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[54] PROCESS FOR PRODUCING ARTICLES FORMED FROM POLYLACTIC ACID AND ARTICLES MADE THEREFROM
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(54) **PROCESS FOR PRODUCING ARTICLES FORMED FROM POLYLACTIC ACID AND ARTICLES MADE THEREFROM**

VERFAHREN ZUR HERSTELLUNG VON GEGENSTÄNDEN AUS POLYMILCHSÄURE UND DARAUS HERGESTELLTE ARTIKEL

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The file contains technical information submitted after the application was filed and not included in this specification

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Description**FIELD**

5 [0001] The present invention relates generally to polylactic acid (PLA), and more specifically to articles formed from polylactic acid that are biodegradable, possess a high modulus of elasticity, and increased tensile strength. Processes for forming both dense and porous articles from polylactic acid are also disclosed.

BACKGROUND

10 [0002] Polylactic acids (PLA) are aliphatic polyesters and are considered useful biodegradable materials because of their hydrolytic property. Additionally, the degradative product of polylactic acid (*i.e.*, lactic acid) is readily absorbed in vivo. As such, PLA is commonly used for medical purposes, such as in surgical sutures, in sustained-release capsules in drug delivery systems, and as reinforcing materials for bone fractures. However, conventional processes for forming PLA articles possess undesirable features or attributes, such as, for example, processing above the melt temperature of the PLA polymer that degrades the PLA polymers and undesirably colors the polymer, and reduces physical properties such as tensile strength and matrix modulus. Additionally, conventional process are forced to use low molecular weight PLA due to the high melt viscosity.

15 [0003] US2002/0192449 discloses aliphatic polyester microfibers, films having a microfibrillated surface, and methods of making the same. Microfibers can be prepared by imparting fluid energy, typically in the form of high-pressure water jets, to a highly oriented, highly crystalline, aliphatic polyester film to liberate microfibers therefrom. The fibrils are entangled, twisted and knotted together.

20 [0004] Thus, there exists a need in the art for a process for making a PLA polymer and a PLA polymer article that is biodegradable, possesses a high modulus of elasticity, and has increased tensile strength.

SUMMARY

25 [0005] One aspect relates to a PLA article that includes an expanded PLA polymer comprising a beta crystal phase and nodes and fibrils. The fibrils include polymer chains oriented along a fibril axis. In at least one embodiment, the PLA polymer includes at least one comonomer. Additionally, the PLA polymer has a first melt enthalpy greater than 30 J/g, an inherent viscosity greater than 3.8 dL/g and a calculated molecular weight greater than 190,000 g/mol. The PLA polymer article may have a matrix tensile strength greater than or equal to 110 MPa, or 115 MPa, and a matrix modulus greater than or equal to 3000 MPa. A filler material and/or a coating material may be placed on and/or in the PLA article. In one or more embodiments, the PLA article is microporous. The article may be densified to form a dense article having a porosity less than 10%.

30 [0006] Disclosed is a process for forming a porous article that includes expanding a PLA polymer preform at a temperature above the glass transition temperature of the PLA polymer and below a melting temperature of the PLA polymer to create a porous PLA article having nodes and fibrils. The preform may be in the form of film, rods, tubes, or discs. The expansion of the preform may occur at a temperature from 60°C to 185°C. A filler material and/or a coating material may be placed on and/or in the PLA article. The porous PLA article may be microporous. Additionally, the porous article may be compressed at a temperature below the melting temperature of the PLA polymer to form a dense PLA article that has a porosity less than about 10%.

35 [0007] Further disclosed is a process for forming a microporous article that includes (1) lubricating a PLA polymer powder to form a lubricated PLA polymer, (2) subjecting the lubricated PLA polymer to pressure and to a temperature above the glass transition temperature of the PLA polymer and below a melting temperature of the PLA polymer to form a preform, and (3) expanding the preform at a temperature below the melt temperature of the PLA polymer to form a porous article having a structure of nodes and fibrils. The porous article may be a microporous article. The lubricated PLA polymer may be calendered or ram extruded below the melt temperature of the PLA polymer. The PLA polymer may be expanded at a temperature that is 80°C or less below the melt temperature. The lubricant may be removed from the preform prior to expanding the preform. The porous article may be compressed to form a dense article having a porosity of less than about 10%.

40 [0008] Further disclosed is a process for forming a porous article that includes (1) lubricating a PLA polymer powder to form a lubricated PLA polymer and (2) calendering the lubricated PLA polymer at a temperature above the glass transition temperature of said PLA polymer and below a melting temperature of the PLA polymer to form a porous article having a structure of nodes and fibrils. The calendering may occur at a temperature from 60°C to 185°C. The lubricant may be removed from the porous article to form a non-lubricated article and the non-lubricated article may be calendered to form a dense article having a porosity less than 10%.

45 [0009] Further disclosed is a process for forming a dense article that includes applying pressure and heat (e.g. cal-

endering) to a PLA polymer powder having an inherent viscosity greater than 3.8 dL/g and a molecular weight greater than 190,000 g/mol at a temperature below the melt temperature of the PLA polymer to form a dense article (e.g., a calendered PLLA film). The dense article may be drawn in one or more direction at a temperature below the melt temperature of the PLA polymer to form a second dense article (e.g., fibrillated (dense) article). The fibrillated (dense) article has a structure of nodes and fibrils and a beta crystal phase. The dense article has a porosity less than 10%.

[0010] Further disclosed is a dense article that includes a PLA film having a porosity of less than 10%.

[0011] A further embodiment relates to a PLA polymer article that includes (1) an expanded PLA polymer comprising a beta crystal phase and having nodes and fibrils and (2) at least one filler material. The filler material may include inorganic materials (e.g., silica) carbon black, aerogels, metals, semi-metals, ceramics, carbon/metal particulate blends, activated carbon, hydrogel materials, bioactive substances, stiffening agents, and combinations thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The accompanying drawings are included to provide a further understanding of the disclosure and are incorporated in and constitute a part of this specification, illustrate embodiments, and together with the description serve to explain the principles of the disclosure.

FIG. 1 is a wide angle X-ray diffraction (WAXD) pattern of the PLLA polymer of Example 2 according to at least one embodiment;

FIG. 2 is a wide angle X-ray diffraction (WAXD) pattern of the PLLA polymer of Example 3 in accordance with at least one embodiment;

FIG. 3 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 1 and FIG. 2 comparing the integrated intensity of Example 2 with the meridional intensity of Example 3 in accordance with at least one embodiment;

FIG. 4 is a differential scanning calorimetry (DSC) thermogram depicting a peak melting temperature and melt enthalpy of the unexpanded PLLA polymer of Example 1 according to at least one embodiment;

FIG. 5 is a differential scanning calorimetry (DSC) thermogram depicting a peak melting temperature and melt enthalpy of the expanded porous PLLA polymer of Example 3 according to at least one embodiment;

FIG. 6 is a differential scanning calorimetry (DSC) thermogram depicting a peak melting temperature and melt enthalpy of the expanded porous PLLA polymer of Example 4 in accordance with one embodiment;

FIG. 7 is a differential scanning calorimetry (DSC) thermogram depicting a peak melting temperature and melt enthalpy of the expanded porous PLLA polymer of Example 5 according to at least one embodiment;

FIG. 8 is a scanning electron micrograph (SEM) of the surface of an interior view of the expanded porous PLLA polymer of Example 3 taken at 40,000x magnification in accordance with one embodiment of;

FIG. 9 is a scanning electron micrograph (SEM) of the surface of an interior view of the expanded porous PLLA polymer of Example 4 taken at 20,000x magnification according to an embodiment;

FIG. 10 is a scanning electron micrograph (SEM) of the surface of an interior view of the expanded porous PLLA polymer of Example 5 taken at 35,000x magnification in accordance with an embodiment;

FIG. 11 is a scanning electron micrograph (SEM) of the surface of an interior view of the expanded porous PLLA polymer of Example 14 taken at 8,000x magnification in accordance with an embodiment;

FIG. 12 is a scanning electron micrograph (SEM) of the surface of an interior view of the expanded porous PLLA polymer of Example 15 taken at 45,000x magnification according to one embodiment;

FIG. 13 is a graphical illustration of the data from Table 2 showing the formation of a microporous structure as a function of melt enthalpy and inherent viscosity according to one embodiment;

FIG. 14 is a scanning electron micrograph (SEM) of the surface of an interior view of the continuous, cohesive opaque tape of Example 30 taken at 35,000x magnification in accordance with an embodiment;

FIG. 15 is a scanning electron micrograph (SEM) of the cross-section of the tape produced in Example 29 taken at 15,000x magnification according to one embodiment;

FIG. 16 is a scanning electron micrograph (SEM) of the surface of the sheet produced in Example 27 taken at 20,000x magnification in accordance with one embodiment;

FIG. 17 is a powder X-ray diffraction (XRD) pattern plotting intensity vs. 2-theta indicating the formation of a beta crystal phase in a calendered PLA article of Example 29 in accordance with one embodiment;

FIG. 18 is a wide angle X-ray diffraction (WAXD) pattern of the PLLA powder of Example 34 in accordance with at least one embodiment;

FIG. 19 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 18 according to at least one embodiment;

FIG. 20 is a scanning electron micrograph (SEM) of the surface of the PLLA film of Example 35 taken at 35,000x magnification in accordance with an embodiment;

FIG. 21 is a scanning electron micrograph (SEM) of the surface of the PLLA film of Example 36 taken at 45,000x magnification in accordance with an embodiment;

FIG. 22 is a wide angle x-ray diffraction (WAXD) pattern of the PLLA film of Example 36 according to one embodiment;

FIG. 23 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 22 in accordance with an embodiment;

FIG. 24 is a scanning electron micrograph (SEM) of the surface of the PLLA film of Example 37 taken at 25,000x magnification in accordance with an embodiment;

FIG. 25 is a scanning electron micrograph (SEM) of the surface of the PLLA film of Example 39 taken at 25,000x magnification in accordance with an embodiment;

FIG. 26 is a wide angle x-ray diffraction (WAXD) pattern of the PLLA film of Example 39 in accordance with one exemplary embodiment;

FIG. 27 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) pattern of FIG. 26 according to at least one embodiment;

FIG. 28 is a scanning electron micrograph (SEM) of the surface of the compressed PLLA polymer of Example 32 taken at 30,000x magnification according to at least one exemplary embodiment; and

FIG. 29 is a scanning electron micrograph (SEM) of the PLLA/silica film of Example 42 taken at 25,000x according to an exemplary embodiment.

GLOSSARY

[0013] As used herein, the term "lubricant" is meant to describe a processing aid that includes, and in some embodiments, consists of, an incompressible fluid that is not a solvent for the polymer at processing conditions. The fluid-polymer surface interactions are such that it is possible to create a homogenous mixture.

[0014] As used herein, the term "PLA" refers to polylactic acid and polylactide.

[0015] As used herein, the term "PLLA" refers to poly L-lactic acid and poly L-lactide.

[0016] As used herein, the term "PDLA" refers to poly D-lactic acid and poly D-lactide.

[0017] As used herein, the term "cohesive" is meant to describe a tape or precursor material that is sufficiently strong for further processing.

[0018] As used herein, the term "uniaxial" is meant to describe a polymer, membrane, preform, or article that is expanded in only one direction.

[0019] As used herein, the term "biaxial" is meant to describe a polymer, membrane, preform, or article that is expanded in at least two directions.

[0020] As used herein, the term "microporous" is meant to define an article, such as a membrane, that has pores that are not visible to the naked eye.

[0021] As used herein, the terms "melting point", "melt temperature", and "melting temperature" are used interchangeably herein and are meant to define the peak of the melt endotherm as measured by differential scanning calorimetry (DSC) during the first heating of the PLA polymer.

[0022] As used herein, the term "fibril axis" is meant to describe the long dimension of the fibril.

[0023] As used herein, the terms "dense" and "densified" are meant to describe a PLA polymer article that has a porosity less than 10%.

DETAILED DESCRIPTION

[0024] Persons skilled in the art will readily appreciate that various aspects of the present disclosure can be realized by any number of methods and apparatus configured to perform the intended functions. It should also be noted that the accompanying figures referred to herein are not necessarily drawn to scale, but may be exaggerated to illustrate various aspects of the present disclosure, and in that regard, the figures should not be construed as limiting.

[0025] The present disclosure relates to polylactic acid (PLA) polymers and porous articles made therefrom that are bioabsorbable, biodegradable, and possess a high modulus of elasticity and increased tensile strength. The crystallinity of the PLA polymer may be measured by differential scanning calorimetry (DSC). The melt enthalpy of the PLA polymer as measured by DSC is 30 J/g or greater, and in some embodiments, 40 J/g or greater. The PLA polymers can be formed into microporous articles at temperatures below the melting point of the PLA polymer. The PLA polymer articles have a node and fibril microstructure. In at least one embodiment, the fibrils contain PLA polymer chains oriented with the fibril axis. With reference to the PLA polymers and PLA articles described herein, a node may be described as a larger volume of polymer, and is where a fibril originates or terminates with no clear continuation of the same fibril through the node. A fibril may have a width of less than 250 nm, or less than 150 nm.

[0026] In forming the PLA polymers, lactides that are primarily either D-lactide or L-lactide are employed. In one or more embodiment, the lactide utilized in the polymerization process is a high purity L-lactide. It is to be appreciated that

even though the lactide is principally either D-lactide or L-lactide, small amounts of the opposite isomer, as well as small amounts of comonomers such as cyclic esters and carbonates, may be incorporated into the polymer chain so long as the resultant polymer possesses the inherent viscosities and melt enthalpies described herein. Suitable comonomers include, but are not limited to glycolide, trimethylene carbonate, valerolactone, epsilon-caprolactone 1,5-dioxepan-2-one, and 3,6-di-(n-butyl)-1,4-dioxane-2,5-dione. The optional comonomer(s) may be present in the PLA polymers in an amount from 0.001 mol% to 10 mol%, from 0.01 mol% to 7 mol%, or from 0.1 mol% to 5 mol%.

[0027] The conversion of lactide to PLA is initiated by the ring opening polymerization of the lactide. The ring opening may be catalytically mediated by a metal compound, which may or may not also function as an initiator. Additionally, an alcohol may also be added which, along with the metal compound, forms a metal alkoxide *in situ*. Non-limiting examples of suitable metal compounds include, but are not limited to, stannous 2-ethylhexoanate, Zn(II) oxide, and Zn(II) 2-ethylhexoanate. In at least one embodiment, stannous 2-ethylhexoanate by itself or in combination with an alcohol, may be used as a catalyst. However, it is to be appreciated that any catalyst which is able to effect the ring opening polymerization of lactide at temperatures of 150°C or lower is suitable for use.

[0028] The catalyst may be added in amounts ranging from 1,500 mol lactide/1 mole catalyst to 200,000 mol lactide/1 mol catalyst, from 3000 mol lactide/1 mol catalyst to 100,000 mol lactide/1 mol catalyst, or from 7000 mol lactide/1 mol catalyst to 70,000 mol lactide/1 mol catalyst. In one or more embodiment, 35,000 mol lactide/1 mole catalyst is added. Alcohol addition levels range from zero to 1,500 mol lactide/1 mole alcohol, from 200,000 mol lactide/1 mol alcohol to 3,000 mol lactide/1 mol alcohol, or from 70,000 mol lactide/1 mol alcohol to 7,000 mol lactide/1 mol alcohol. In at least one embodiment, 35,000 mol lactide/1 mol alcohol may be added.

[0029] The polymerization reaction occurs at a temperature less than 150°C, less than 140°C, or less than 110°C. The reaction may be stopped at 90 to 99 percent conversion of lactide to PLA, or at 95 to 99 percent conversion. The resultant PLA polymer is a solid mass, and may be in the form of a billet if the polymerization occurs in an appropriately sized and shaped container. If desired, the residual lactide may be removed from the PLA polymer by extraction using acetone.

