074] Top surface: As shown in FIG. 14A, the top surface of the printed wafer is still rough due to the printing lines. The printing lines can be reduced by certain printing process, such as ironing, which uses a hot nozzle to press the wafer surface. Additional surface treatment methods can be applied to reduce printing lines and thus increase surface smoothness, such as 1) coating, 2) surfacing, 3) film lamination, 4) thermoforming, and 5) compression molding.

[0075] FIG. 15A is an optical image of a printed wafer with a coating, useful within the scope of the present disclosure. FIG. 15B is an optical image of printed wafer without a coating, useful within the scope of the present disclosure. Initial tests by coating were performed by spin coating a UV curable adhesive, such as NOA60 (Norland Products Inc, NJ), which has RI of 1.56. Thus, the coated wafer is shown in FIG. 15A. Further improvement can be made by mixing of NOA160 (RI: 1.60) and NOA60 (1.56), which has an RI of 1.585, which is the same as that of PC.

[0076] Bottom surface: As shown in FIG. 14, the bottom surface of the printed wafer has a high glossy surface. This was achieved by using, 1) a glass building plate, which has surface smoothness at optical quality, and 2) a very thin layer thickness, i.e., 40 µm.

[0077] FIG. 16 is a microscopy image and cross-sectional profile of a printed optical wafer, useful within the scope of the present disclosure. The surface produced has very faint printing lines, at a magnitude of approximately 0.5 µm, which are almost invisible to human eyes, as shown in FIG. 16.

[0078] FIG. 17 is an exemplary flow chart for a method 1700 of fabricating an optical article, useful within the scope of the present disclosure. In step 1710, a surface treatment is applied to the building plate. In step 1720, the building plate is heated to a predetermined plate temperature. In step 1730, a thermoplastic is dispensed through the nozzle, the nozzle being heated to a predetermined nozzle temperature. The nozzle or the building plate is translated according to a first predetermined pattern at a predetermined printing speed to form a first layer. In step 1740, additional layers can be printed. In step 1750, the printed part or wafer is cooled and solidified.

[0079] In the preceding description, specific details have been set forth, such as a particular geometry of a processing system and descriptions of various components and processes used therein. It should be understood, however, that techniques herein may be practiced in other embodiments that depart from these specific details, and that such details are for purposes of explanation and not limitation. Embodiments disclosed herein have been described with reference to the accompanying drawings. Similarly, for purposes of explanation, specific numbers, materials, and configurations have been set forth in order to provide a thorough understanding. Nevertheless, embodiments may be practiced without such specific details. Components having substantially the same functional constructions are denoted by like reference characters, and thus any redundant descriptions may be omitted.

[0080] Various techniques have been described as multiple discrete operations to assist in understanding the various embodiments. The order of description should not be construed as to imply that these operations are necessarily order dependent. Indeed, these operations need not be performed in the order of presentation. Operations described may be performed in a different order than specifically described unless expressly indicated otherwise. Various additional operations may be performed and/or described operations may be omitted.

[0081] Those skilled in the art will also understand that there can be many variations made to the operations of the techniques explained above while still achieving the same objectives of the disclosure. Such variations are intended to be covered by the scope of this disclosure. As such, the foregoing descriptions of embodiments are not intended to be limiting. Rather, any limitations to embodiments are presented in the following claims.

[0082] Embodiments of the present disclosure may also be as set forth in the following parentheticals.

- [0083] (1) A fused filament fabrication 3D printing method for fabricating an optical article, comprising: applying a surface treatment to a building plate; heating the building plate to a predetermined plate temperature; dispensing a thermoplastic through a nozzle set at a predetermined nozzle temperature onto the building plate while translating the nozzle or the building plate according to a first predetermined pattern at a predetermined printing speed to form a first layer; and solidifying the first layer, wherein a range of the predetermined plate temperature is between 30°C lower than a glass transition temperature of the thermoplastic and 20°C higher than the glass transition temperature of the thermoplastic, and a range of the predetermined nozzle temperature is at least 100 °C higher than the glass transition temperature of the thermoplastic, and at least 50 °C lower than a degradation temperature of the thermoplastic.
- [0084] (2) The method of (1), wherein the first predetermined pattern is a parallel linear line pattern, a circular pattern, or a spiral pattern.
- [0085] (3) The method of either (1) or (2), wherein a diameter of the nozzle is between 0.1 mm to 1.0 mm, or 0.3 to 0.6 mm, or 0.4 to 0.5 mm.
- [0086] (4) The method of any one of (1) to (3), wherein a cross-sectional shape of the nozzle is circular, square, or rectangular.
- [0087] (5) The method of any one of (1) to (4), wherein a range of a thickness of the first layer is 0.02 mm to 0.1 mm or 0.04 mm to 0.06 mm.
- [0088] (6) The method of any one of (1) to (5), wherein a range of the predetermined printing speed is 1 mm/s to 100 mm/s or 5 mm/s to 30 mm/s.
- [0089] (7) The method of any one of (1) to (6), wherein a material of the thermoplastic is polycarbonate (PC), alicyclic polycarbonate copolymer, poly(methyl methacrylate) (PMMA), poly(methyl methacrylimide) (PMMI), polyamide (PA), polyester, copolyester, polysulfone (PSU), cellulose triacetate (TAC), thermoplastic polyurethane (TPU), or cyclic olefin copolymer (COC).
- [0090] (8) The method of any one of (1) to (7), wherein the surface treatment includes application of a solvent, a plasma, or a corona to a surface of the building plate.
- [0091] (9) The method of (8), wherein the solvent is acetone, isopropyl alcohol, methanol, or methyl ethyl ketone.
- [0092] (10) The method of any one of (1) to (9), wherein a material of the building plate is glass, chrome plated stainless steel, nickel plated stainless steel, or nickel.

[0093] (11) The method of any one of (1) to (10), wherein the dispensing the thermoplastic through the nozzle to form the first layer further comprises repeating the dispensing the thermoplastic through the nozzle set at the predetermined nozzle temperature onto the building plate while translating the nozzle according to a second predetermined pattern at the predetermined printing speed to form at least one additional layer.

[0094] (12) The method of (11), wherein the second predetermined pattern is the same as the first predetermined pattern with a predetermined offset to dispense the thermoplastic in voids formed between lines of the first predetermined pattern and no grids are formed between the lines of the first predetermined pattern and lines of the second predetermined pattern.

[0095] (13) The method of (11), wherein a range of a thickness of each additional layer of the at least one additional layer is 0.04 mm to 0.2 mm or 0.06 mm to 0.1 mm.

[0096] (14) The method of (11), further comprising applying a surface smoothing process to a surface of the first layer and/or a surface of the last layer of the at least one additional layer.

[0097] (15) The method of (14), wherein the surface smoothing process is application of a coating material, mechanical surfacing, film lamination, thermoforming, or compression molding.

[0098] (16) The method of any one of (1) to (15), wherein the first predetermined pattern is a spiral.

[0099] (17) The method of any one of (1) to (15), wherein the first predetermined pattern is a grid.

[00100] (18) The method of any one of (1) to (17), wherein the nozzle comprises a dual channel dispensing tip configured to dispense two lines of the polymer at once.

[00101] (19) The method of any one of (1) to (18), wherein the building plate includes a heated shroud formed along a perimeter and on a top surface of the building plate.

[00102] (20) The method of any one of (1) to (19), wherein the predetermined plate temperature is 140°C and the predetermined nozzle temperature is 285°C.

WHAT IS CLAIMED IS:

1. A fused filament fabrication 3D printing method for fabricating an optical article, comprising:

applying a surface treatment to a building plate;

5 heating the building plate to a predetermined plate temperature;

dispensing a thermoplastic through a nozzle set at a predetermined nozzle temperature onto the building plate while translating the nozzle or the building plate according to a first predetermined pattern at a predetermined printing speed to form a first layer; and

solidifying the first layer, wherein

10 a range of the predetermined plate temperature is between 30°C lower than a glass transition temperature of the thermoplastic and 20°C higher than the glass transition temperature of the thermoplastic, and

a range of the predetermined nozzle temperature is at least 100 °C higher than the glass transition temperature of the thermoplastic, and at least 50 °C lower than a degradation temperature
15 of the thermoplastic.