[0030] Solution viscosity correlates with polymer chain length, and is commonly used to monitor polymerization reactions and to characterize the final polymer. As such, the molecular weight of the PLA polymers formed from the process described above may be calculated from the solution viscosity. The PLA polymers may have an inherent viscosity greater than 3.8 dL/g, greater than 4.5 dL/g, greater than 5.0 dL/g, greater than 6.0 dL/g, or greater than 7.0 dL/g. The PLA polymers have a calculated molecular weight (Mw) greater than 190,000 g/mol, greater than 250,000 g/mol, greater than 290,000 g/mol, greater than 380,000 g/mol, or greater than 490,000 g/mol.

Bulk Polymerization Article Formation

[0031] The PLA polymer article formed from the bulk polymerization of PLA polymers may be cut, sawn, skived, milled, or otherwise partitioned or divided into a PLA polymer preform that may be subsequently expanded into a microporous article. It is to be appreciated that residual monomer (unreacted monomers) may be removed (e.g., with acetone) before and/or after expansion. Preform shapes include sheets, films, rods, tubes, discs, and the like. To form a microporous article, the PLA polymer preform may be first heated to a temperature below the melting point of the PLA polymer. The preform may be heated to a temperature of 170°C. The PLA polymer preform may then be expanded, which causes the crystalline PLA polymer to reorient and form beta phase crystals while simultaneously forming a highly-fibrillated microporous structure. The presence of beta phase crystals may be determined through wide angle X-ray diffraction (WAXD). The PLA polymer preform may be expanded at temperatures from at least 1° above the glass transition temperature of the PLA polymer to at least 1°C below the melt temperature of the PLA polymer, or from 60°C to 185°C.

[0032] The WAXD pattern shown in FIG. 1 indicates no evidence of beta phase crystals in the preform article. In contrast, the WAXD patterns shown in FIG. 2 of expanded PLLA are consistent with conversion of as polymerized crystalline phases into a beta crystalline phase. It is to be noted that the beta crystal is primarily located in the fibrils. A useful signal for the presence of beta phase crystals is the observation by WAXD of (023)Beta peak depicted by reference numeral 20 and (003)Beta peak depicted by reference numeral 10 as shown in FIG. 3. FIG. 3 is a 2-theta vs intensity plot of the WAXD patterns of FIG. 1 and FIG. 2 comparing the integrated intensity of Example 2 with the meridional intensity of Example 3.

[0033] The degree of fibrillation, porosity, and beta-crystal content increases with increasing expansion, with expansions of 400%, 600%, and greater being easily achieved. Expansion of the PLA polymer preform, either uniaxial or biaxial, may be conducted at rates up to 1,000%/second, up to 5,000%/second, up to 10,000%/second, or from 1%/second to 5,000%/second, or from 1% to 10,000%/second. The expansion ratios may be greater than 3:1, greater than 5:1, greater than 7:1, greater than 10:1, greater than 15:1, greater than 20:1, greater than 25:1, greater than 30:1, greater than 35:1, greater than 40:1, greater than 45:1, or greater than 50:1. When the PLA polymer preform is expanded, it forms an expanded PLA polymer article that has a microstructure of nodes and fibrils, such as is shown at least in FIGS. 8, 9, and 10. FIGS. 8, 9, and 10 depict an exemplary nodes 30 and fibrils 40 in the expanded PLA polymer article.

[0034] In addition, the PLA polymer expanded article may be formed into a densified PLA material with a porosity less than 10%, or less than 5%. In one embodiment, the PLA polymer article may be compressed at a temperature from at least 1° above the glass transition temperature to at least 1°C below the melt temperature of the PLA polymer, or from 60°C to 185°C. The initial expanded form is largely opaque. The largely opaque sample may then be compressed to form a sample that is largely translucent and dense. It is to be understood to one of skill in the art that various times, temperatures, and pressure may be utilized to achieve a densified article.

PLA Powder Article Formation

[0035] In another embodiment, a microporous PLA polymer article is formed from PLA powder. In this embodiment, the PLA polymers have an inherent viscosity of greater than 3.8 dL/g and a calculated molecular weight greater than 190,000 g/mol. The PLA polymers can be formed into microporous articles at temperatures below the melting point of the PLA polymer.

[0036] The PLA polymer powder may be formed by the process set forth above, with the exception that the polymerization process is stopped at 40% completion. At lactide to PLA polymer conversion, the reaction mass is a slush of liquid lactide and crystalline PLA polymer particles. This reaction mixture is permitted to cool and solidify. Once cooled, the solidified mass of PLA polymer is broken into small pieces. The mass of PLA polymers may be broken by hand. The lactide is extracted from the broken pieces with acetone in an appropriate extractor (e.g., a Soxhlet extractor), which leaves behind PLA polymer powder. Agglomerations of the PLA polymer powder may be broken and sifted using an appropriately sized sizing screen.

[0037] Alternatively, the PLA polymer powder may be formed through precipitation in which poly-L-lactide is added to anhydrous o-xylene, heated, and then cooled to room temperature. A PLA precipitate is then filtered from the o-xylene. Hexanes may be added to the PLA precipitate to form a hexane/PLA slurry. A lubricant (e.g., a light mineral oil) may be added to the slurry. A free-flowing PLA polymer powder is obtained after the hexanes have been evaporated.

[0038] As with the bulk polymerization described above, solution viscosity may be used to calculate the molecular weight of the PLA polymers in a powder form. The PLA polymers may have an inherent viscosity greater than 3.8 dL/g, greater than 4.5 dL/g, greater than 5.0 dL/g, greater than 6.0 dL/g, or greater than 7.0 dL/g. The PLA polymers have a calculated molecular weight (Mw) greater than 190,000 g/mol, greater than 250,000 g/mol, greater than 290,000 g/mol, greater than 380,000 g/mol, or greater than 490,000 g/mol.

Paste Processing PLA Polymer Powder

[0039] In one embodiment, the PLA polymer powder may be formed into a microporous article through paste processing the PLA polymer powder. In forming a porous article from a PLA polymer powder, the PLA polymer powder is first mixed with a lubricant, such as a light mineral oil. Other suitable lubricants include aliphatic hydrocarbons, aromatic hydrocarbons, and the like, and are selected according to flammability, evaporation rate, and economic considerations. It is to be appreciated that the term "lubricant", as used herein, is meant to describe a processing aid that includes (or consists of) an incompressible fluid that is not a solvent for the polymer at the process conditions. The fluid-polymer surface interactions are such that it is possible to create a homogenous mixture. It is also to be noted that that choice of lubricant is not particularly limiting and the selection of lubricant is largely a matter of safety and convenience. It is to be appreciated that any of the lubricants described herein may be utilized as the lubricant so long as the fluid-polymer surface interactions are such that it is possible to create a homogenous mixture. The lubricant may be added to the PLA polymer powder in a ratio from 1 ml/100 g to 100 ml/100 g or from 10 ml/100 g to 70 ml/100 g.

[0040] The PLA polymer powder and lubricant may be mixed so as to uniformly or substantially uniformly distribute the lubricant in the mixture. It is to be appreciated that various times and mixing methods may be used to distribute the PLA polymer powder in the mixture. Once blended, PLA polymer powder/lubricant mixture is in a paste-like state. The PLA polymer powder can be formed into solid shapes (e.g. fibers, tubes, tapes, sheets, three dimensional self-supporting structures, etc.) without exceeding the melt temperature of the PLA polymer. The lubricated PLA polymer powder may be heated to a point below the melting temperature of the PLA polymer powder and sufficient pressure and shear are applied to form inter-particle connections and create a solid form. The lubricated PLA polymer powder can be formed into solid shapes such as fibers, tubes, tapes, sheets, three dimensional self-supporting structures, etc. without exceeding the melt temperature of the polymer. Non-limiting examples of methods of applying pressure and shear include ram extrusion (e.g., typically called paste extrusion or paste processing when lubricant is present) and calendering.

[0041] The lubricated PLA polymer powder may be ram extruded to produce a cohesive tape. As used herein, the term "cohesive tape" is meant to describe a tape that is sufficiently strong for further processing. The ram extrusion occurs below the melting temperature of the PLA polymer. Alternatively, the lubricated PLA polymer powder may be calendered at a temperature below the melting temperature of the PLA polymer to produce a cohesive tape. The calendering occurs at temperatures from at least 1° above the glass transition temperature to at least 1°C below the melt

temperature of the PLA polymer, or from 60°C to 185°C. The tape formed has an indeterminate length and a thickness less than 1 mm. Tapes may be formed that have a thickness from 0.01 mm to 1 mm from 0.08 mm to 0.5 mm, or from 0.05 mm to 0.2 mm, or even thinner. In exemplary embodiments, the tape has a thickness from 0.05 mm to 0.2 mm.

[0042] In a subsequent step, the lubricant may be removed from the tape. In instances where a mineral oil is used as the lubricant, the lubricant may be removed by washing the tape in hexane or other suitable solvent. The wash solvent is chosen to have excellent solubility for lubricant and sufficient volatility to be removed below the melting point of the PLA polymer. If the lubricant is of sufficient volatility, the lubricant may be removed without a washing step, or it may be removed by heat and/or vacuum. The tape is then optionally permitted to dry, typically by air drying. However, any conventional drying method may be used as long as the temperature of heating the sample remains below the melting point of the PLA polymer.

[0043] The tapes, once dried, may be continuously processed or they may be cut to suitable sizes for expansion. Expansion of the samples occurs at temperatures below the melt temperature of the PLA polymer and above the glass transition temperature (T_g) of the PLA polymer. Expansion occurs below the melting point of the PLA polymer, such as, for example, 80°C below the melting point of the PLA copolymer, 70°C below the melting point, 60°C below the melting point, 50°C below the melting point, 40°C below the melting point, 30°C below the melting point, 25°C below the melting point, 15°C below the melting point, 10°C below the melting point, 5°C below the melting point or 1°C below the melting point. The samples may be expanded in one or more directions to form a porous PLA membrane. Additionally, the expansion ratios may be greater than 3:1, greater than 5:1, greater than 7:1, greater than 10:1, greater than 15:1, greater than 20:1, greater than 25:1, greater than 30:1, greater than 35:1, greater than 40:1, greater than 45:1, or greater than 50:1.

[0044] The porous microstructure of the expanded membrane is affected by the temperature and rate at which it is expanded. The geometry of the nodes and fibrils can be controlled by the selection of PLA polymer, the rate of expansion, temperature of expansion, and/or ultimate expansion ratio.

[0045] The expanded PLA polymer articles made in accordance with the processes described herein have a matrix tensile strength greater than or equal to 110 MPa, greater than or equal to 150 MPa, or greater than or equal to 200 MPa. Further, the PLA polymer articles have a matrix modulus greater than or equal to 3000 MPa, greater than or equal to 4000 MPa, or greater than or equal to 5000 MPa.

[0046] In addition, the expanded PLA polymer articles have a percent porosity that is greater than 10%, greater than or equal to 15%, greater than or equal to 20%, greater than or equal to 25%, greater than or equal to 30%, greater than or equal to 35%, greater than or equal to 40%, greater than or equal to 45%, greater than or equal to 50%, greater than or equal to 55%, greater than or equal to 60%, greater than or equal to 65%, greater than or equal to 70%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, or up to (and including) 90%. In exemplary embodiments, the PLA polymer articles may have a percent porosity from 25% to 90%, from 40% to 90%, from 50% to 90%, or from 60% to 90%.

Dry Processing PLA Polymer Powder

[0047] The PLA polymer powder may be calendered to produce a cohesive dense tape. The dry processing of the PLA polymer powder forms beta crystals. The calendering occurs at temperatures from at least 1° above the glass transition temperature to at least 1°C below the melt temperature of the PLA polymer, or from 60°C to 185°C. The tape formed has an indeterminate length and a thickness less than 1 mm. Tapes may be formed that have a thickness from 0.01 mm to 1 mm from 0.08 mm to 0.5 mm, or from 0.05 mm to 0.2 mm, or even thinner. In exemplary embodiments, the tape has a thickness from 0.05 mm to 0.2 mm. It is to be understood to one of skill in the art that various times, temperatures, and pressures may be utilized to achieve a densified article.

[0048] The dense tape may be continuously processed or may be cut to suitable sizes for expansion. Expansion of the dry tape occurs at temperatures below the melt temperature of the PLA polymer and above and above the glass transition temperature (T_g) of the PLA polymer. The expansion may occur 80°C below the melting point of the PLA copolymer, 70°C below the melting point, 60°C below the melting point, 50°C below the melting point, 40°C below the melting point, 30°C below the melting point, 25°C below the melting point, 15°C below the melting point, 10°C below the melting point, 5°C below the melting point or 1°C below the melting point. The expansion may be in one or more directions to form a dense PLA article. Additionally, the expansion ratios may be greater than 3:1, greater than 5:1, greater than 7:1, greater than 10:1, greater than 15:1, greater than 20:1, greater than 25:1, greater than 30:1, greater than 35:1, greater than 40:1, greater than 45:1, or greater than 50:1.

[0049] The incorporation of filler materials and/or coatings in or on the PLA polymer articles described herein is considered to be within the purview of the invention. For instance, a filler material may be blended with a PLA polymer before calendering or ram extruding (and optionally expansion), or may be positioned on the PLA polymer article and locked in place with a suitable hydrogel. Non-limiting examples of suitable filler materials include inorganic materials (e.g., silica) carbon black, aerogels, metals, semi-metals, ceramics, carbon/metal particulate blends, activated carbon, hydrogel materials, bioactive substances, stiffening agents, and combinations thereof. Filler materials may be incorpo-

rated into the PLA polymer article in amounts from 1.0% to 80%, or from 20% to 60%, or from 1% to 30% by weight of the PLA article. Alternatively, suitable non-reactive filler materials may be incorporated into the PLA polymer articles during polymerization of the PLA polymer.

[0050] Various components can be coprocessed with or placed on and/or within the PLA articles. In particular, components (or chemical compositions) may be added to the PLA polymer either during or after polymer synthesis in such a manner that the added component(s) become intimately mixed in the polymer, such as in a blend or as a covalently bonded component of the PLA polymer chain. The added components could alternatively, or additionally, be placed outside the polymer on surfaces of the fibrils of the expanded PLA polymer. Further, the components may be placed within void spaces (e.g., pores) or between the fibrils in the expanded PLA article. The components added to or within the PLA article may be absorbable or non-absorbable. The added compositions can include useful substances that are releasably contained therein.

[0051] The components may include viscous chemical compositions, such as, but not limited to, a hydrogel material. Biologically active substances may optionally be combined with a hydrogel material or with any other added chemical component. With hydrogel materials, for example, the biologically active substances may be released directly from the hydrogel material or they may be released as the hydrogel material and the underlying expanded material are absorbed by the body of an implant recipient.

[0052] Suitable hydrogel materials include, but are not limited to, polyvinyl alcohol, polyethylene glycol, polypropylene glycol, dextran, agarose, alginate, carboxymethylcellulose, hyaluronic acid, polyacrylamide, polyglycidol, poly(vinyl alcohol-co-ethylene), poly(ethyleneglycol-co-propyleneglycol), poly(vinyl acetate-co-vinyl alcohol), poly(tetrafluoroethylene-co-vinyl alcohol), poly(acrylonitrile-co-acrylamide), poly(acrylonitrile-co-acrylic acid-acrylamidine), poly(acrylonitrile-co-acrylic acid-co-acrylamidine), polyacrylic acid, poly-lysine, polyethyleneimine, polyvinyl pyrrolidone, polyhydroxyethylmethacrylate, polysulfone, mercaptosilane, aminosilane, hydroxylsilane, polyallylamine, polyaminoethylmethacrylate, polyomithine, polyaminoacrylamide, polyacrolein, acryloxysuccinimide, or their copolymers, either alone or in combination. Suitable solvents for dissolving the hydrophilic polymers include, but are not limited to, water, alcohols, dioxane, dimethylformamide, tetrahydrofuran, and acetonitrile, etc.

[0053] Optionally, the compositions can be chemically altered after being combined with the expanded PLA polymer. These chemical alterations can be chemically reactive groups that interact with polymeric constituents of the expanded PLA polymer or with chemically reactive groups on the compositions themselves. The chemical alterations to these compositions can serve as attachment sites for chemically bonding yet other chemical compositions, such as biologically active substances. "Bioactive substances" include enzymes, organic catalysts, ribozymes, organometallics, proteins, glycoproteins, peptides, polyamino acids, antibodies, nucleic acids, steroidal molecules, antibiotics, antimycotics, cytokines, carbohydrates, oleophobic, lipids, extracellular matrix material and/or its individual components, pharmaceuticals, and therapeutics. One non-limiting example of a chemically-based bioactive substance is dexamethasone. Cells, such as, mammalian cells, reptilian cells, amphibian cells, avian cells, insect cells, planktonic cells, cells from non-mammalian marine vertebrates and invertebrates, plant cells, microbial cells, protists, genetically engineered cells, and organelles, such as mitochondria, are also bioactive substances. In addition, non-cellular biological entities, such as viruses, virens, and prions are considered bioactive substances herein.

[0054] Besides the utilization of added components for chemically or biologically active functions, the added components may also (or alternatively) serve a physical or mechanical function. For example, the added component can act as a void filler to facilitate further modification either prior to or during implantation. Such use of a carvable implant material may be of particular benefit for use in surgery, especially in plastic and reconstructive surgery. The material may include a porous expanded structure having a coating of a biocompatible stiffening agent to render the porous construct adequately rigid for carving to better adapt the implant for its intended use. The coating may be applied in a manner that allows the porous construct to become impregnated by the stiffening agent. Stiffening agents as used herein would be composed of one or more absorbable materials, including synthetic biodegradable polymers and biologically derived materials which, if degrading faster than the base structure, would allow delayed ingrowth of tissue into the porous construct after the stiffening agent is degraded through absorption.

[0055] Suitable materials for a polymeric biodegradable support member include, but are not limited to, polyglycolide (PGA), copolymers of glycolide, glycolide/L-lactide copolymers (PGA/PLLA), lactide/trimethylene carbonate copolymers (PLA/TMC), glycolide/trimethylene carbonate copolymers (PGA/TMC), polylactides (PLA), stereo-copolymers of PLA, poly-L-lactide (PLLA), poly-DL-lactide (PDLA), L-lactide/DL-lactide copolymers, copolymers of PLA, lactide/tetramethylglycolide copolymers, lactide/.alpha.-valerolactone copolymers, lactide/.epsilon.-caprolactone copolymers, hyaluronic acid and its derivatives, polydepsipeptides, PLA/polyethylene oxide copolymers, unsymmetrical 3,6-substituted poly-1,4-dioxane-2,5-diones, poly-.beta.-hydroxybutyrate (PHBA), poly-4-hydroxybutyrate (P4HB), P4HB/PHBA copolymers, PHBA/bhydroxyvalerate copolymers (PHBA/HVA), poly-p-dioxanone (PDS), poly-a-valerlactone, poly-e-caprolactone, methacrylate-N-vinyl-pyrrolidone copolymers, polyesteramides, polyesters of oxalic acid, polydihydropyranes, polyalkyl-2-cyanoacrylates, polyurethanes, polyvinylalcohol, polypeptides, poly-B-malic acid (PMLA), poly-B-alcanoic acids, polybutylene oxalate, polyethylene adipate, polyethylene carbonate, polybutylene carbonate, and other polyesters containing

silyl ethers, acetals, or ketals, alginates, and blends or other combinations of the aforementioned polymers. In addition to the aforementioned aliphatic link polymers, other aliphatic polyesters may also be appropriate for producing aromatic/aliphatic polyester copolymers. These include aliphatic polyesters selected from the group of oxalates, malonates, succinates, glutarates, adipates, pimelates, suberates, azelates, sebacates, nonanedioates, glycolates, and mixtures thereof. These materials are of particular interest as biodegradable support membranes in applications requiring temporary support, such as during tissue or organ regeneration.

TEST METHODS

[0056] It should be understood that although certain methods and equipment are described below, other methods or equipment determined suitable by one of ordinary skill in the art may be alternatively utilized. It is to be understood that the following examples were conducted on a lab scale but could be readily adapted to a continuous or semi-continuous process.

Scanning Electron Microscopy (SEM)

[0057] SEM images were collected using an Hitachi SU8000 FE Ultra High Resolution Scanning Electron Microscope with Dual SE detectors. Cross-sectioned samples were prepared using a Cooled straight-razor blade method. Surface and cross-sectioned samples were mounted onto a 25 mm diameter metal stub with a 25 mm carbon double sided adhesive. The mounted samples were sputter coated with platinum.

Powder Wide Angle X-ray Diffraction (WAXD)

[0058] Diffraction patterns from calendered PLA powder were collected using a Bruker Discovery D-8 instrument. The X-Ray source was CuK α element with a wavelength of 0.1542 nm running at 40 kV/60 mA. The instrument was configured in a Brentano-Bragg geometry. Diffraction intensity was measured using a 0D scintillation counter rotating at 0.02 degree 2-theta increments for a one second duration. The range of 2-theta was 10 degrees to 35 degrees. The instrument was calibrated using a polycrystalline silicon and an automated internal calibration algorithm. PLA polymer was placed on the Bruker Discovery D-8 stage and aligned with the beam line.

2-Dimensional Wide Angle X-Ray Diffraction (WAXD) - Method 1

[0059] Diffraction patterns from PLA polymer and expanded films were collected using a Molecular Metrology instrument configured for 2-D WAXD observations. The X-Ray source was a Rigaku MicroMax Sealed Micro Source CuK α element with a wavelength of 0.1542 nm running at 45 kV/66 mA. To collect two-dimensional diffraction information at wide angles a 20 cm x 20 cm Fujifilm BAS SR2040 imaging plate was placed in the instrument vacuum chamber perpendicular to the X-Ray beam line at a camera length of 146 mm. Camera length was calibrated by collecting a WAXD pattern from a tricosane standard and calculating the camera length from the 110 reflection at q of 15.197 nm⁻¹ or d -spacing 0.4134 nm. PLLA polymer billets approximately 1.5 mm thick were placed on a motorized stage and aligned perpendicular to the beam line. The vacuum chamber was then sealed and evacuated to 66 Pa (500 mTorr) below atmospheric pressure and the beam shutter opened. Diffraction patterns were collected at ambient temperature for a period of 0.5 to 1 hour, depending on the thickness and scattering intensity of the film sample. The diffraction data were collected from the Fujifilm BAS SR2040 image plates using a General Electric Typhoon FLA7000 image plate reader. Diffraction pattern images were saved as grayscale TIFF files and subsequently analyzed using POLAR analysis software.

2-Dimensional Wide Angle X-Ray Diffraction (WAXD) - Method 2

[0060] Diffraction patterns from PLA powder and films were collected using a SaxLab Ganesha instrument configured for 2-D WAXD observations. The X-Ray source was a sealed CuK α element with a wavelength of 0.1542 nm running at 45kV/66mA. To collect two-dimensional diffraction information at wide angles a 0.3M Pilatus photon counting detector with pixel dimensions of 175umx175um was placed in the instrument vacuum chamber perpendicular to the X-Ray beam line at a camera length of 101 mm. Camera length was calibrated by collecting a WAXD pattern from a silver behenate standard. Powder and film samples approximately 0.5mm thick were placed on a motorized stage and aligned perpendicular to the beam line. The vacuum chamber was then sealed and evacuated to 66 Pa (500 mTorr) below atmospheric pressure and the beam shutter opened. Diffraction patterns were collected at ambient temperature for a period of 10 minutes. Diffraction pattern images were saved as grayscale TIFF files and subsequently analyzed using POLAR analysis software.

Gurley Flow

[0061] The Gurley air flow test measures the time in seconds for 100 cm³ of air to flow through a 6.45 cm² aperture at 12.4 cm of water pressure. An aperture of 0.645 cm² was actually used and the time observed divided by a factor of 10 to normalize observations for the aperture size. The actual air volume was 300 cm³ and the time observed divided by an additional factor of 3 to normalize observations for the volume size. Thus, the measured time was divided by a total factor of 30 to obtain the Gurley flow. The samples were measured in a Gurley Densometer Model 4110 Automatic Densometer equipped with a Gurley Model 4320 automated digital timer. The reported result is the average of 3 measurements.

Differential Scanning Calorimetry

[0062] DSC data were collected using a TA Instruments Q2000 DSC between 0°C and 250°C using a heating rate of 10 °C/min. Approximately 5 to 10 mg of the sample was placed into a standard Tzero pan and lid combination available from TA Instruments. A linear integration method from 140°C to 200°C was used to integrate to obtain the first melt enthalpy data.

Solution Viscosity

[0063] A sample of the virgin polylactate polymer resin was dissolved into chloroform solvent. Using the results from proton NMR, the weight of the virgin polymer resin added to the chloroform was adjusted to give a solution concentration of 0.1 g/dL of actual polymer. Solution was charged to a Cannon #75 capillary L158 solution viscometer, which was then immersed in a 25.0°C water bath and equilibrated for 15 minutes. The formula used to calculate inherent viscosity was as follows:

$$\eta_{\text{inh}} = \frac{\ln \frac{t}{t_s}}{C}$$

Where: η_{inh} = inherent viscosity (dL/g)
 t = elution time of the solution (s)
 t_s = elution time of the solvent (s)
 C = polymer concentration (g/dL);

$$= \frac{1}{\text{polymer fraction}} \cdot \frac{\text{wt virgin polymer resin (g)}}{\text{Volume (dL)}}$$

Solution-Viscosity Molecular Weight

[0064] A relationship between solution viscosity and molecular weight of PLLA in chloroform at 25°C has been proposed as follows (D.W. Grijpma, J.P. Pennings, and A.J. Pennings, Colloid Polym Sci 272:1068-1081, 1994):

$$[\eta] = 5.45 \cdot 10^{-4} \cdot M_v^{0.73} \quad (\text{Equation 1})$$

Where: $[\eta]$ = intrinsic viscosity (dL/g)
 M_v = Solution-viscosity molecular weight

[0065] Intrinsic viscosity may be calculated by measuring inherent viscosity at several concentrations, and in the region where the inherent viscosity-concentration relationship is linear, extrapolating a line to zero concentration (ASTM D2857-95). For polymer-solvent systems such as PLLA in chloroform, the slopes of the inherent viscosity vs. concentration line change very little for samples described herein. The approximate intrinsic viscosity was estimated from a single-concentration measurement according to the following formula (F.W. Billmeyer, J Polymer Science 1949 4(1):83-86):

$$[\eta] = \frac{4}{c} (\eta_r^{1/4} - 1) \quad (\text{Equation 2})$$

5
Where: $[\eta]$ = intrinsic viscosity (dL/g) η_r = relative viscosity $\cong \frac{t}{t_s}$ c = polymer concentration (g/dL);

Substituting Equation 2 into Equation 1:

$$\frac{4}{c} (\eta_r^{1/4} - 1) = 5.45 \cdot 10^{-4} \cdot M_v^{0.73} \quad (\text{Equation 3})$$

15
Rearranging Equation 3 to solve directly for solution-viscosity molecular weight:

$$M_v = e^{\frac{1}{0.73} \ln \left(\frac{4(\eta_r^{1/4} - 1)}{5.45 \cdot 10^{-4} c} \right)} \quad (\text{Equation 4}).$$

Thickness measurement

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[0066] Thickness was measured by placing the sample between the two plates of a Mitutoyo Model ID-C112EX thickness gauge mounted on a Mitutoyo Model 7004 cast base (Mitutoyo Corporation, Kawasaki, Japan). The average of 3 measurements was reported.

Porosity Calculation

30
[0067] Porosity is reported as the volume fraction of void space measured in the microporous PLA article. Density was used to calculate the porosity of expanded materials, using 1.23 g/cc as an approximation of the full density of the PLA samples. The relative crystal content of the polymer affects the density of the polymer. Uniaxially stretched samples were die cut to form strips. Each sample was weighed using a Sartorius Model MC 210 P balance, and then the thickness of the samples was taken using a Mitutoyo thickness gauge (Mitutoyo Corporation, Kawasaki, Japan). Using this data, the bulk density of uniaxially expanded samples were calculated with the following formula:

$$\rho_{bulk} = \frac{m}{w \cdot l \cdot t}$$

40
where: ρ_{bulk} = bulk density (g/cc)
 m = mass (g)
 w = width (cm)
 l = length (cm)
45
 t = thickness (cm).

[0068] Biaxially stretched samples were die cut as circles, and the bulk density calculated as follows:

$$\rho_{bulk} = \frac{m}{\pi \cdot r^2 \cdot t}$$

50
where: ρ_{bulk} = bulk density (g/cc)
 m = mass (g)
 π = 3.142
55
 r = radius (cm)
 t = thickness (cm)

[0069] Porosity is calculated as:

$$P=100 \cdot \left(1 - \frac{\rho_{\text{bulk}}}{\rho} \right)$$

where: P= % porosity

ρ_{bulk} = bulk density (g/cc)

ρ =polymer density, 1.23 g/cc.

Matrix Tensile Strength And Matrix Modulus

[0070] Tensile break load was measured using an INSTRON 5500R tensile test machine equipped with flat-faced grips and a 900 N load cell. The gauge length was 19 mm and the cross-head speed was 20.3 cm/min. For longitudinal MTS measurements, the larger dimension of the sample was oriented in the calendering direction, which was designated the "machine direction". For the transverse MTS measurements, the larger dimension of the sample was oriented perpendicular to the calendering direction, which was designated the "transverse direction".

[0071] The sample from the density measurement was used for tensile testing. The sample dimensions were 50 mm in length, 5 mm in width, and approximately 0.5 mm thick. The effective thickness is calculated from the mass, the area, and the density of the sample. Two samples were then tested individually on the tensile tester. The average of the two maximum load (*i.e.*, the peak force) measurements was reported. The longitudinal and transverse MTS were calculated using the following equation:

$$MTS = (\text{maximum load /cross-section area}) * (\text{density of "Polymer"}) / \text{density of the sample},$$

wherein the density of PLA is taken to be 1.23 g/mL.

[0072] Matrix modulus is calculated using the following equation: *MatrixModulus* = (*small strain slope of load-displacement curve /cross-section area*)*(*density of "Polymer"*) / *density of the sample*.

Proton Nuclear Magnetic Resonance (NMR)

[0073] A sample for ¹H Solution NMR collection was prepared by dissolving approximately 2 mg of polymer in approximately 2 mL CDCl₃. A Bruker BioSpin Avance II 300 MHz system was used to collect ¹H NMR data at 300.13 MHz. A Bruker BioSpin 5mm BBFO probe was installed in a standard bore 7.05T Bruker BioSpin ultra-shielded superconducting magnet. Temperature during NMR acquisition was 300K (26.9° C). Software used for data acquisition and data processing was Topspin 1.3 or higher. The data was collected and processed using the conditions specified in Table 1. The spectra were referenced to the chloroform peak at 7.27 ppm.

[0074] The methine proton appearing as a quadruplet between 5.00 to 5.10 ppm was assigned to lactate ester in the cyclic lactide form, and the methine proton appearing as a quadruplet between 5.12 to 5.24 ppm was assigned to lactate ester in the polymer form. Relative amounts of lactate ester in the form of lactide or polymer were determined by calculating the percent area of the quadruplet peaks with respect to each other.