2. The method of claim 1, wherein the first predetermined pattern is a parallel linear line pattern, a circular pattern, or a spiral pattern.

20 3. The method of claim 1, wherein a diameter of the nozzle is between 0.1 mm to 1.0 mm.

4. The method of claim 1, wherein a cross-sectional shape of the nozzle is circular, square, or rectangular.

25 5. The method of claim 1, wherein a range of a thickness of the first layer is 0.02 mm to 0.1 mm.

6. The method of claim 1, wherein a range of the predetermined printing speed is 1 mm/s to 100 mm/s.

30

7. The method of claim 1, wherein a material of the thermoplastic is polycarbonate (PC), alicyclic polycarbonate copolymer, poly(methyl methacrylate) (PMMA), poly(methyl methacrylimide) (PMMI), polyamide (PA), polyester, copolyester, polysulfone (PSU), cellulose triacetate (TAC), thermoplastic polyurethane (TPU), or cyclic olefin copolymer (COC).

5

8. The method of claim 1, wherein the surface treatment includes application of a solvent, a plasma, or a corona to a surface of the building plate.

9. The method of claim 8, wherein the solvent is acetone, isopropyl alcohol, methanol, or methyl ethyl ketone.

10

10. The method of claim 1, wherein a material of the building plate is glass, chrome plated stainless steel, nickel plated stainless steel, or nickel.

15

11. The method of claim 1, wherein the dispensing the thermoplastic through the nozzle to form the first layer further comprises repeating the dispensing the thermoplastic through the nozzle set at the predetermined nozzle temperature onto the building plate while translating the nozzle according to a second predetermined pattern at the predetermined printing speed to form at least one additional layer.

20

12. The method of claim 11, wherein the second predetermined pattern is the same as the first predetermined pattern with a predetermined offset to dispense the thermoplastic in voids formed between lines of the first predetermined pattern and no grids are formed between the lines of the first predetermined pattern and lines of the second predetermined pattern.

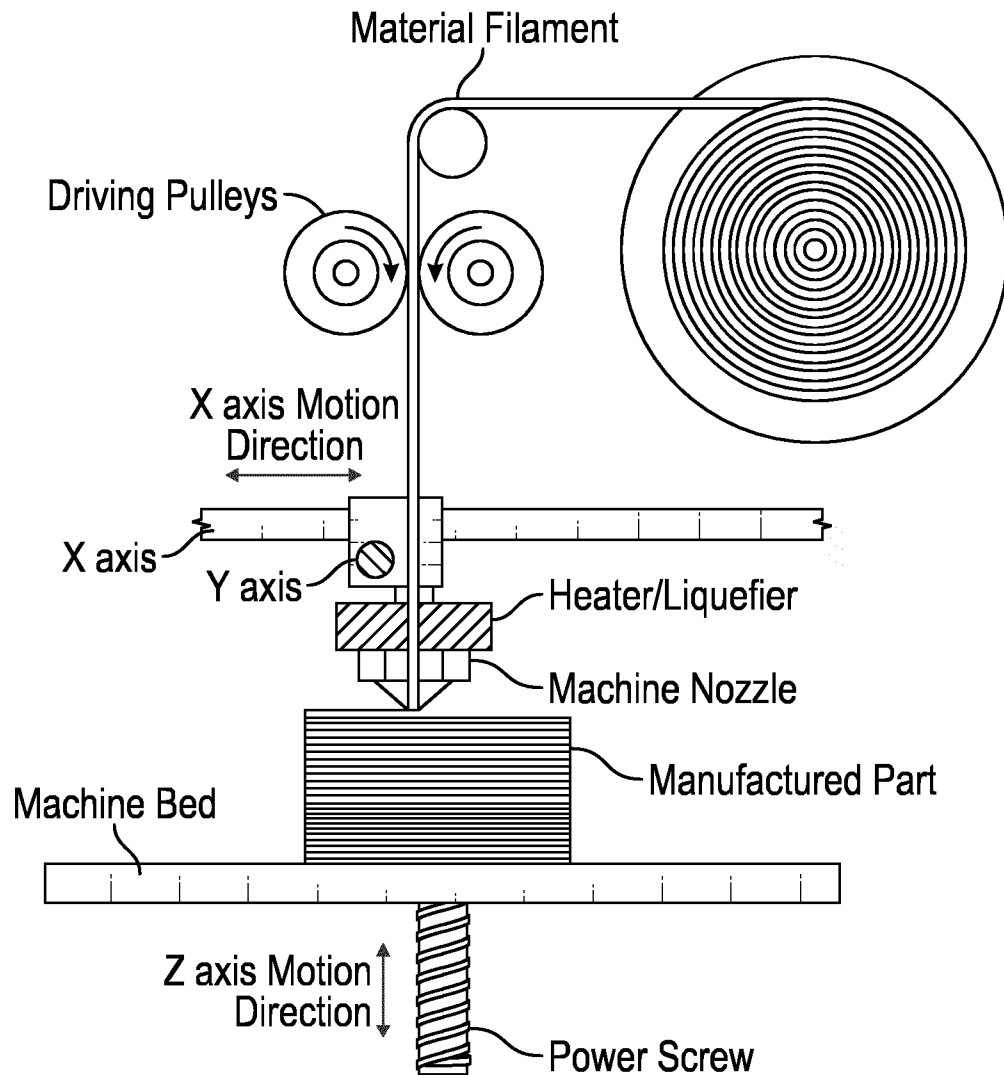
25

13. The method of claim 11, wherein a range of a thickness of each additional layer of the at least one additional layer is 0.04 mm to 0.2 mm.

14. The method of claim 11, further comprising applying a surface smoothing process to a surface of the first layer and/or a surface of the last layer of the at least one additional layer.

30

15. The method of claim 14, wherein the surface smoothing process is application of a coating material, mechanical surfacing, film lamination, thermoforming, or compression molding.

**FIG. 1**

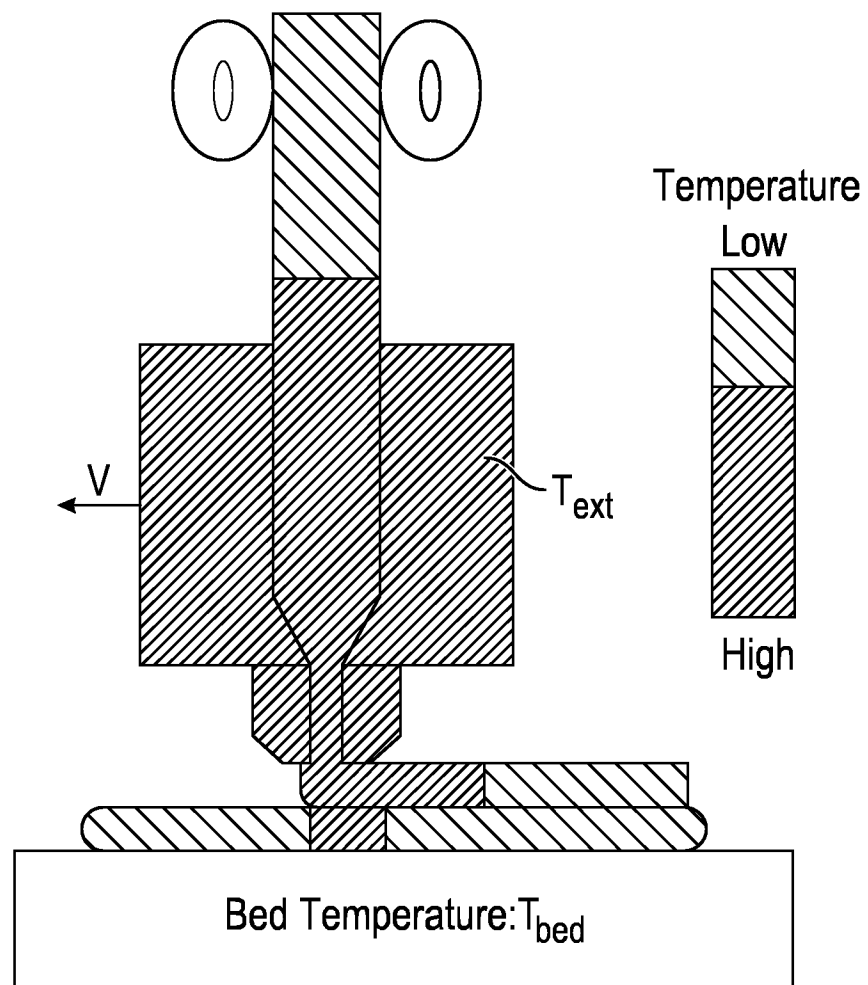
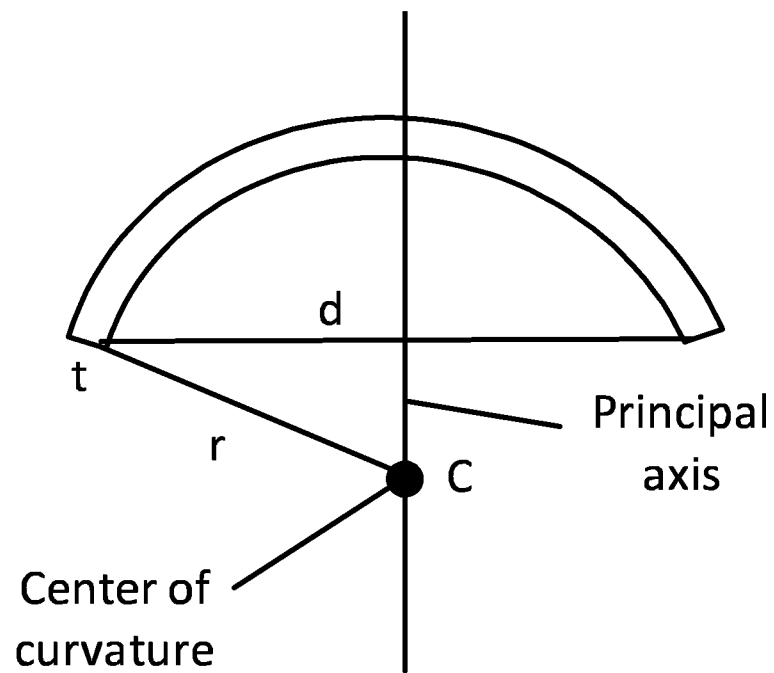