Table 1

NMR Acquisition Parameters

¹ H NMR Frequency	300.13 MHz
Transmitter offset	6.175 ppm
Spectral Width	6188 Hz
Pulse Length (30°)	3.9 microseconds
Acquired data points	198018
Acquisition Time	16 seconds
Recycle delay	5 seconds
Sample spinning speed	20 Hz

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(continued)

NMR Acquisition Parameters

Number of scans	128
Total data points after zero fill	256k
Line broadening	0.3 Hz

EXAMPLES

Example 1 - illustrative

[0075] In a nitrogen purged glovebag, a 250 ml square glass bottle was filled to the top with L-lactide powder, then the bottle was closed with a polytetrafluoroethylene-lined polybutylene screw cap. The bottle was placed in a 130°C oven and the L-lactide was melted. Additional L-lactide powder was added to the bottle, bringing the total charge weight to 314.87 g (2.1846 mol) of L-lactide. The screw cap was loosely placed upon the bottle, and the assembly placed in a vacuum chamber. Vacuum was drawn, then the chamber flooded with nitrogen. The bottle was removed from the chamber and the cap quickly tightened. The bottle was placed back in the 130°C oven to continue the melting process.

[0076] When the L-lactide was completely melted, the cap was removed and 20.2 μ l (6.24x10⁻⁵ mol) of stannous 2-ethylhexoanate, and 6.54 μ l (6.24x10⁻⁵ mol) of 1,5-pentanediol were added to the bottle using a positive-displacement micro pipette. The bottle was vacuum/nitrogen purged and swirled. The bottle was then placed in a 110°C oven, and swirled occasionally over the next few hours. After 7 days in the oven, the bottle was removed. The polymer billet formed therein was freed by breaking the glass bottle using a hammer.

[0077] Analysis by proton nuclear magnetic resonance (NMR) showed 91.00% of lactate ester as polymer. Differential Scanning Calorimetry (DSC) measured a peak melting temperature at 188.69°C with a melt enthalpy of 68.19 J/g. The DSC thermogram is depicted in FIG. 4. The inherent viscosity was determined to be 9.64 dL/g, and the corresponding solution-viscosity molecular weight was calculated to be 781,000 g/mol.

Example 2 - illustrative

[0078] The material of Example 1 was cut on a bandsaw into slices approximately 1 mm thick, approximately 20 mm width, approximately 50 mm length. A wide angle x-ray diffraction (WAXD) pattern of the PLLA polymer is shown in FIG. 1. The circular WAXD pattern of FIG. 1 and the graphical depiction of FIG. 3 show an absence of beta crystals.

Example 3

[0079] The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 0.1 mm/s. The total displacement was 40 mm. A microporous structure was observed using scanning electron microscopy (SEM). An SEM of the surface of an interior view of the expanded porous PLLA polymer taken at 40,000x magnification is shown in FIG. 8. The SEM shows the presence of nodes 30 and fibrils 40. Differential Scanning Calorimetry (DSC) measured the peak melting temperature of the polymer at 186.12°C with a melt enthalpy of 54.56 J/g. The DSC thermogram is depicted in FIG. 5. The multiple peaks depicted in FIG. 5 indicate the presence of multiple crystal phases.

[0080] The WAXD pattern of FIG. 2 shows a single circular diffraction with a d-spacing that corresponds to the residual crystalline PLA monomer as well as numerous discrete diffraction spots in the equatorial and meridional directions. This diffraction pattern and the associated d-spacings and the graphical depiction of FIG. 3 indicate the presence of beta crystals.

Example 4

[0081] The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 1 mm/s. The total displacement was 60 mm. A microporous structure was observed using scanning electron microscopy (SEM). An SEM of the surface of an interior view of the expanded porous PLLA polymer taken at 20,000x magnification is shown

in FIG. 9. The SEM shows the presence of nodes 30 and fibrils 40. Differential Scanning Calorimetry (DSC) measured a peak melting temperature of the polymer at 185.69°C with a melt enthalpy of 44.48 J/g. The DSC thermogram is depicted in FIG. 6. The multiple peaks depicted in FIG. 6 indicate the presence of multiple crystal phases.

5 **Example 5**

10 **[0082]** The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 10 mm/s. The total displacement was 60 mm. A microporous structure was observed using scanning electron microscopy (SEM). An SEM of the surface of an interior view of the expanded porous PLLA polymer taken at 35,000x magnification is shown in FIG. 10. The SEM shows the presence of nodes 30 and fibrils 40. Differential Scanning Calorimetry (DSC) measured a peak melting temperature of the polymer at 186.96°C with a melt enthalpy of 40.70 J/g. The DSC thermogram is depicted in FIG. 7. The multiple peaks depicted in FIG. 7 indicate the presence of multiple crystal phases.

15 **Example 6**

20 **[0083]** The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 100 mm/s. The total displacement was 60 mm. A microporous structure was visually observed using scanning electron microscopy (SEM).

25 **Example 7**

30 **[0084]** The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 500 mm/s. The total displacement was 40 mm. A microporous structure was visually observed using scanning electron microscopy (SEM).

35 **Example 8**

40 **[0085]** The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 180°C. The samples had a gauge length of 10 mm, were drawn uniaxially with a crosshead displacement rate of 10 mm/s. The total displacement was 60 mm. A microporous structure was visually observed using scanning electron microscopy (SEM).

45 **Example 9**

50 **[0086]** The slices of Example 2 were drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 160°C. The samples had a gauge length of 10 mm and were drawn uniaxially with a crosshead displacement rate of 10 mm/s. The total displacement was 60 mm. A microporous structure was visually observed using scanning electron microscopy (SEM).

[0087] Table 1 sets forth the results of Examples 2, 3-9, and 11.

55

Table 1

	Matrix		
	MTS	Modulus	Porosity
ID	MPa	MPa	%
Example 2	49.9	2898	0
Example 3	175.7	5028	27.89
Example 4	217.0	4458	28.45
Example 5	172.5	3954	15.46
Example 6	84.9	4284	12.6
Example 7	159.6	4280	16.75
Example 8	176.3	5002	20.47
Example 9	173.7	4947	14.23
Example 11	213.0	3919	21

Example 10

[0088] In order to get better release of the PLLA polymer from the glass reaction container, a 1 L cylindrical bottle was silanized by adding 1 ml of octadecyltrichlorosilane and 20 ml of chloroform, closing with a cap, shaking the bottle occasionally over several hours, and allowing the mixture to stand overnight. The bottle was then emptied, rinsed 5 times with 20 ml of chloroform for each rinse, then rinsed 2 times with 100 ml of a 1:1 solution of methanol and water, then rinsed several times with methanol and dried using nitrogen. The bottle was further dried by putting it into a 130°C oven.

[0089] In a nitrogen purged glove box, 1000.2 g (6.934 mol) of L-lactide powder was added to the silanized bottle, which was then closed with a PTFE-lined polybutylene cap. The bottle was placed in a 130°C oven and the L-lactide was melted. During the course of melting, degassing was done by drawing vacuum on the L-lactide to a level of about 399 Pa (3.0 Torr) for one minute followed by pressurization with Nitrogen to 13789 Pa (2 psig).

[0090] When the L-lactide was completely melted, the bottle was moved to a nitrogen glove box, the cap was removed, and 211.9 μl of catalyst solution was added to the bottle using a positive-displacement micro pipette. The catalyst solution consisted of 64.2 μl (1.98×10^{-4} mol) of stannous 2-ethylhexoanate and 147.7 μl of anhydrous toluene. The bottle was vacuum purged and swirled. The bottle was then placed in a 130°C oven and swirled occasionally over a duration of 30 minutes. The bottle was then placed in a 110°C oven. After 3 days in the oven, the bottle was removed. The polymer billet formed therein was freed by breaking the glass bottle.

[0091] Analysis by proton nuclear magnetic resonance (NMR) showed 93.6% of lactate ester as polymer. Differential Scanning Calorimetry (DSC) measured a peak melting temperature at 185.7°C with a melt enthalpy of 65.5 J/g. The inherent viscosity was determined to be 10.2 dL/g and the corresponding solution-viscosity molecular weight was calculated to be 853,000 g/mol.

Example 11

[0092] The material of Example 10 was cut on a lathe into a slice approximately 1 mm thick. The slice was machined into a dogbone shape with a gauge length of 6 mm. The dogbone sample was drawn uniaxially in a tensile machine (Instron Model 5965 Norwood, MA, 02062) equipped with a convection oven set to 145°C. The crosshead displacement rate was 100 mm/min and the total displacement was 62 mm. The porosity of the resultant expanded sample was calculated to be 21%.

Example 12

[0093] In order to get better release of the PLLA polymer from the glass reaction container, a 1 L cylindrical bottle was silanized by adding 1 ml of octadecyltrichlorosilane and 20ml of chloroform, closing with a cap, shaking the bottle occasionally over several hours, and allowing the mixture to stand overnight. The bottle was then emptied, rinsed 5 times with 20 ml of chloroform for each rinse, and dried overnight in a 110°C oven.

[0094] In a nitrogen purged glovebag, 999.01 g (6.9313 mol) of L-lactide powder was added to the silanized bottle,

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which was then closed with a PTFE-lined polybutylene cap. The bottle was placed in a 130°C oven and the L-lactide was melted.

5 [0095] When the L-lactide was completely melted, the cap was removed and 64.2 μl (1.98×10^{-4} mol) of stannous 2-ethylhexoanate, and 20.7 μl (1.98×10^{-4} mol) of 1,5-pentanediol were added to the bottle using a positive-displacement micro pipette. The bottle was vacuum/nitrogen purged and swirled. The bottle was then placed in a 110°C oven and swirled occasionally over the next few hours. After 16 days in the oven, the bottle was removed. The polymer billet formed therein was freed by breaking the glass bottle using a hammer.

10 [0096] Analysis by proton nuclear magnetic resonance (NMR) showed 90.35% of lactate ester as polymer. Differential Scanning Calorimetry (DSC) measured a peak melting temperature at 178.24°C with a melt enthalpy of 42.92 J/g. The inherent viscosity was determined to be 8.84 dL/g and the corresponding solution-viscosity molecular weight was calculated to be 683,000 g/mol.

Example 13

15 [0097] The material of Example 12 was cut using a bandsaw into slices perpendicular to the cylinder axis to yield a disc approximately 5 mm thick and approximately 10 cm diameter. The disc was then milled on both faces to a consistent thickness.

Example 14

20 [0098] A disc from Example 13 having a thickness of 3.0 mm was restrained in an apparatus capable of stretching the disc in all directions in the plane of the disc at an equal rate within a temperature controlled environment. The sample temperature was approximately 168°C and the radial displacement rate was 1.27 mm/s. The total radial displacement was 134 mm. A microporous structure was observed using scanning electron microscopy (SEM). An SEM of the surface of an interior view of the expanded porous PLLA polymer taken at 8,000x magnification is shown in FIG. 11. The porosity of the sample was calculated to be 62.2%.

Example 15

30 [0099] A disc from Example 13 having a thickness of 2.2 mm was restrained in an apparatus capable of stretching the disc in all directions in the plane of the disc at an equal rate within a temperature controlled environment. The sample temperature was approximately 168°C and the radial displacement rate was 1.27 mm/s. The total radial displacement was 221 mm. A microporous structure was observed using scanning electron microscopy (SEM). An SEM of the surface of an interior view of the expanded porous PLLA polymer taken at 45,000x magnification is shown in FIG. 12. The porosity of the sample was calculated to be 48.2%.

Example 16

40 [0100] A disc from Example 13 having a thickness of approximately 2.0 mm was restrained in an apparatus capable of stretching the disc in all directions in the plane of the disc at an equal rate within a temperature controlled environment. The platen temperature set-point was set to 180°C and the apparatus was permitted to equilibrate. To directly ascertain material temperature, a T-type thermocouple was adhered to the top surface of the disc from Example 13 using Kapton tape. The disc was loaded into the apparatus chamber for a dwell time of 10 minutes. After dwelling, the material temperature was observed to be 168.4°C.

Example 17

50 [0101] Into a 2 oz square glass bottle 15.16 g (0.1052 mol) of L-lactide powder and 4.9 μl (1.5×10^{-5} mol) of stannous 2-ethylhexoanate was added. A foil lined screw cap was loosely placed upon the bottle, and the assembly placed in a vacuum chamber. Vacuum was drawn, then the chamber flooded with nitrogen. The bottle with cap was removed from the chamber and the cap quickly tightened. The bottle was placed in a 110°C oven and occasionally swirled over the next few hours during the melting process. After 6 days in the oven the bottle was removed.

55 [0102] Analysis by proton NMR showed 99.73% of lactate ester as polymer. DSC measured peak melting temperature at 190.47°C with a melt enthalpy of 84.34 J/g at a temperature ramp rate of 10°C/min. Inherent viscosity was 5.34 dL/g in chloroform at 25°C at 0.1 g/dL polymer concentration.

Example 18

5 [0103] Into a 20 ml glass ampule 28.97 g (0.2010 mol) of L-lactide powder and 9.3 μ l (2.8×10^{-5} mol) of stannous 2-ethylhexoanate was added. A vacuum line was fitted to the stem of the ampule, vacuum was drawn, then the ampule was flooded with nitrogen and the stem flame sealed. The ampule was placed in a 110°C oven and occasionally shaken during the melting process. After 18 days in the oven the ampule was removed. Analysis by proton NMR showed 99.77% of lactate ester as polymer. DSC measured peak melting temperature at 189.77°C with a melt enthalpy of 61.84 J/g at a temperature ramp rate of 10°C/min. Inherent viscosity was 5.41 dL/g in chloroform at 25°C at 0.1 g/dL polymer concentration.

10 Examples 19-25

15 [0104] Examples 19-25 were conducted using the synthesis method and ratios of lactide, stannous 2-ethylhexoanate, and 1,5-pentanediol described in Example 12, except that 250 ml square bottles were utilized. PLA was prepared at various temperatures and various ratios of D and L isomer content. Physical properties were characterized, and samples were pulled on the MTS tensile tester and examined for evidence of microporous structure formation by scanning electron micrographs (SEMS). Results and parameters of Examples 3-9 and 19-25 are shown in Table 2. FIG. 13 is a graphical illustration of the data from Table 2 showing the formation of a microporous structure as a function of melt enthalpy and inherent viscosity.

Table 2

Mole Fract. L Isomer	Synth. Temp. C	PLA Melt Temp. C	PLA Melt Enthalpy J/g	Inherent Visc. dL/g	Visc. M.W. x10 ³ g/mole	Gauge Length mm	Draw Conditions			Oven Temp. C	Micro Porosity Observed
							Displacement rate mm/sec	Total Displacement mm	Displacement mm		
Ex. 3	110	188.7	68.19	9.641	781	10	0.1	40	170	Yes	
Ex. 4	110	188.7	68.19	9.641	781	10	1.0	60	170	Yes	
Ex. 5	110	188.7	68.19	9.641	781	10	10.0	60	170	Yes	
Ex. 6	110	188.7	68.19	9.641	781	10	100.0	60	170	Yes	
Ex. 7	110	188.7	68.19	9.641	781	10	500.0	40	170	Yes	
Ex. 8	110	188.7	68.19	9.641	781	10	10.0	60	180	Yes	
Ex. 9	110	188.7	68.19	9.641	781	10	100.0	60	160	Yes	
Ex. 19	140	178.1	46.30	7.210	497	10	10.0	40	160	Yes	
Ex. 20	150	175.1	40.09	6.828	459	10	1.0	40	150	Yes	
Ex. 21	110	191.6	73.25	4.456	248	5	0.5	20	170	No	
Ex. 22	160	169.1	26.22	6.451	419	10	10.0	40	160	No	
Ex. 23	0.975	110	158.4	6.833	465	10	10.0	20	150	No	
			31.93						140	No	
									130	No	
									120	No	
									110	Yes	

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(continued)

PLA Physical Characteristics as Synthesized				Draw Conditions							
Mole Fract. L Isomer	Synth. Temp. C	PLA Melt Temp. C	PLA Melt Enthalpy J/g	Inherent Visc. dL/g	Visc. M.W. x10 ³ g/mole	Gauge Length mm	Displacement rate mm/sec	Total Displacement mm	Oven Temp. C	Micro Porosity Observed	
Ex. 24	0.975	125	153.7	27.20	4.978	291	10	10.0	40	130	No
Ex. 25	0.950	125	144.6	23.20	6.184	396	10	10.0	40	120	No

Example 26

[0105] The synthesis method described in Example 12 was used, except that a 250 ml square bottle was utilized. 301.54 g (2.0940 mol) of L-lactide, 6.78 μl (2.09×10^{-5} mol) of stannous 2-ethylhexoanate, and 2.19 μl (2.09×10^{-5} mol) of 1,5-pentanediol were polymerized at 110°C for 38 days. Analysis by proton nuclear magnetic resonance (NMR) showed 42.96% of lactate ester as polymer. The bottle was removed from the oven, and the paste-like mixture of PLA/lactide was emptied from the bottle by means of a spatula. The mixture was allowed to cool and solidify, was broken into small pieces, and the lactide extracted with acetone in a Soxhlet extractor for 2 days. The recovered PLA powder was dried overnight in a vacuum chamber.

[0106] Differential Scanning Calorimetry (DSC) measured peak melting temperature at 183.65°C with a melt enthalpy of 84.12 J/g. The inherent viscosity was determined to be 3.82 dL/g and the corresponding solution-viscosity molecular weight was calculated to be 198,000 g/mol.

Example 27

[0107] The PLA powder of Example 26 was calendered at 110°C to form a sheet. A scanning electron micrograph (SEM) of the cross-section of the sheet taken at 20,000x magnification is shown in FIG. 16. The properties of the PLA polymer sheet are set forth in Table 3.

Table 3

Thickness	0.8 mm
Matrix Tensile Strength	35 MPa

Example 28

[0108] The synthesis method described in Example 12 was used, except that a 250 ml square bottle was utilized. 329.58 g (2.2867 mol) of L-lactide, 3.70 μl (1.14×10^{-5} mol) of stannous 2-ethylhexoanate, and 1.20 μl (1.14×10^{-5} mol) of 1,5-pentanediol were polymerized at 110°C for 52 days. Analysis by proton nuclear magnetic resonance (NMR) showed 40.37% of lactate ester as polymer. The bottle was removed from the oven, and the paste-like mixture of PLA/lactide was emptied from the bottle by means of a spatula. The mixture was allowed to cool and solidify, was broken into small pieces, and the lactide extracted with acetone in a Soxhlet extractor for 1 day. The recovered PLA powder was dried overnight in a vacuum chamber.

[0109] Differential Scanning Calorimetry (DSC) measured peak melting temperature at 194.55°C with a melt enthalpy of 74.38 J/g. The inherent viscosity was 5.37 dL/g and the corresponding solution-viscosity molecular weight was calculated to be 325,000 g/mol.

Example 29

[0110] The PLA powder formed in Example 28 was lubricated with mineral oil at a ratio of 40 ml/100 g of the PLA powder. The lubricated PLA powder was fed into the nip of 2 counter rotating steel rolls 304.8 mm in diameter pre-heated to 110°C with the gap between the rolls set at 0.127 mm. The speed was 0.914 meter/min. This process yielded a continuous, cohesive opaque tape. The tape was rinsed in hexane to remove the mineral oil and allowed to air dry. Properties of the cohesive opaque tape are shown in Table 4. The porosity was measured from tape bulk density of 0.81 g/cc and a polymer density 1.23 g/cc. A scanning electron micrograph (SEM) of the cross-section of the tape taken at 15,000x magnification is shown in FIG. 15. A useful signal for the presence of beta phase crystals is the observation by a powder XRD of (023)Beta peak depicted by reference numeral 20 and (003)Beta peak depicted by reference numeral 10 as shown in FIG. 17. Properties of the cohesive opaque tape are shown in Table 4.

Table 4

Thickness	0.9 mm
Matrix Tensile Strength	1.51 MPa
Porosity	35%

Example 30

5 [0111] The PLLA powder formed in Example 26 was lubricated with mineral oil at a ratio of 40 ml/100 g of the PLLA powder. The lubricated PLA powder was fed into the nip of 2 counter rotating steel rolls 304.8 mm in diameter pre-heated to 110°C with the gap between the rolls set at 0.127 mm. The speed was 0.914 meter/min. This process yielded a continuous, cohesive opaque tape. A scanning electron micrograph (SEM) of the surface of an interior view of the continuous, cohesive opaque tape taken at 35,000x magnification is shown in FIG. 14.

Example 31

10 [0112] An opaque section of the expanded PLA article of Example 14 was fed into the nip of 2 counter rotating steel rolls 304.8 mm in diameter pre-heated to 170°C with the gap between the rolls set at 0.127 mm. The speed was 0.914 meter/min. The process yielded a sample that was largely translucent. The gap between the rollers was reduced to 0.05 mm, and the largely translucent sample was passed through the counter rotating steel rolls. The sample that emerged was fully translucent, indicating that the sample was densified. The matrix tensile strength of the densified PLLA material as determined by ASTM D368 type V test was determined to be 123.1 MPa. The result is an average of multiple tensile pulls from sibling samples cut from within the same densified article.

Example 32

20 [0113] A 24 mm PLA disc was die cut from the expanded porous PLLA described in Example 15. The thickness of the disc was 0.075 mm and the porosity was calculated to be 50.6%. The disc was placed between 2 sheets of 0.125 mm thick polyimide film and compressed between the 152 mm x 152 mm platens of a heated press (Model No. 3312, Carver, Inc. Wabash, IN). The disc was placed in the press at 120°C and 89 KN. The heat was immediately turned off and the PLLA disc was held under pressure as the press was allowed to cool to 48°C over a time period of 73 minutes. A 7 mm disc was cut from the compressed PLLA disc and the thickness and mass were measured. The porosity was calculated to be 6.6%. A scanning electron micrograph (SEM) of the surface of the compressed PLLA polymer taken at 30,000x magnification is shown in FIG. 28. Evidence of the fibrillated structure is visible in the image.

Example 33

30 [0114] The material of Example 1 was cut on a bandsaw into a slice approximately 1 mm thick, approximately 50 mm width, approximately 50 mm length. The slice was drawn uniaxially in an MTS machine (810 Model No. 318.10 commercially available from MTS Systems Corporation, Eden Prairie, MN) with a 2.5kN MTS Force Transducer (Model No. 661-18E-02, commercially available from MTS Systems Corporation, Eden Prairie, MN) equipped with a convection oven set to 170°C. The sample had a gauge length of 20 mm and was drawn uniaxially with a crosshead displacement rate of 200 mm/s. The total displacement was 40 mm. The sample was removed from the grips, rotated 90 degrees, trimmed to a width of 50 mm, and reloaded into the grips such that the second draw was perpendicular to the first draw. The sample had a gauge length of 20 mm and was drawn uniaxially a second time with a crosshead displacement rate of 20 mm/s. The total displacement was 20 mm. The porosity was calculated to be 46.7%. The Gurley flow was determined to be 0.468 seconds.

Example 34 - illustrative

45 [0115] Approximately 2 grams of PLLA from Example 12 was weighed into each of four 2-liter glass bottles, the total PLLA charge weight among the 4 bottles being 8.39 g. The bottles were filled to the 1.8 L mark with anhydrous o-xylene, the headspace purged with nitrogen from a hose, and a PTFE-lined PBT cap quickly screwed into place. The four bottles were placed in a 140°C oven, and occasionally swirled by hand. After approximately 2.5 hours, the PLLA was solvated into the o-xylene, and the oven temperature reduced to 70°C for overnight. The bottles were removed from the oven the next morning, and allowed to cool and stand at room temperature for another day. The PLLA precipitate was filtered from the o-xylene, placed into a 250 ml bottle, and the bottle filled with hexanes. The bottle was shaken, centrifuged, and decanted, with this washing process being repeated an additional 2 times. The PLLA precipitate was transferred to a 500 ml wide-mouth glass jar by means of a spatula, and the remaining PLLA precipitate on the sides of the 250 ml bottle was washed into the 500 ml jar using several 10 ml portions of hexanes. A small amount of additional hexanes were added as needed to form a slurry by stirring with the spatula. 1.55 g of a light-grade mineral oil lubricant was added to the PLLA/hexanes slurry, and slurry was then stirred for several minutes. The hexanes were evaporated by impinging an air stream into the 500 ml jar while continuously stirring with the spatula. The slurry turned into crumbs, and the crumbs into a fine free-flowing powder as the hexanes evaporated. The jar was placed in a vacuum chamber for several

hours to remove the remaining hexanes. The jar was removed from the vacuum chamber and weighed, and had a net weight of 7.96 g. The mixture content of the resulting powder was calculated to be 80.5% PLLA, 19.5% mineral oil by weight. A wide angle x-ray diffraction (WAXD) pattern of the PLLA powder is shown in FIG. 18. FIG. 19 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 18, which shows the absence of beta crystals.

5 The inherent viscosity was determined to be 5.83 dL/g.

Example 35

10 [0116] A portion of the PLLA/mineral-oil powder of Example 34 was poured into the nip of 2 counter rotating steel rolls 203.2 mm in diameter, having a roll speed of 0.914 meter/minute, a surface temperature of 125°C, and gapped at 0.025 mm. The resulting film was approximately 0.4 mm thickness. The film was immersed approximately 10 minutes in a hexanes bath to remove the mineral oil lubricant. This wash was repeated an additional 2 times, with fresh hexanes being used each time. The porosity of the film was calculated to be 26.4%. A scanning electron micrograph (SEM) of the surface of an interior view of the calendered PLLA film taken at 35,000x magnification is shown in FIG. 20. The

15 inherent viscosity was determined to be 6.04 dL/g.

Example 36

20 [0117] A portion of the calendered PLLA film from Example 35 was cut into a strip measuring 10.2 mm width, 0.390 mm thickness, and approximately 50 mm in length. The strip was drawn in an Instron machine (Model No. 5965 commercially available from Illinois Tool Works Inc., Norwood, MA), equipped with a convection oven set to 160°C. The sample gauge length was set to 10 mm. After equilibrating 10 minutes in the oven, the sample was then drawn uniaxially with a crosshead displacement rate of 1 mm/s and a total displacement of 100 mm. A microporous structure was observed using scanning electron microscopy (SEM). The porosity was calculated to be 49.34%. A scanning electron micrograph (SEM) of the surface of an interior view of the expanded PLLA film taken at 45,000x magnification is shown in FIG. 21. A wide angle x-ray diffraction (WAXD) pattern of the expanded PLLA film is shown in FIG. 22. FIG. 23 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 22, which shows the presence of beta crystals. The inherent viscosity was determined to be 5.98 dL/g.

25 A wide angle x-ray diffraction (WAXD) pattern of the expanded PLLA film is shown in FIG. 22. FIG. 23 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 22, which shows the presence of beta crystals. The inherent viscosity was determined to be 5.98 dL/g.

Example 37

30 [0118] A portion of the calendered PLLA film from Example 35 was cut into in strip measuring 37.8 mm width, 0.434 mm thickness, and approximately 50 mm in length. The strip was drawn in an Instron machine (Model No. 5965 commercially available from Illinois Tool Works Inc., Norwood, MA), equipped with a convection oven set to 160°C. The sample gauge length was set to 10 mm. After equilibrating 10 minutes in the oven, the sample was then drawn uniaxially with a crosshead displacement rate of 1 mm/s and a total displacement of 60 mm. The sample was removed from the grips, and the thickness measured to be 0.156 mm. The sample was trimmed to a length of 20.1 mm along the axis of draw, rotated 90 degrees and reloaded into the grips such that 20.1 mm was the new width. After equilibrating 10 minutes in the oven, the sample was then drawn uniaxially a second time, this instance being perpendicular to the first draw, with a crosshead displacement rate of 1 mm/s and a total displacement of 40 mm. A microporous structure was observed using scanning electron microscopy (SEM). The porosity was calculated to be 47.31%. A scanning electron micrograph (SEM) of the surface of an interior view of the PLLA film taken at 25,000x magnification is shown in FIG. 24. The inherent viscosity was determined to be 6.33 dL/g.

35 The sample was removed from the grips, and the thickness measured to be 0.156 mm. The sample was trimmed to a length of 20.1 mm along the axis of draw, rotated 90 degrees and reloaded into the grips such that 20.1 mm was the new width. After equilibrating 10 minutes in the oven, the sample was then drawn uniaxially a second time, this instance being perpendicular to the first draw, with a crosshead displacement rate of 1 mm/s and a total displacement of 40 mm. A microporous structure was observed using scanning electron microscopy (SEM). The porosity was calculated to be 47.31%. A scanning electron micrograph (SEM) of the surface of an interior view of the PLLA film taken at 25,000x magnification is shown in FIG. 24. The inherent viscosity was determined to be 6.33 dL/g.

Example 38

45 [0119] A portion of the PLLA/mineral-oil powder of Example 34 was washed 3 times with hexanes to remove the mineral oil. The mineral-oil free PLLA powder was poured into the nip of 2 counter rotating steel rolls 203.2 mm in diameter, having a roll speed of 0.914 meter/minute, a surface temperature of 125°C, and gapped at 0.025 mm. The resulting film was approximately 0.7 mm in thickness. The porosity of the film was calculated to be 5.66%.

Example 39

55 [0120] The calendered PLLA film from Example 38 was cut into in strip measuring 10.8 mm width, 0.711 mm thickness, and approximately 50 mm in length. The strip was drawn in an Instron machine (Model No. 5965 commercially available from Illinois Tool Works Inc., Norwood, MA), equipped with a convection oven set to 160°C. The sample had a gauge length of 10 mm, and was drawn uniaxially with a crosshead displacement rate of 1 mm/s. The total displacement was 100 mm. A fibrillated structure. was observed using scanning electron microscopy (SEM). The porosity was calculated

to be 6.98%. A scanning electron micrograph (SEM) of the surface of an interior view the dense PLLA film taken at 25,000x magnification is shown in FIG. 25. A wide angle x-ray diffraction (WAXD) pattern of the PLLA film is shown in FIG. 26. FIG. 27 is an intensity vs. 2-theta plot of the wide angle X-ray diffraction (WAXD) patterns of FIG. 26, which shows the presence of beta crystals.

Example 40

[0121] A powder consisting of PLLA and light-grade mineral oil lubricant was prepared according to the method of Example 34, with a yield of 8.02 g. The mixture content of the resulting powder was calculated to be 80.4% PLLA and 19.6% mineral oil by weight.

Example 41

[0122] 2.67 g of Syloid 620 silica powder (W. R. Grace & Co., Connecticut) was added to the PLLA/mineral oil powder of Example 40. This new mixture was thoroughly mixed by tumbling the jar container for several hours. The mixture content of the resulting powder was calculated to be 60.3% PLLA, 14.7% mineral oil and 25.0% silica by weight.

Example 42

[0123] A portion of the PLLA/mineral-oil/silica powder of Example 41 was poured into the nip of 2 counter rotating steel rolls 203.2 mm in diameter, having a roll speed of 0.914 meter/minute, a surface temperature of 125°C, and gapped at 0.025 mm. The first pass through the nip resulted in the formation of large flakes. The flakes were collected and the material passed through the nip a second time, which resulted in the formation of a coherent film. The film was rotated 90 degrees and passed through the nip a third time, the orientation passing through the nip being perpendicular to the second pass. The film was rotated 90 degrees and passed through the nip a fourth time, the orientation passing through the nip being parallel to the second pass. The film was immersed approximately 10 minutes in a hexanes bath to remove the mineral oil lubricant. This wash was repeated an additional 2 times, with fresh hexanes being used each time. After air drying, the film was placed in a vacuum chamber to remove the remaining hexanes. The filled film resulting from this process had a typical thickness of 0.75 mm, good physical integrity, and could be handled without cracking or visible particle shedding. The bulk density was calculated to be 0.767 g/ml. Using 1.23 g/ml as the basis density for PLLA, and 2.20 g/ml as the basis density for silica, the average density of the PLLA/silica solids was calculated to be 1.42 g/ml. The porosity of the PLLA/silica film was calculated to be 46.0%. The matrix tensile strength of the PLLA/silica film was determined to be 15.8 MPa. A scanning electron micrograph (SEM) of the PLLA/silica film taken at 25,000x is shown in FIG. 29.