FIG. 2



d : diameter; r : radius; t : thickness

FIG. 3A

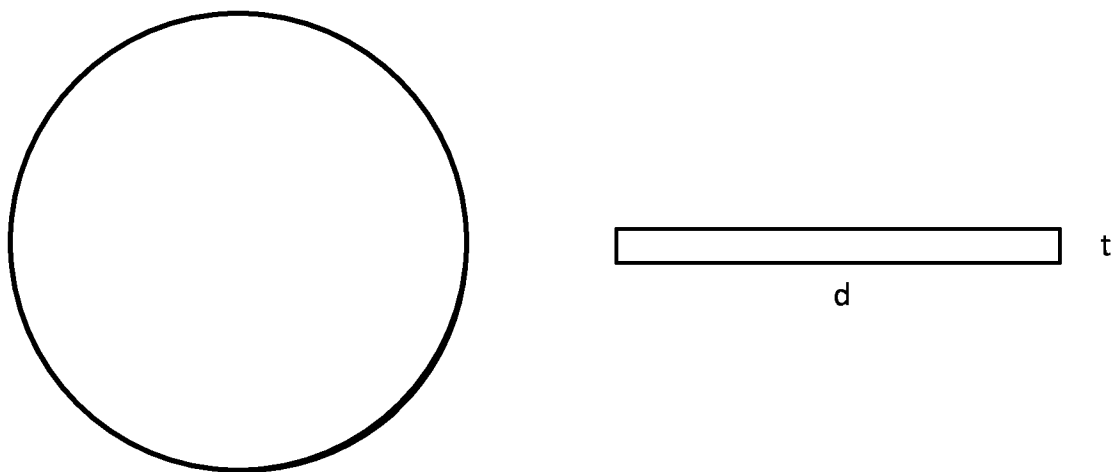
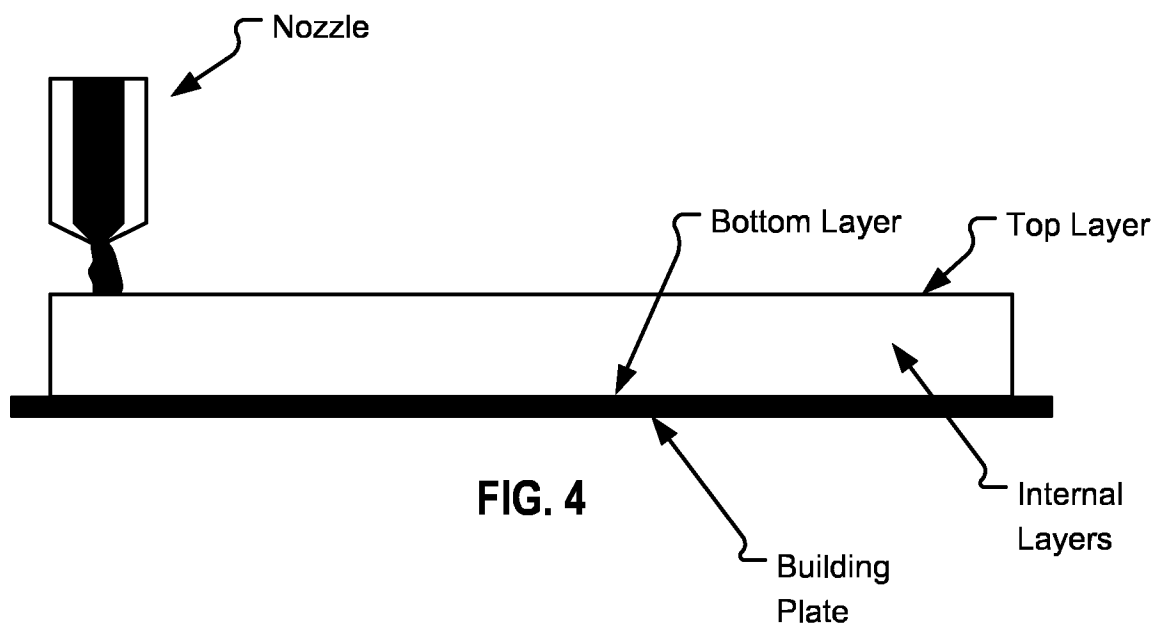
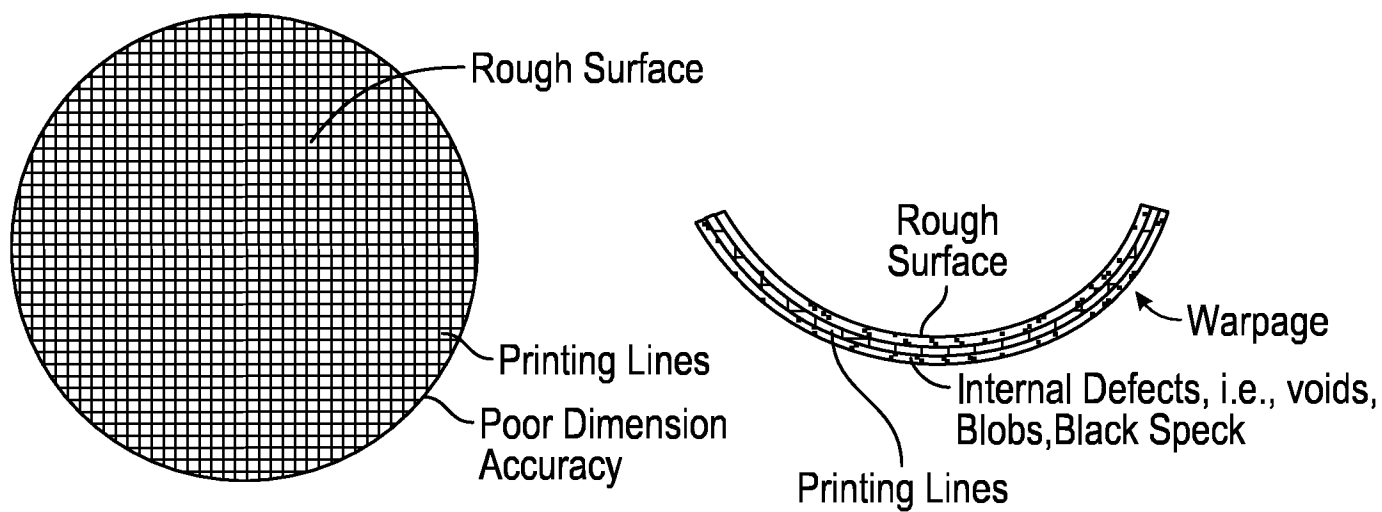


FIG. 3B



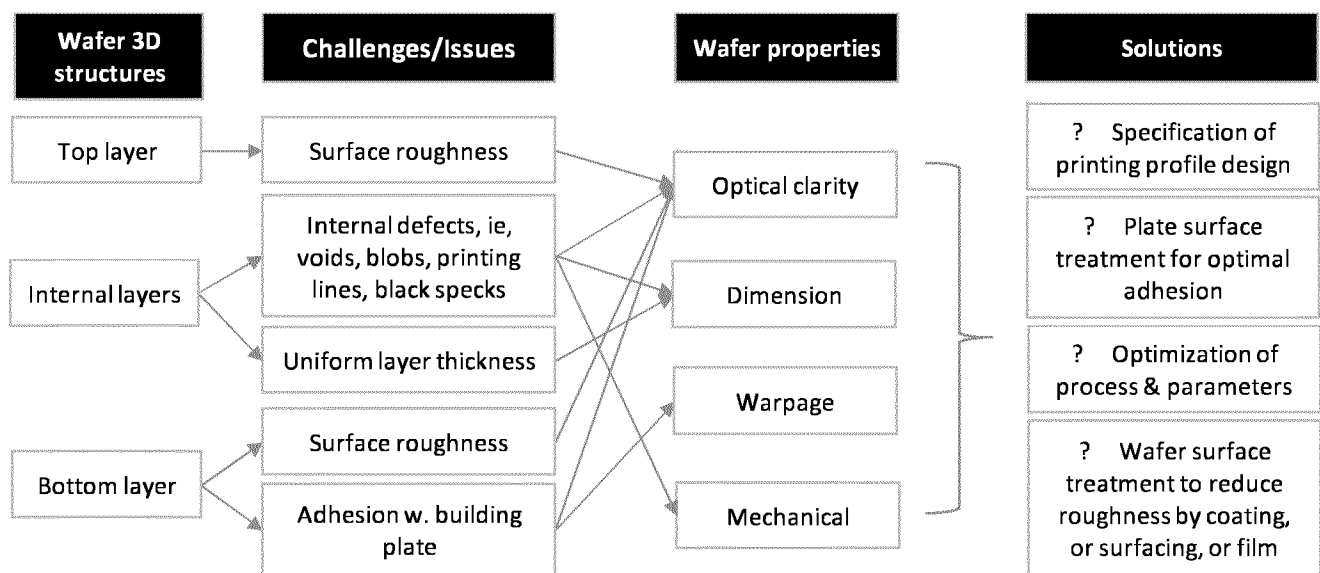


FIG. 6

Quality

Layer Height

0.2mm

Initial Layer Height

0.2mm

Line Width

0.23mm

Wall Line Width

0.23mm

Outer Wall Line Width

0.23mm

Inner Wall(s) Line Width

0.23mm

Top/Bottom Line Width

0.23mm

Infill Line Width

0.23mm

Skirt/Brim Line Width

0.23mm

Prime Tower Line Width

0.23mm

FIG. 7

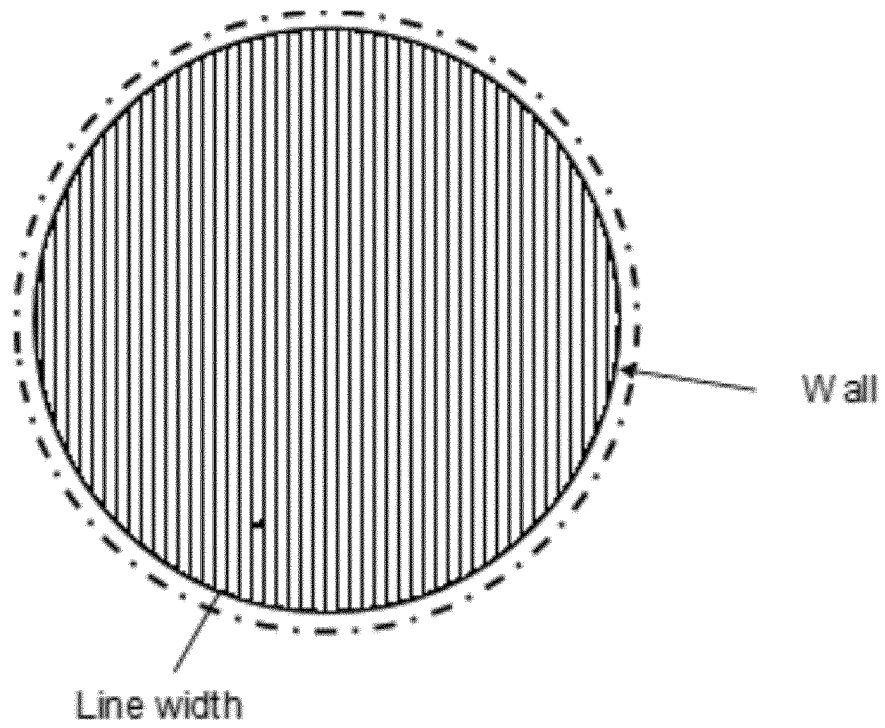


FIG. 8

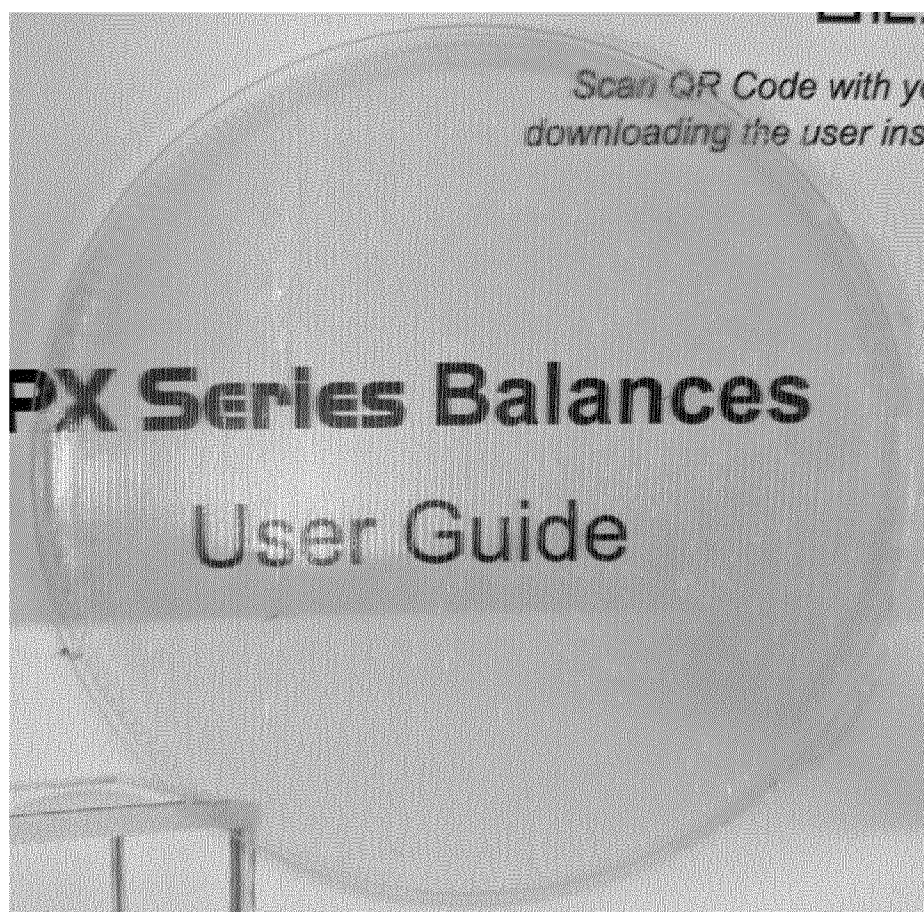


FIG. 9A