[0124] The invention of this application has been described above both generically and with regard to specific embodiments. It will be apparent to those skilled in the art that various modifications and variations can be made in the embodiments without departing from the scope of the disclosure. Thus, it is intended that the embodiments cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

Claims

1. A PLA polymer article comprising:
an expanded PLA polymer comprising a beta crystal phase and having nodes and fibrils.
2. The PLA polymer article of claim 1, wherein said fibrils comprise polymer chains and said polymer chains are oriented along a fibril axis.
3. The PLA polymer article of claim 1, wherein said expanded PLA polymer comprises at least one comonomer; or wherein said expanded PLA polymer comprises poly L-lactic acid (PLLA), poly d-lactic acid (PDLA), poly L-lactide, poly D- lactide, and combinations thereof.
4. The PLA polymer article of claim 1, wherein said expanded PLA polymer has a melt enthalpy as measured by DSC greater than 30 J/g.
5. The PLA polymer article of claim 1, wherein said expanded PLA polymer has an inherent viscosity greater than 3.8 dL/g as measured by the capillary solution viscosimeter according to the method as described in the present de-

scription.

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6. The PLA polymer article of claim 5, wherein said expanded PLA polymer has a molecular weight (Mw) calculated from solution viscosity greater than 150,000 g/mol.
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7. The PLA polymer article of claim 6, wherein said expanded PLA polymer has an inherent viscosity greater than 5 dL/g as measured by the capillary solution viscosimeter according to the method as described in the present description; and optionally wherein said PLA expanded polymer has a molecular weight (Mw) calculated from solution viscosity greater than 290,000 g/mol.
- 15
8. The PLA polymer article of claim 1, wherein said expanded PLA polymer is microporous; or wherein said expanded PLA polymer has a porosity less than 10% as calculated according to the method as described in the present description .
- 20
9. The PLA polymer article of claim 1, wherein said expanded PLA polymer has a matrix tensile strength determined according to the method as described in the present description greater than or equal to 110 MPa.
- 25
10. The PLA polymer article of claim 1, wherein said expanded PLA polymer has a matrix modulus determined according to the method as described in the present description greater than or equal to 3000 MPa.
- 30
11. The PLA polymer article of claim 1, wherein said expanded PLA polymer has a porosity greater than about 25% as calculated according to the method as described in the present description .
- 35
12. The PLA polymer article of claim 1, wherein said PLA polymer comprises at least one member selected from the group consisting of a filler material and a coating material.
13. The PLA polymer article of claim 1, wherein said article is in the form of a fiber, tube, tape, sheet, or a three dimensional self-supporting structure.
14. An article according to claim 1 comprising:
at least one filler material.
15. The article of claim 14, wherein said filler material is selected from the group consisting of inorganic materials, carbon black, aerogels, metals, semi-metals, ceramics, carbon/metal particulate blends, activated carbon, hydrogel materials, bioactive substances, stiffening agents, and combinations thereof; or wherein said PLA polymer comprises poly L-lactic acid (PLLA), poly d-lactic acid (PDLA), poly L-lactide, poly D-lactide, and combinations thereof.

Patentansprüche

- 40
1. PLA-Polymerartikel, umfassend:
ein expandiertes PLA-Polymer, umfassend eine Beta-Kristallphase und mit Knoten und Fibrillen.
- 45
2. PLA-Polymerartikel nach Anspruch 1, wobei die Fibrillen Polymerketten umfassen und die Polymerketten entlang einer Fibrillenachse ausgerichtet sind.
- 50
3. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer mindestens ein Co-Monomer umfasst; oder wobei das expandierte PLA-Polymer Poly-L-Milchsäure (PLLA), Poly-D-Milchsäure (PDLA), Poly-L-Lactid, Poly-D-Lactid und Kombinationen davon umfasst.
- 55
4. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer eine Schmelzenthalpie wie durch DSC gemessen von mehr als 30 J/g aufweist.
5. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer eine inhärente Viskosität von mehr als 3,8 dl/g wie durch den Kapillarlösungviskosimeter gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben gemessen aufweist.
6. PLA-Polymerartikel nach Anspruch 5, wobei das expandierte PLA-Polymer ein Molekulargewicht (Mw) aufweist,

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das aus Lösungsviskosität von mehr als 150.000 g/mol berechnet wird.

- 5 7. PLA-Polymerartikel nach Anspruch 6, wobei das expandierte PLA-Polymer eine inhärente Viskosität von mehr als 5 dl/g wie durch den Kapillarlösungsviskosimeter gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben gemessen aufweist; und wobei optional das expandierte PLA-Polymer ein Molekulargewicht (Mw) aufweist, das aus Lösungsviskosität von mehr als 290.000 g/mol berechnet wird.
- 10 8. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer mikroporös ist; oder wobei das expandierte PLA-Polymer eine Porosität von weniger als 10 % wie gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben berechnet aufweist.
- 15 9. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer eine Matrixzugfestigkeit, die gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben bestimmt ist, von mehr als oder gleich 110 MPa aufweist.
- 20 10. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer einen Matrixmodul, der gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben bestimmt ist, von mehr als oder gleich 3000 MPa aufweist.
- 25 11. PLA-Polymerartikel nach Anspruch 1, wobei das expandierte PLA-Polymer eine Porosität von mehr als etwa 25 % wie gemäß dem Verfahren wie in der vorliegenden Beschreibung beschrieben berechnet aufweist.
- 30 12. PLA-Polymerartikel nach Anspruch 1, wobei das PLA-Polymer mindestens ein Element umfasst, das aus der Gruppe ausgewählt ist, die aus einem Füllmaterial und einem Beschichtungsmaterial besteht.
- 35 13. PLA-Polymerartikel nach Anspruch 1, wobei der Artikel in der Form einer Faser, eines Rohres, eines Bandes, einer Folie oder einer dreidimensionalen selbsttragenden Struktur ist.
- 40 14. Artikel nach Anspruch 1, umfassend:
mindestens ein Füllmaterial.
- 45 15. Artikel nach Anspruch 14, wobei das Füllmaterial aus der Gruppe ausgewählt ist, die aus anorganischen Materialien, Ruß, Aerogelen, Metallen, Halbmetallen, Keramik, Kohlenstoff-/Metallpartikel-Gemischen, Aktivkohle, Hydrogelmaterialien, bioaktiven Substanzen, Versteifungsmitteln und Kombinationen davon besteht; oder wobei das PLA-Polymer Poly-L-Milchsäure (PLLA), Poly-D-Milchsäure (PDLA), Poly-L-Lactid, Poly-D-Lactid und Kombinationen davon umfasst.

Revendications

- 40 1. Article de polymère d'acide polylactique (PLA) comprenant :
un polymère de PLA expansé comprenant une phase bêta cristalline et ayant des nœuds et des fibrilles.
- 45 2. Article de polymère de PLA selon la revendication 1, dans lequel lesdites fibrilles comprennent des chaînes de polymère et lesdites chaînes de polymère sont orientées le long d'un axe de fibrille.
- 50 3. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé comprend au moins un comonomère ; ou dans lequel ledit polymère de PLA expansé comprend l'acide poly-L-lactique (PLLA), l'acide poly-d-lactique (PDLA), le poly-L-lactide, le poly-D-lactide, et des combinaisons de ceux-ci.
- 55 4. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé a une enthalpie de fusion telle que mesurée par calorimétrie différentielle à balayage (DSC), supérieure à 30 J/g.
5. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé a une viscosité inhérente supérieure à 3,8 dL/g telle que mesurée par le viscosimètre capillaire en solution selon le procédé décrit dans la présente description.
6. Article de polymère de PLA selon la revendication 5, dans lequel ledit polymère de PLA expansé a un poids molé-

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culaire (Mw) calculé d'après la viscosité en solution, supérieur à 150 000 g/mol.

- 5
7. Article de polymère de PLA selon la revendication 6, dans lequel ledit polymère de PLA expansé a une viscosité inhérente supérieure à 5 dL/g telle que mesurée par le viscosimètre capillaire en solution selon le procédé décrit dans la présente description ; et facultativement dans lequel ledit polymère de PLA expansé a un poids moléculaire (Mw) calculé d'après la viscosité en solution, supérieur à 290 000 g/mol.
- 10
8. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé est microporeux ; ou dans lequel ledit polymère de PLA expansé a une porosité inférieure à 10 % telle que calculée selon le procédé décrit dans la présente description.
- 15
9. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé a une résistance à la traction de la matrice déterminée selon le procédé décrit dans la présente description, supérieure ou égale à 110 MPa.
- 20
10. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé a un module de matrice déterminé selon le procédé décrit dans la présente description, supérieur ou égal à 3 000 MPa.
- 25
11. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA expansé a une porosité supérieure à 25 % environ telle que calculée selon le procédé décrit dans la présente description.
- 30
12. Article de polymère de PLA selon la revendication 1, dans lequel ledit polymère de PLA comprend au moins un élément choisi parmi le groupe constitué par un matériau de remplissage et un matériau de revêtement.
- 35
13. Article de polymère de PLA selon la revendication 1, dans lequel ledit article est sous la forme d'une fibre, d'un tube, d'un ruban, d'une feuille, ou d'une structure autoporteuse tridimensionnelle.
- 40
14. Article selon la revendication 1 comprenant : au moins un matériau de remplissage.
- 45
- 50
- 55
15. Article selon la revendication 14, dans lequel ledit matériau de remplissage est choisi parmi le groupe constitué par des matériaux inorganiques, le noir de charbon, des aérogels, des métaux, des semi-métaux, des céramiques, des mélanges de particules de carbone/métal, le charbon activé, des matériaux d'hydrogel, des substances bioactives, des agents de raidissement, et des combinaisons de ceux-ci ; ou dans lequel ledit polymère de PLA comprend l'acide poly-L-lactique (PLLA), l'acide poly-D-lactique (PDLA), le poly-L-lactide, le poly-D-lactide, et des combinaisons de ceux-ci.