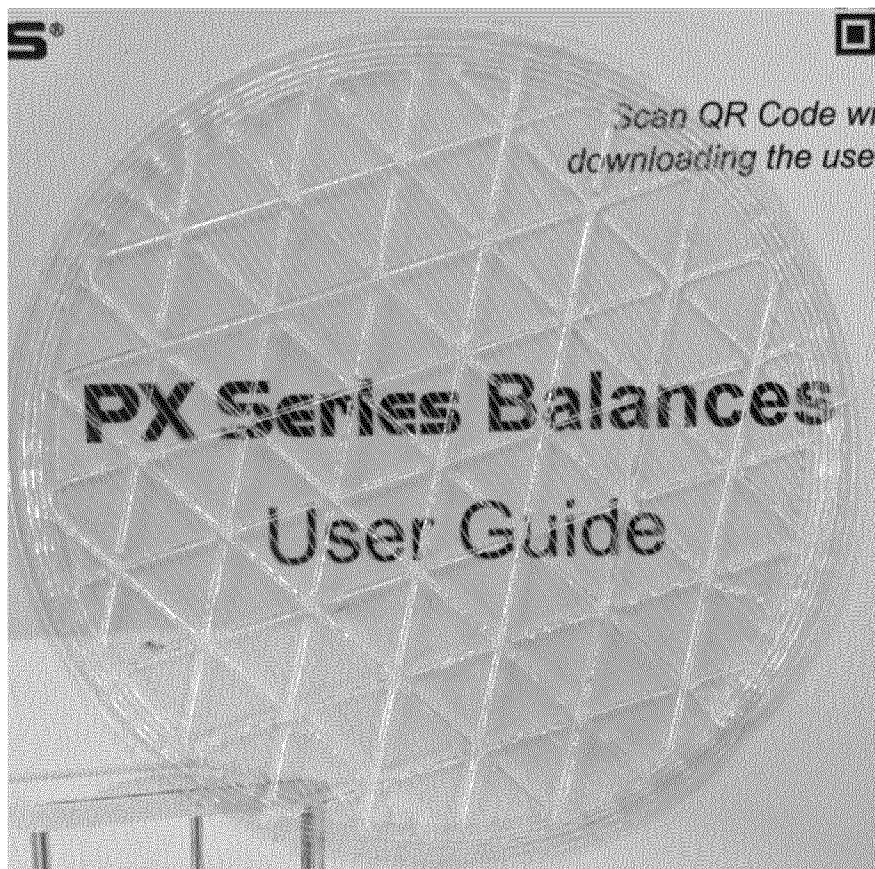


FIG. 9B

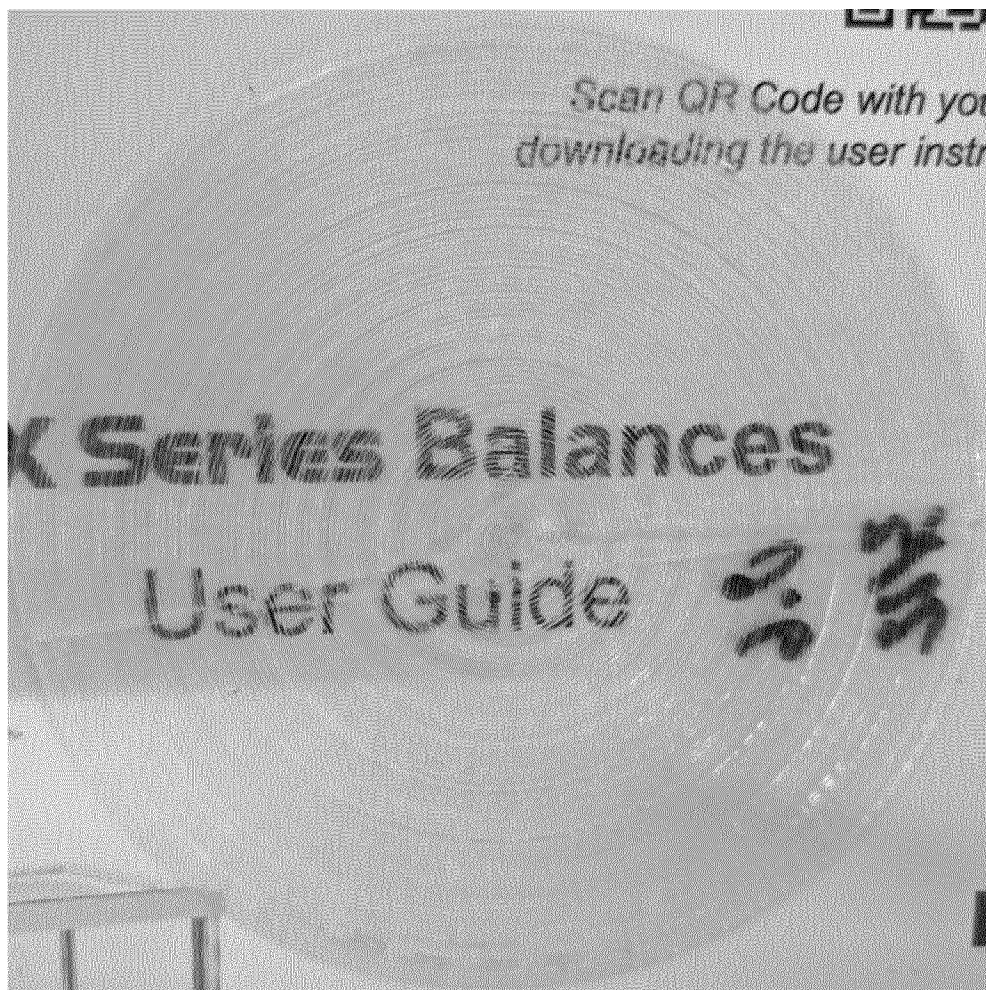


FIG. 9C

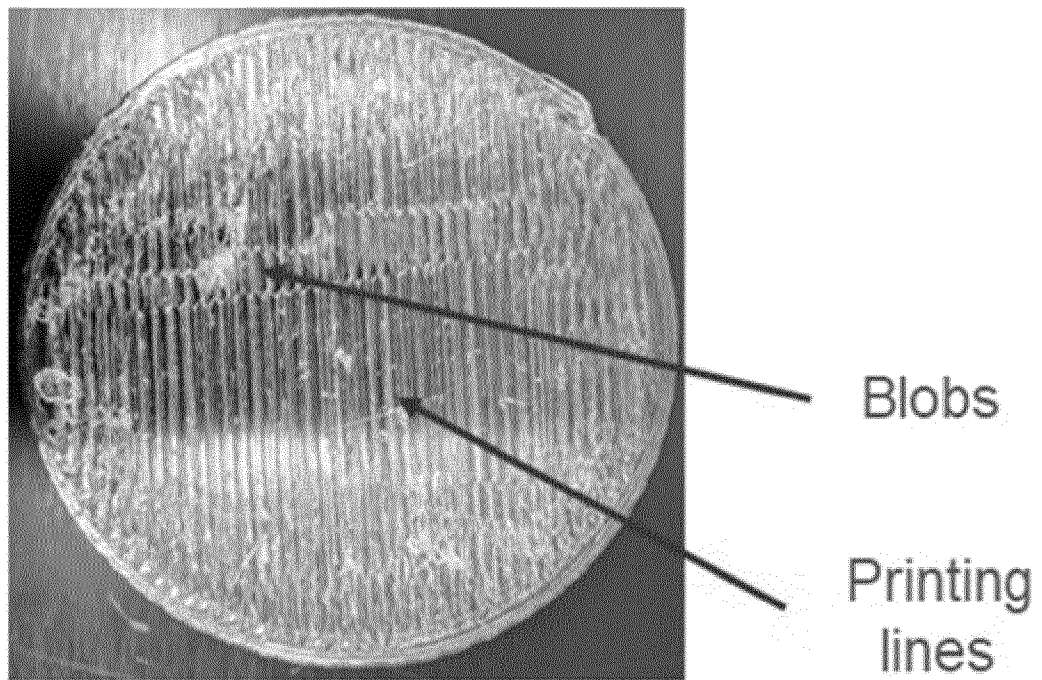


FIG. 10

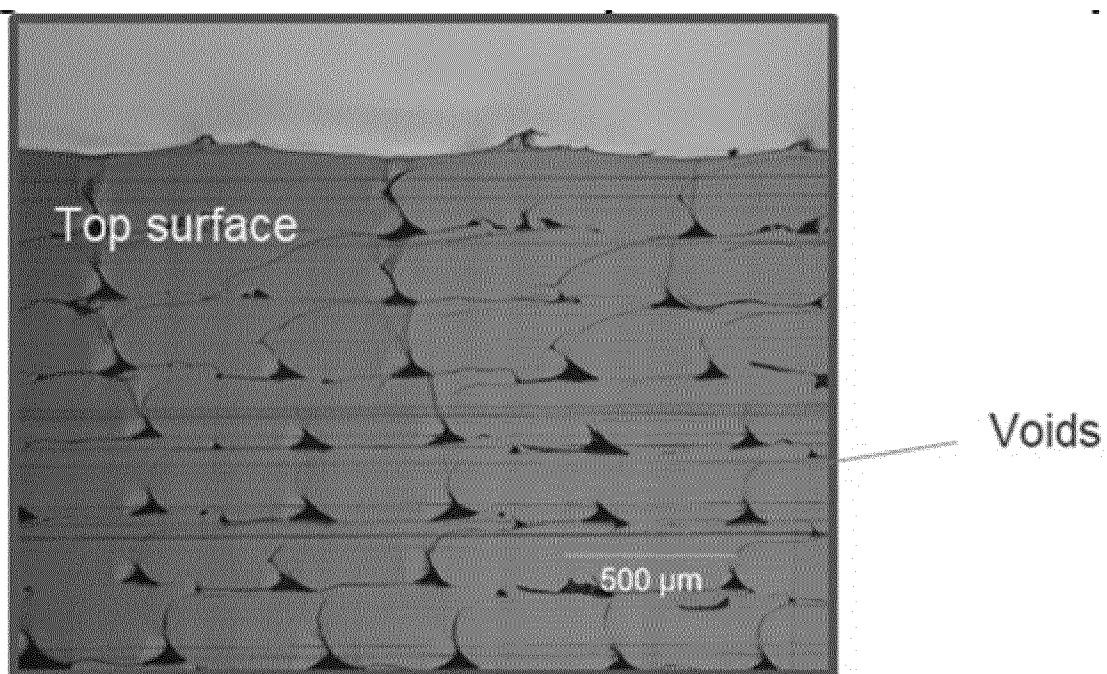


FIG. 11

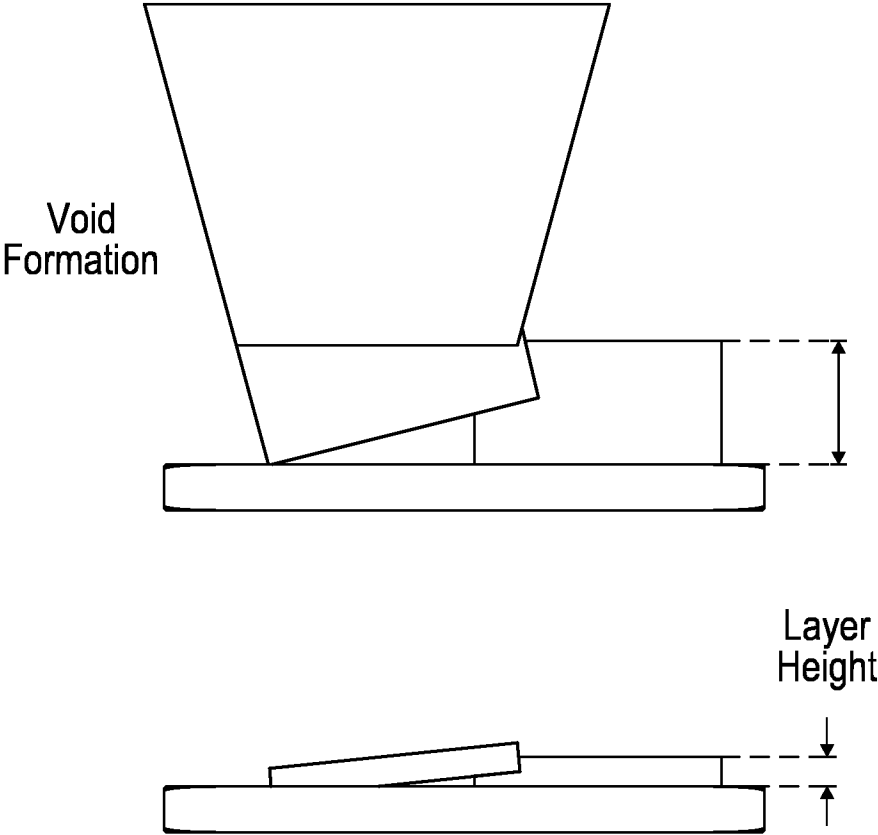


FIG. 12

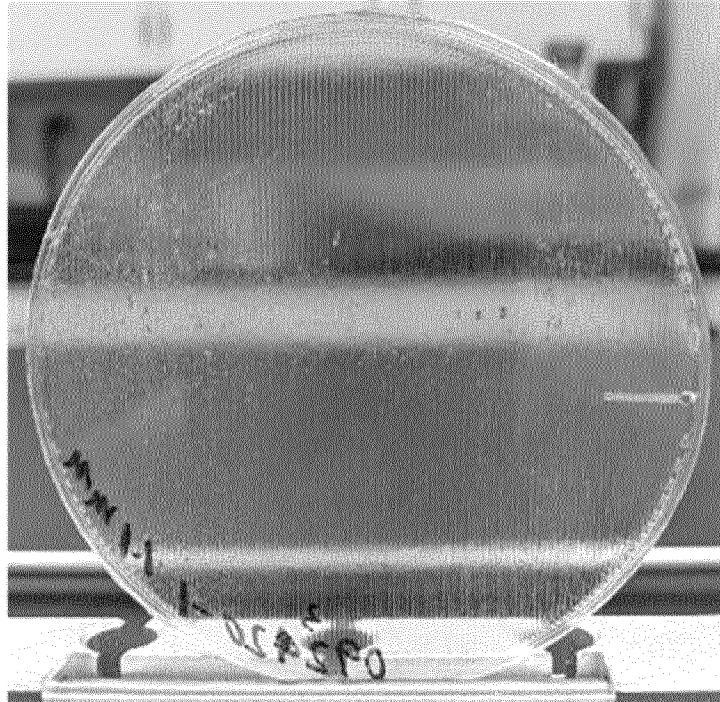


FIG. 13A

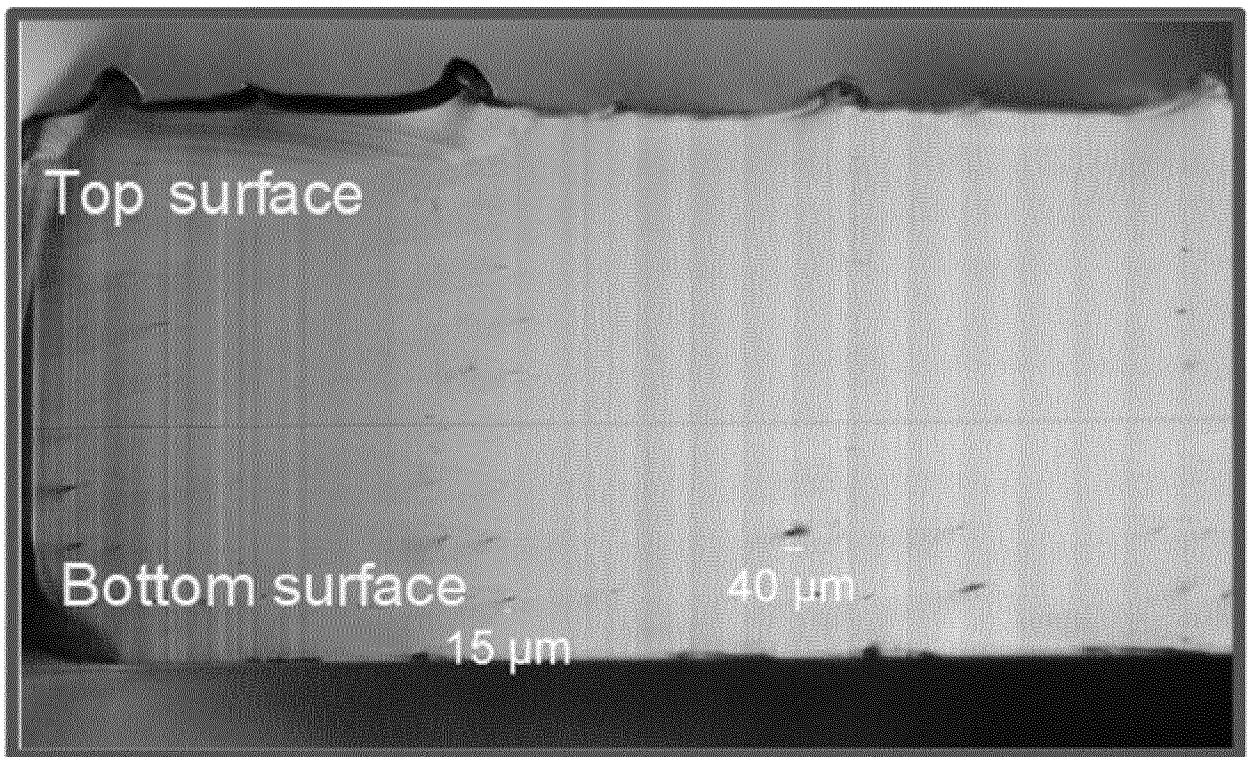


FIG. 13B

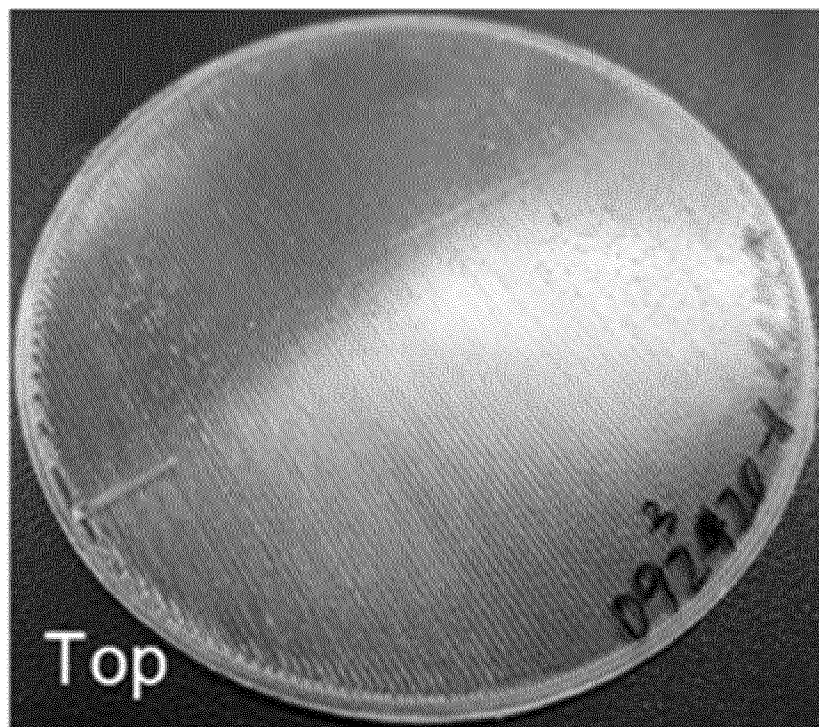


FIG. 14A

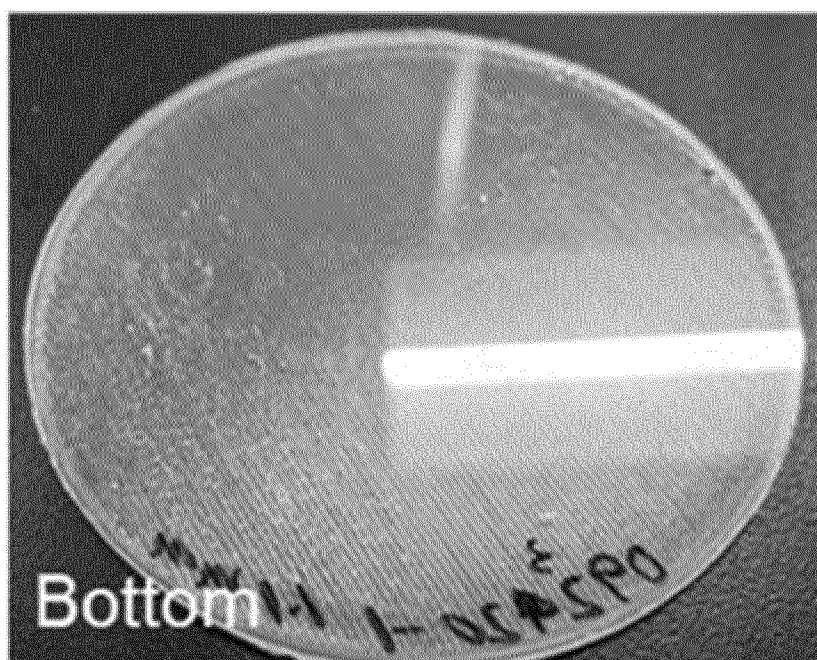


FIG. 14B

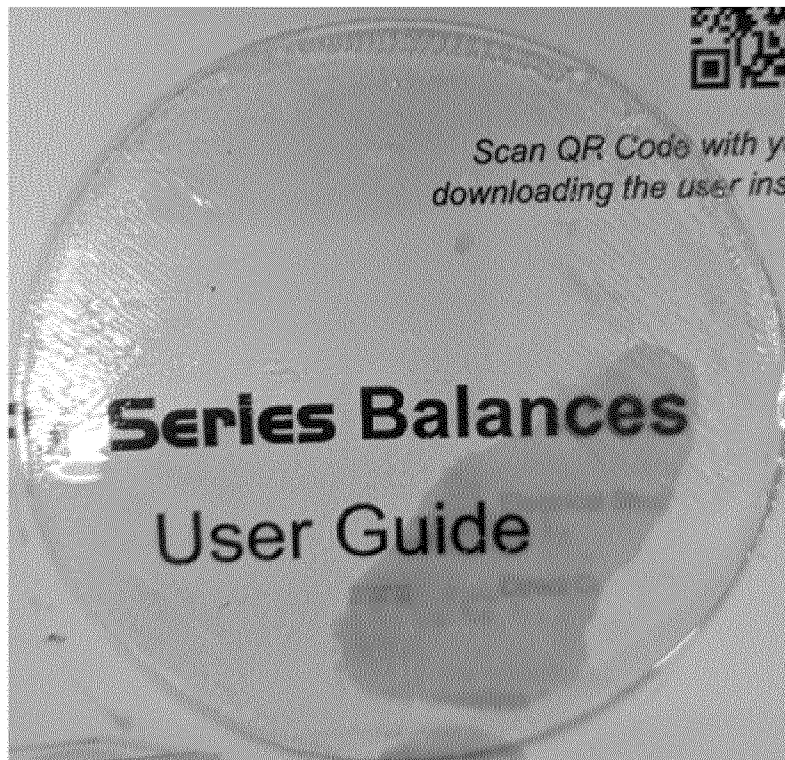


FIG. 15A

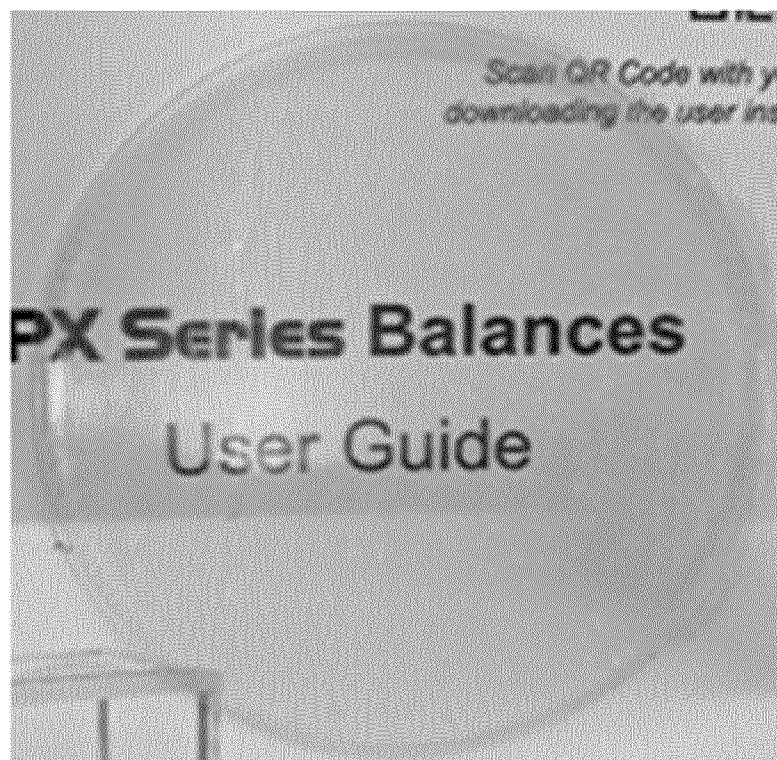


FIG. 15B

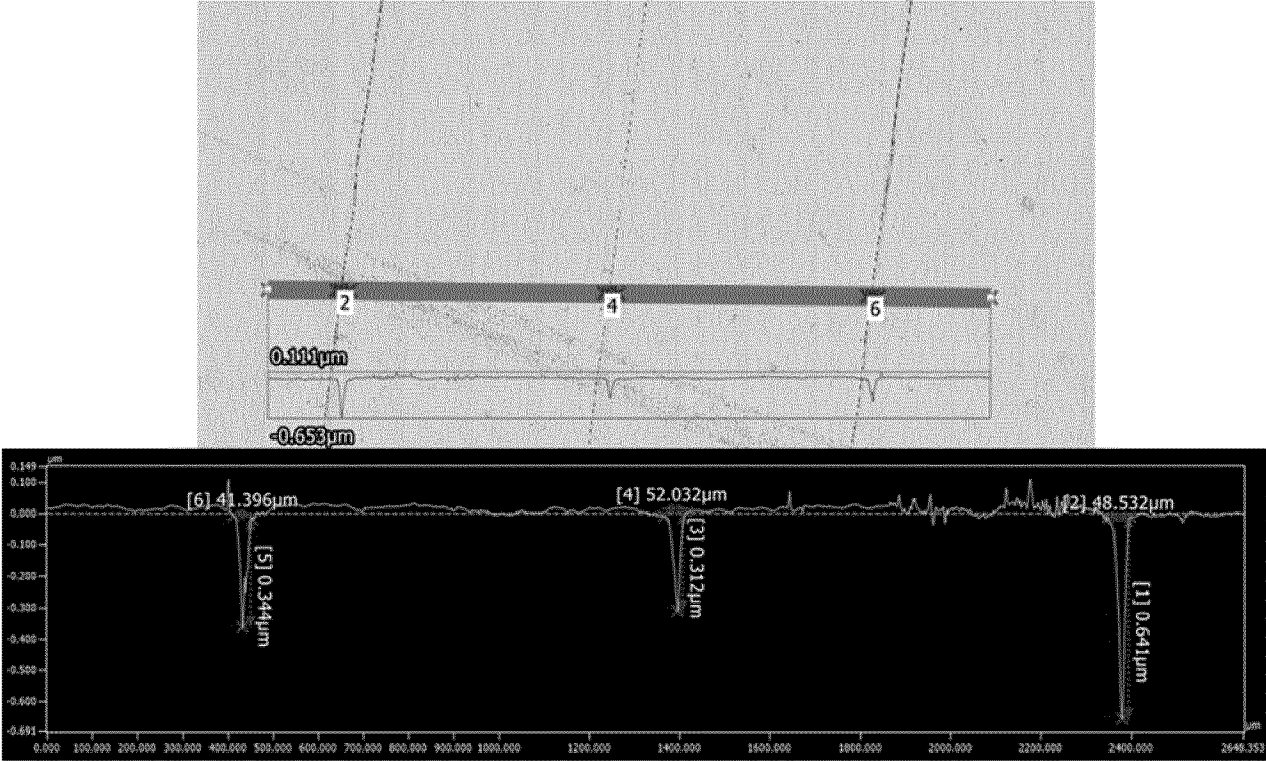
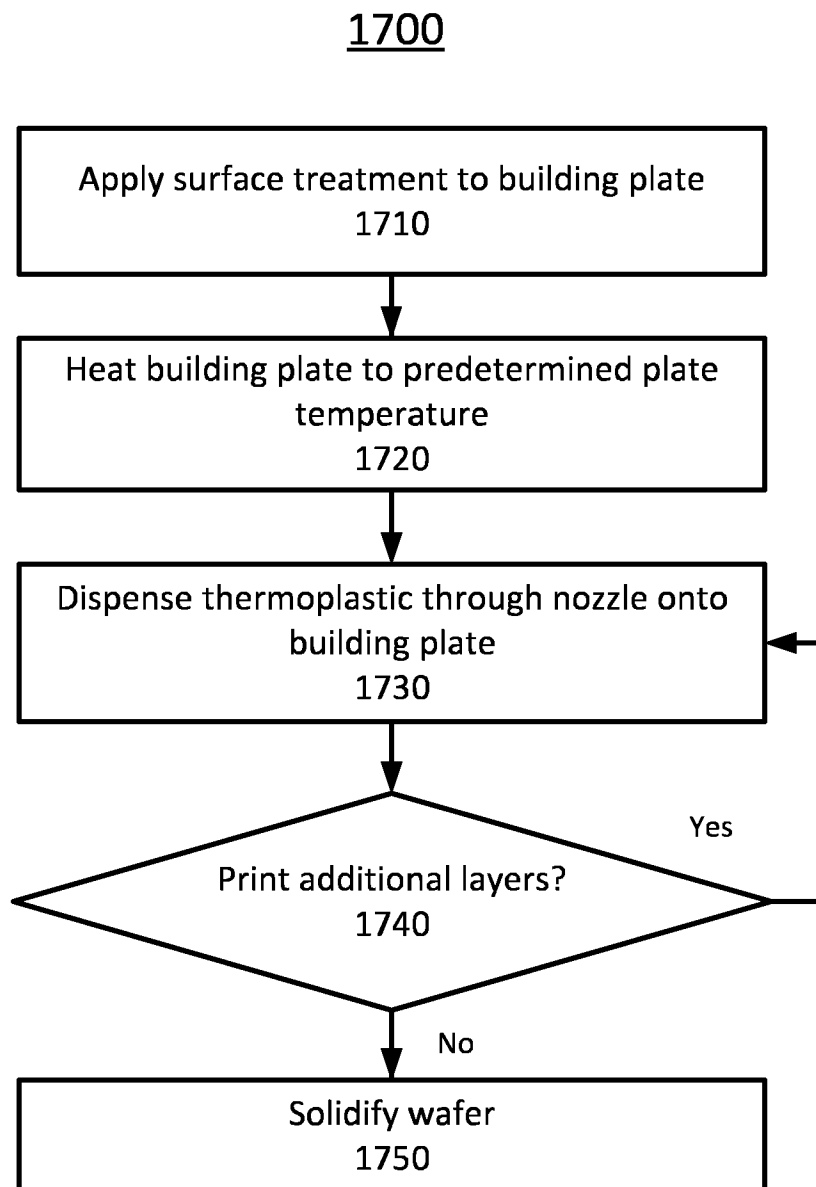


FIG. 16

**FIG. 17**

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2022/086081

A. CLASSIFICATION OF SUBJECT MATTER		
INV.	B29C64/118	B29C64/245
	B33Y50/02	B33Y70/00
		B33Y80/00
ADD.		
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 B33Y B29L		
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)		
EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2020/205565 A1 (ARKEMA FRANCE [FR]; LIU DAVID SHEN REN [US]) 8 October 2020 (2020-10-08)	1, 3, 5-7, 11, 13
Y	page 1, lines 13-16 page 5, lines 23, 24 page 8, lines 17, 18 page 14, line 14 page 23, line 27 page 25, line 11 page 27, lines 8-10 page 28, lines 16, 17 page 30, line 26 claims 6, 20	2, 4, 8-10, 12, 14, 15
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	----- -/-	
☒ 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
3 March 2023		15/03/2023
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Nicolas, Pascal

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2022/086081

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	US 2016/200043 A1 (THIAN ENG SAN [SG] ET AL) 14 July 2016 (2016-07-14) paragraph [0072] -----	8, 9
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Information on patent family members

International application No

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