FIG. 1

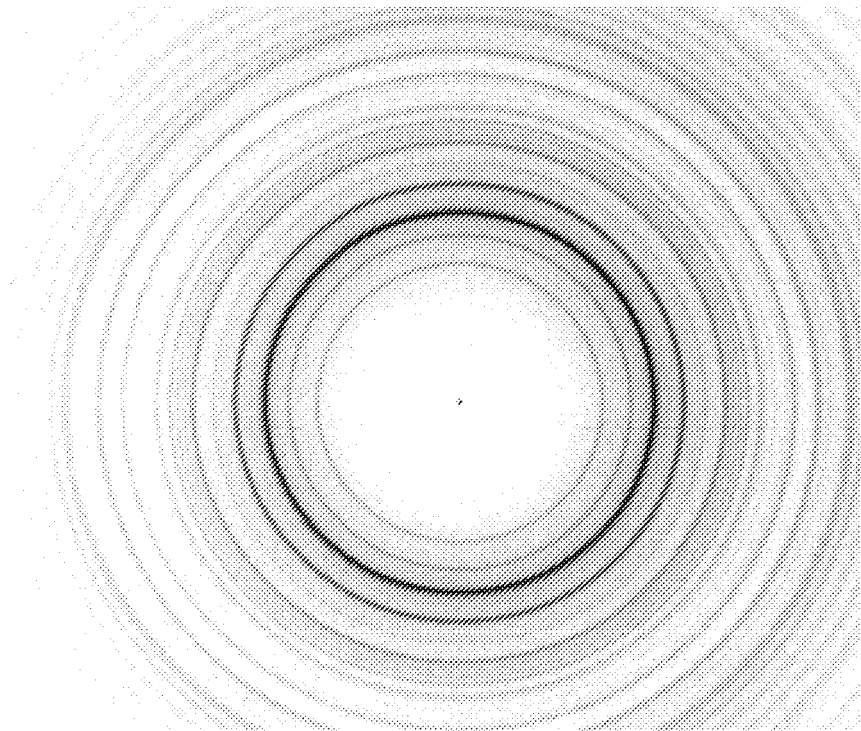


FIG. 2

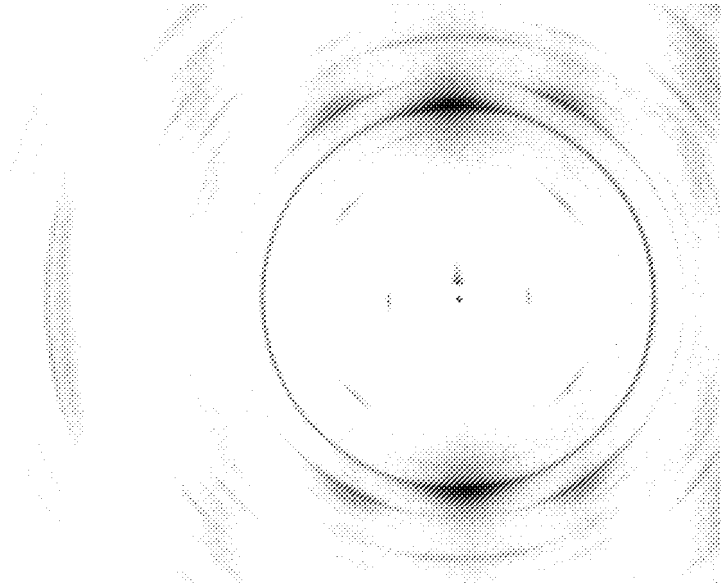


FIG. 3

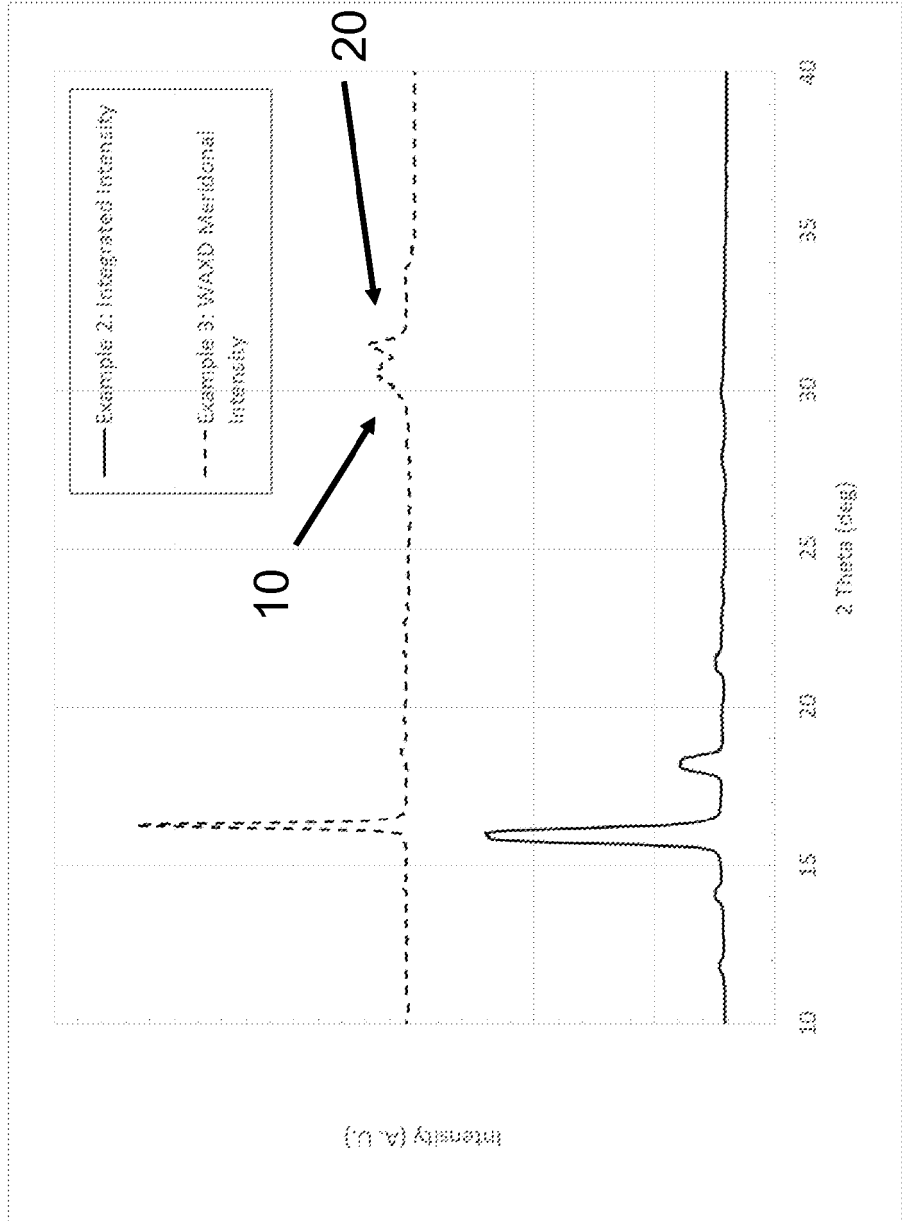


FIG. 4

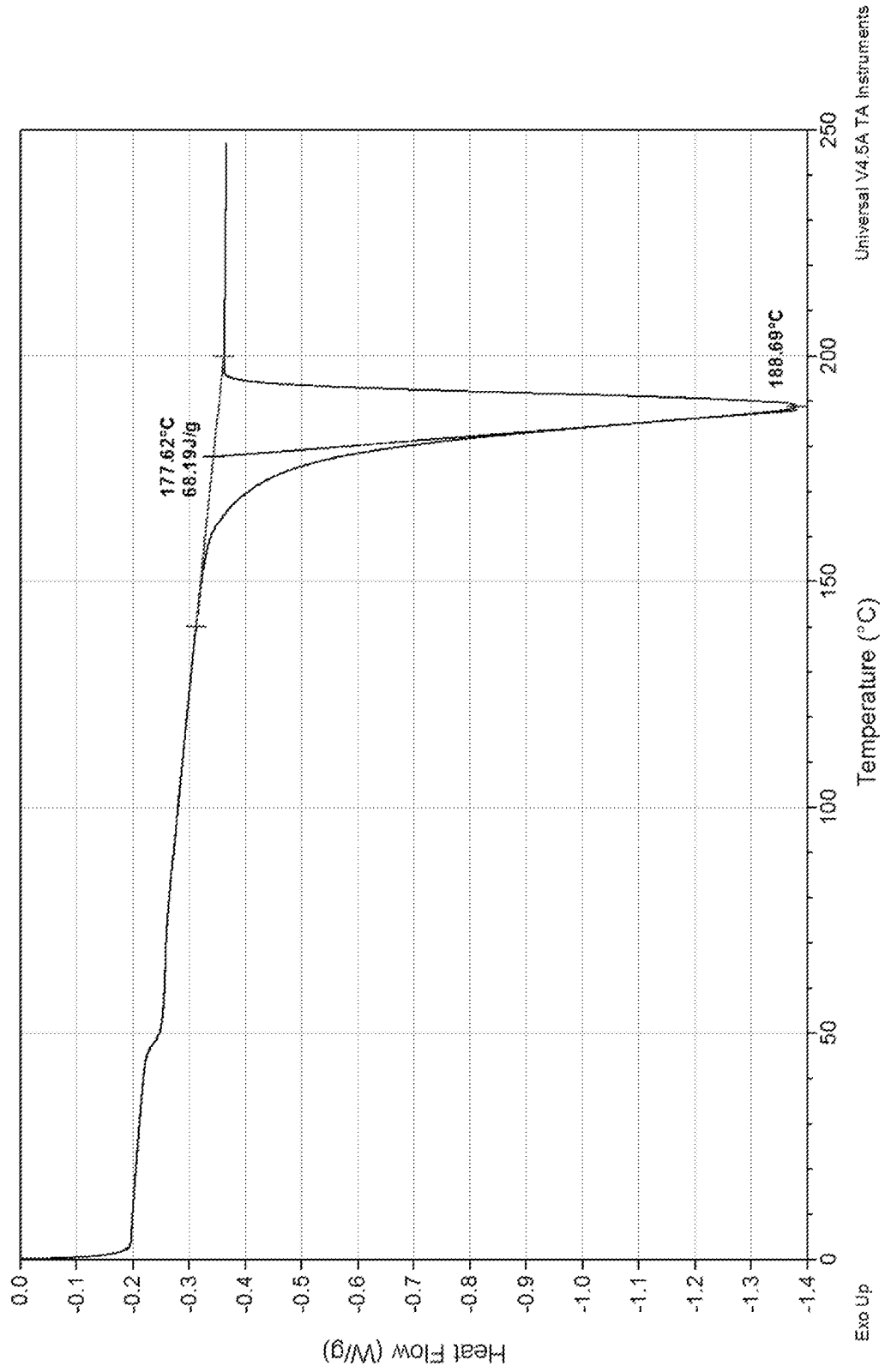


FIG. 5

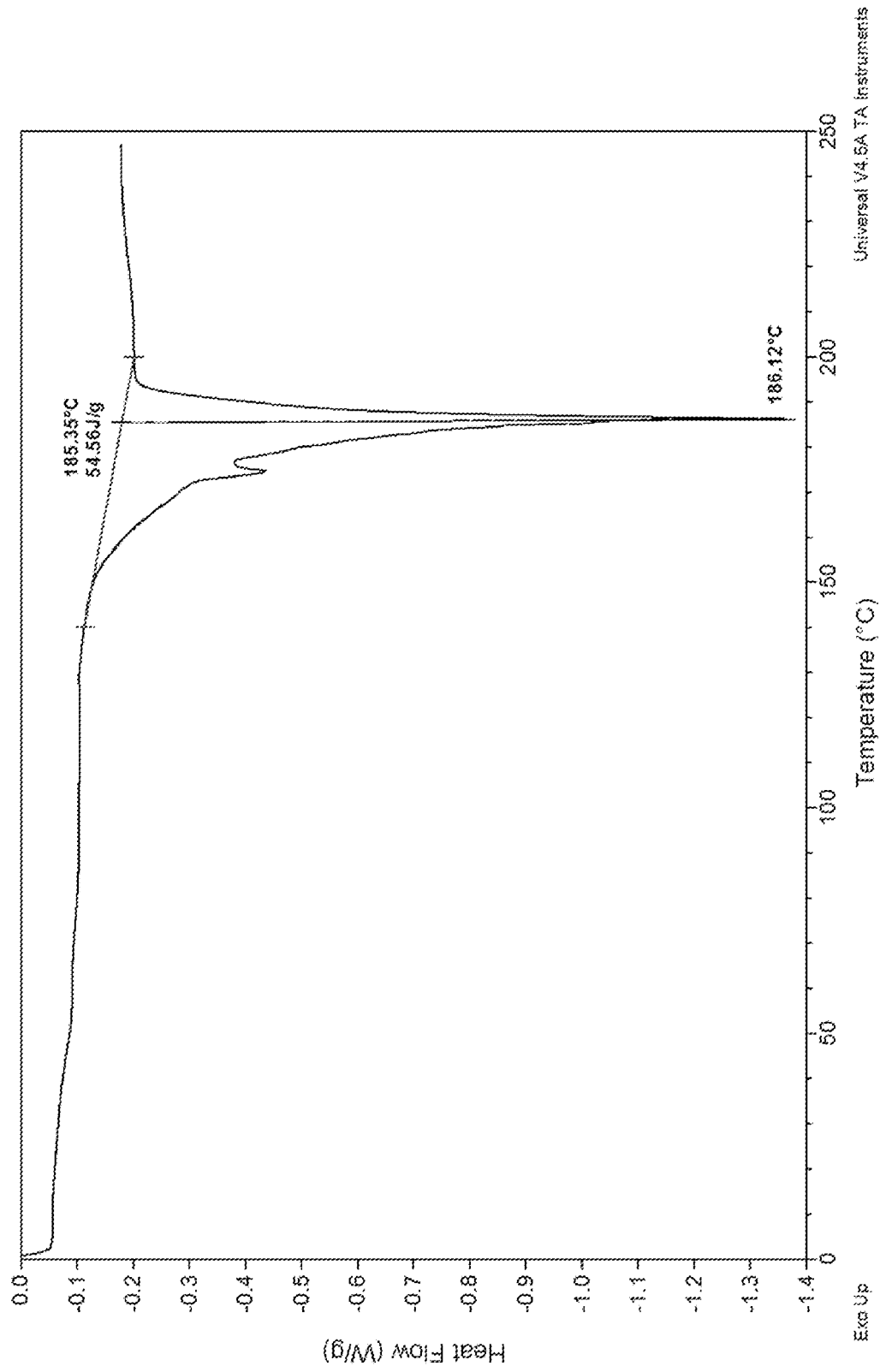


FIG. 6

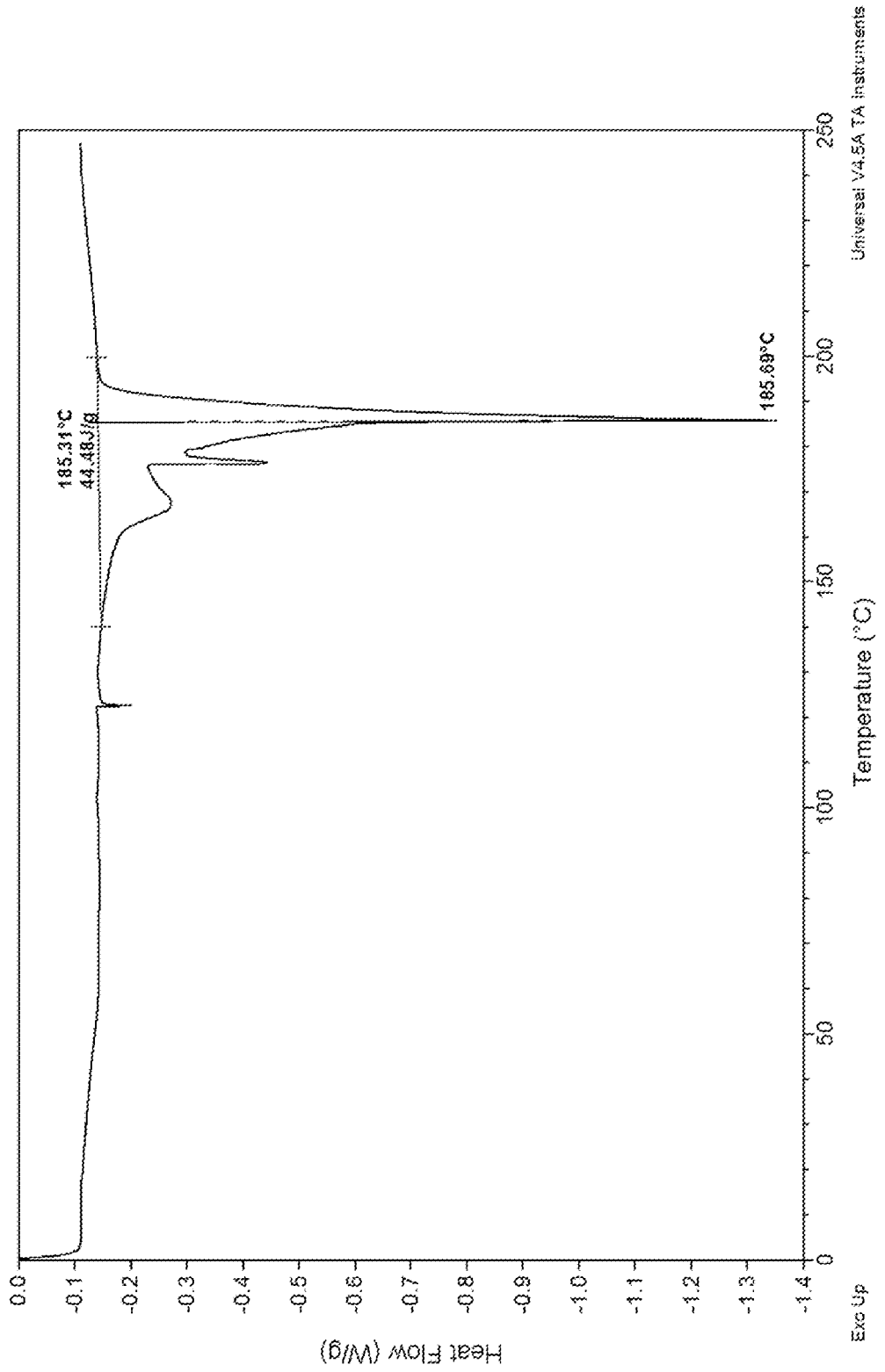


FIG. 7

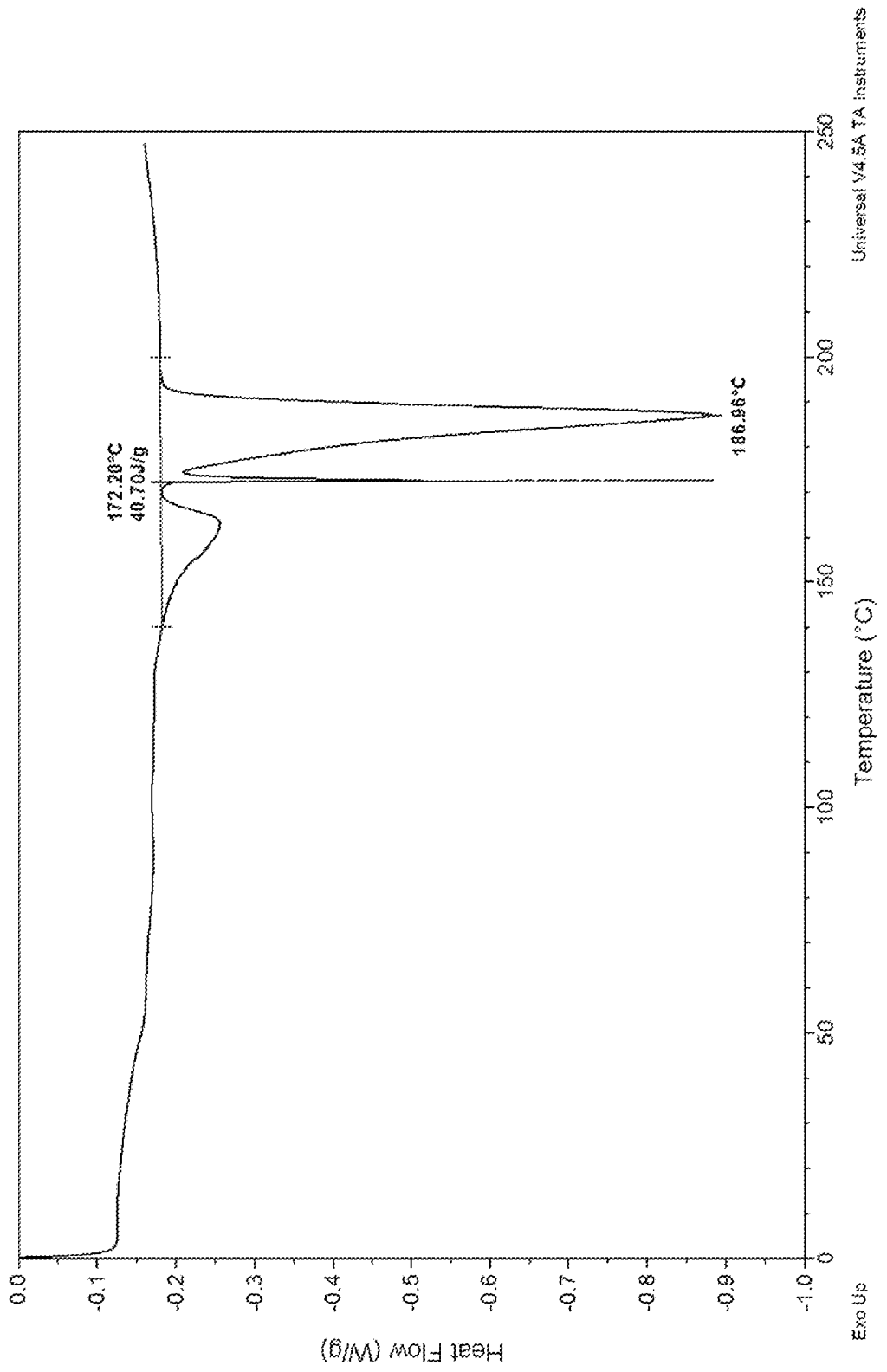


FIG. 9

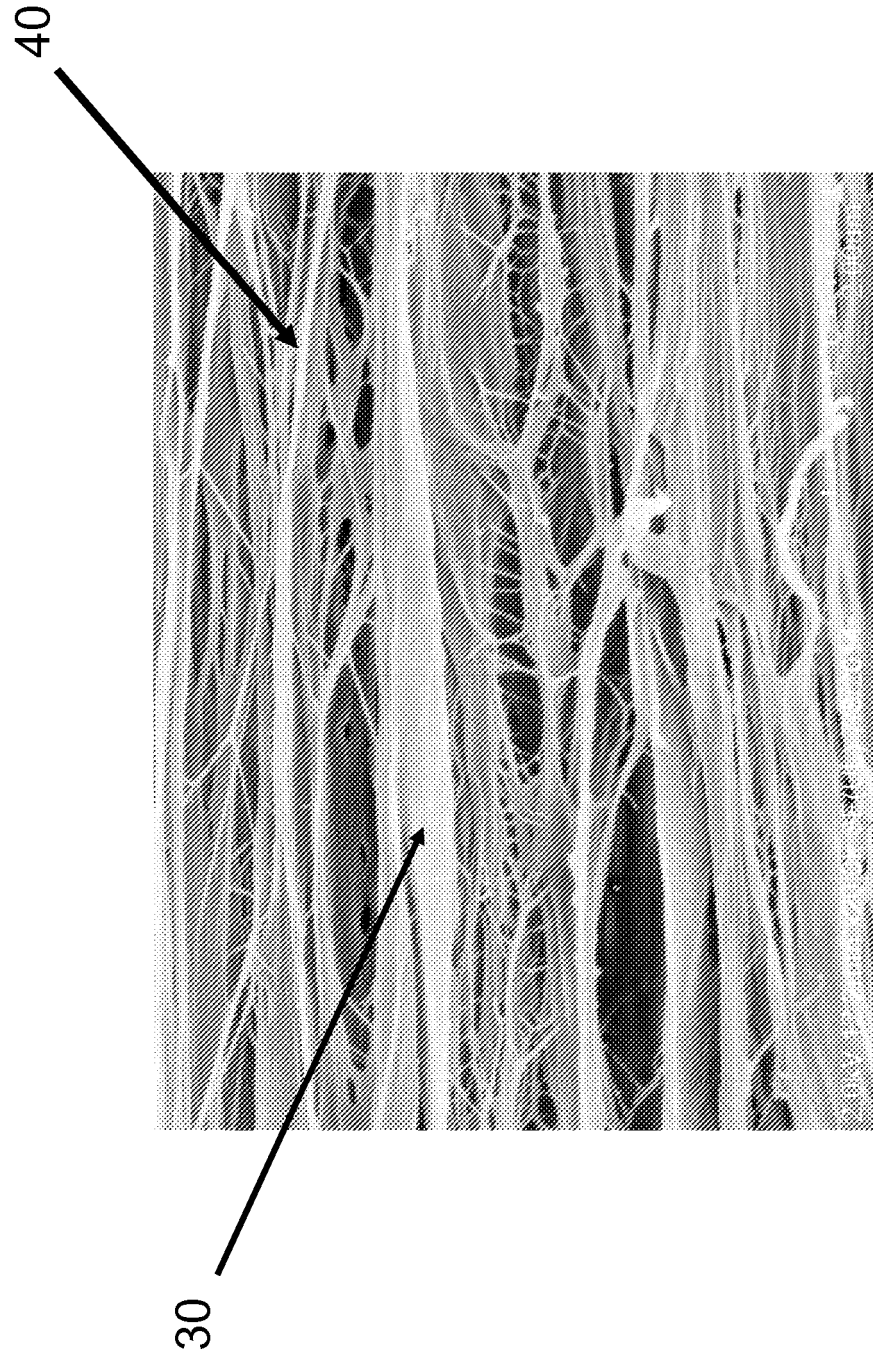


FIG. 11

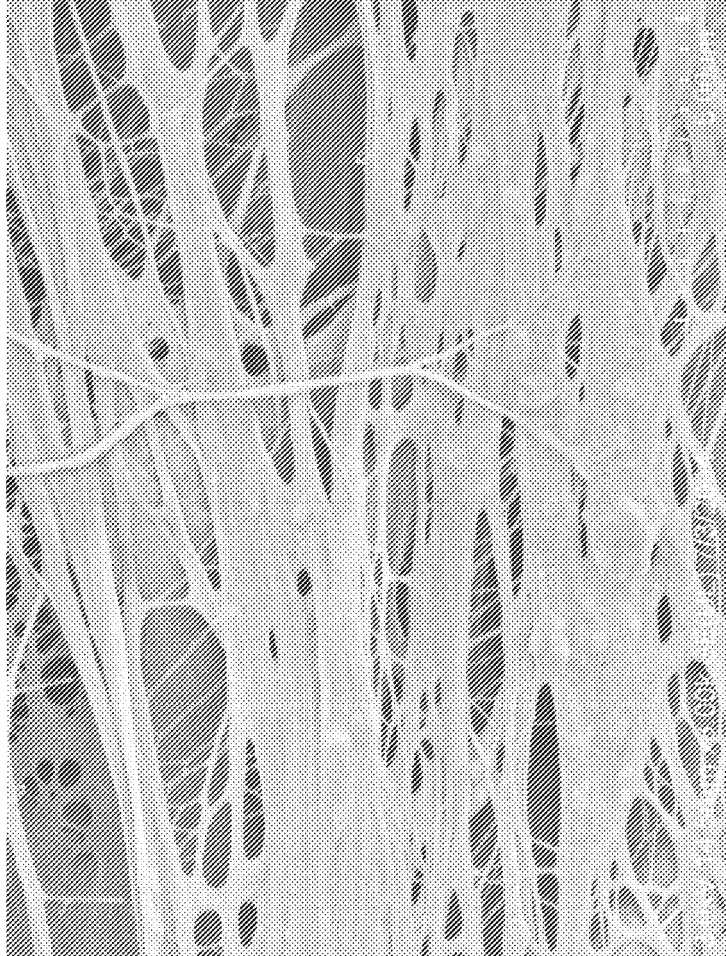


FIG. 12

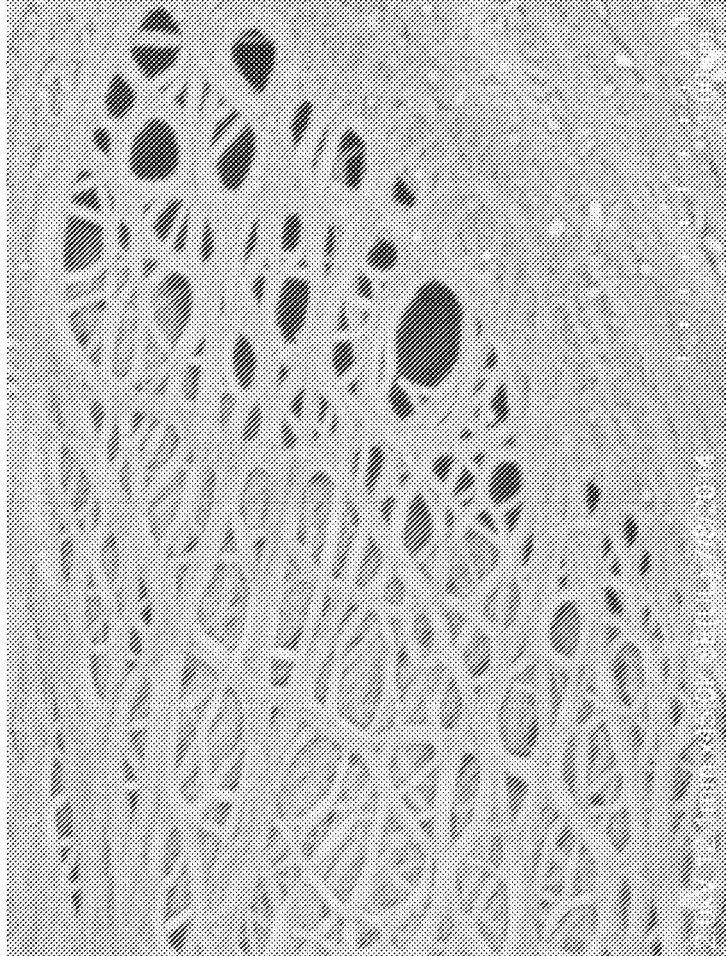


FIG. 13

PLA Micro-Porosity Formation as a Function of Melt Enthalpy and Molecular Weight
Uniaxial Pulls in a Heated Chamber

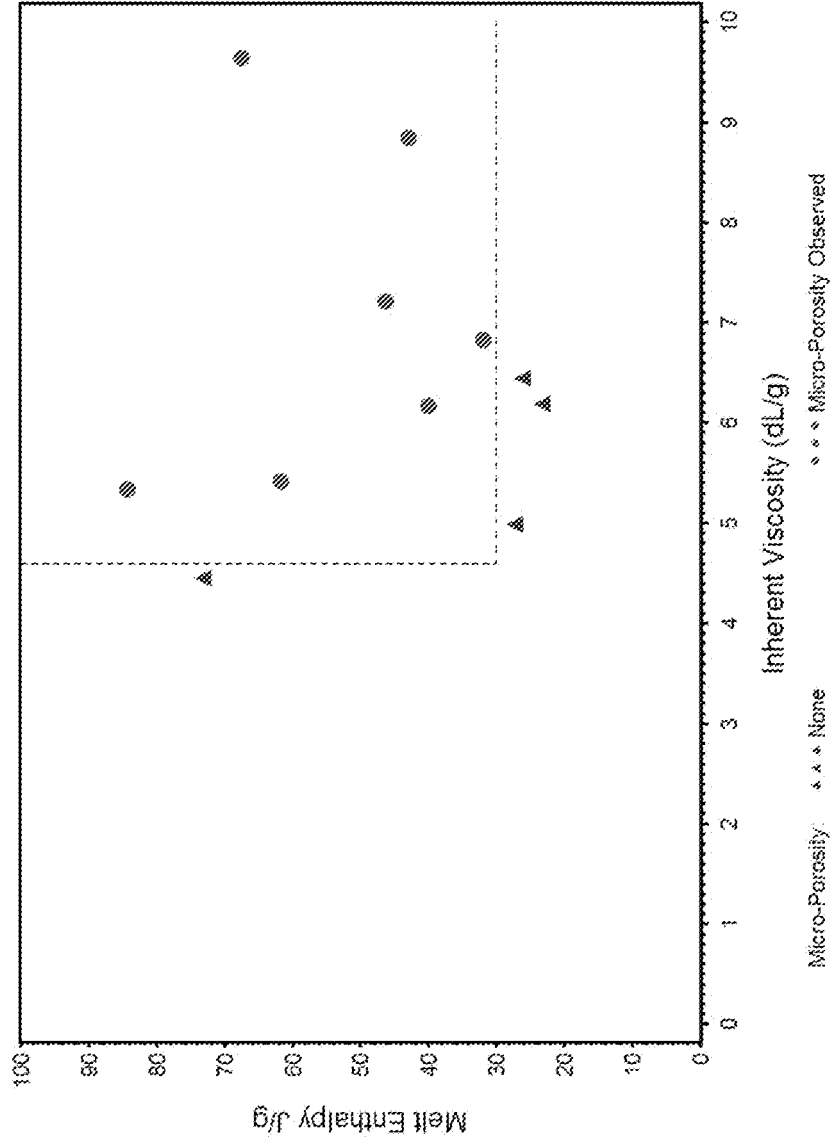


FIG. 15

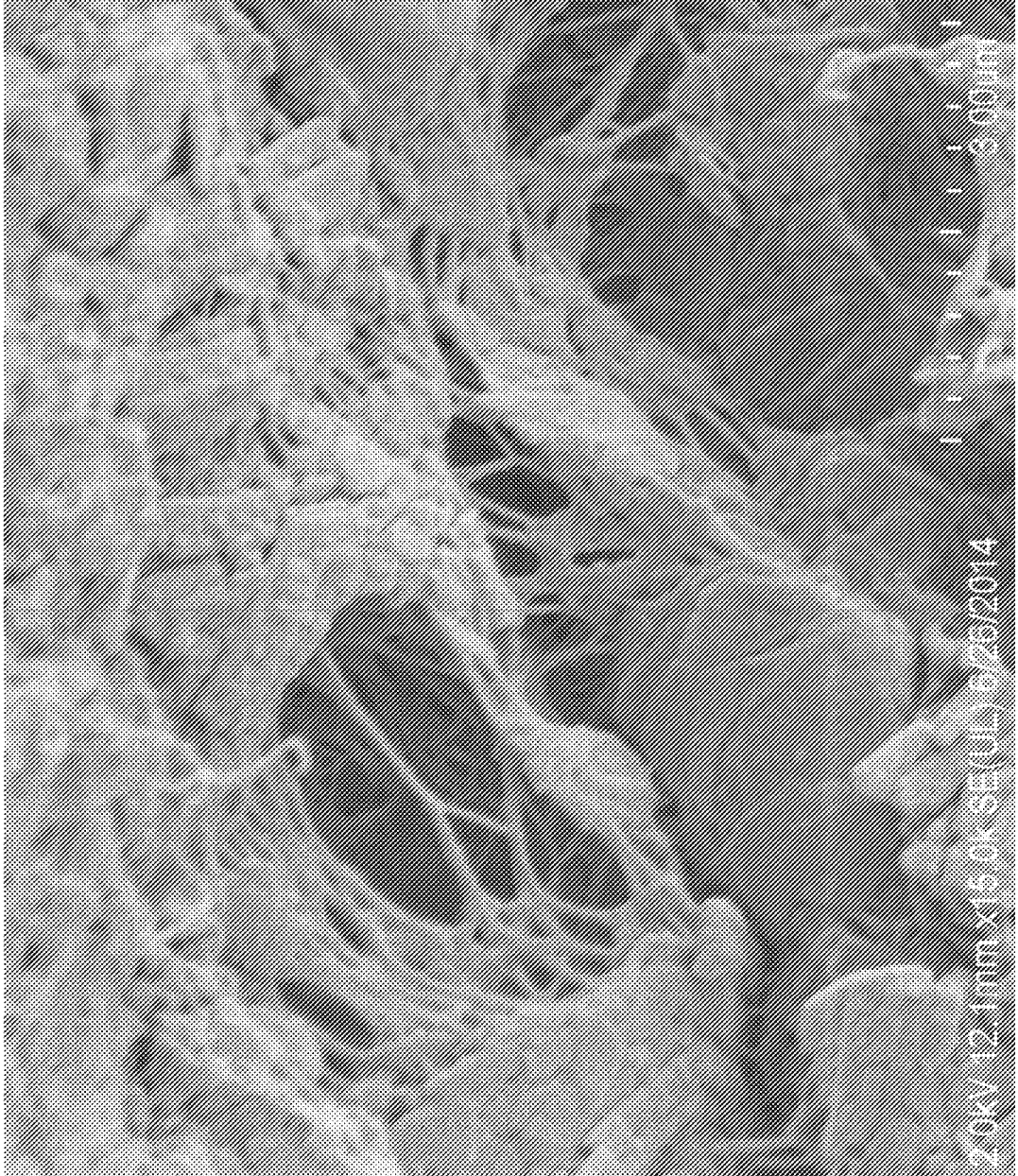


FIG. 16

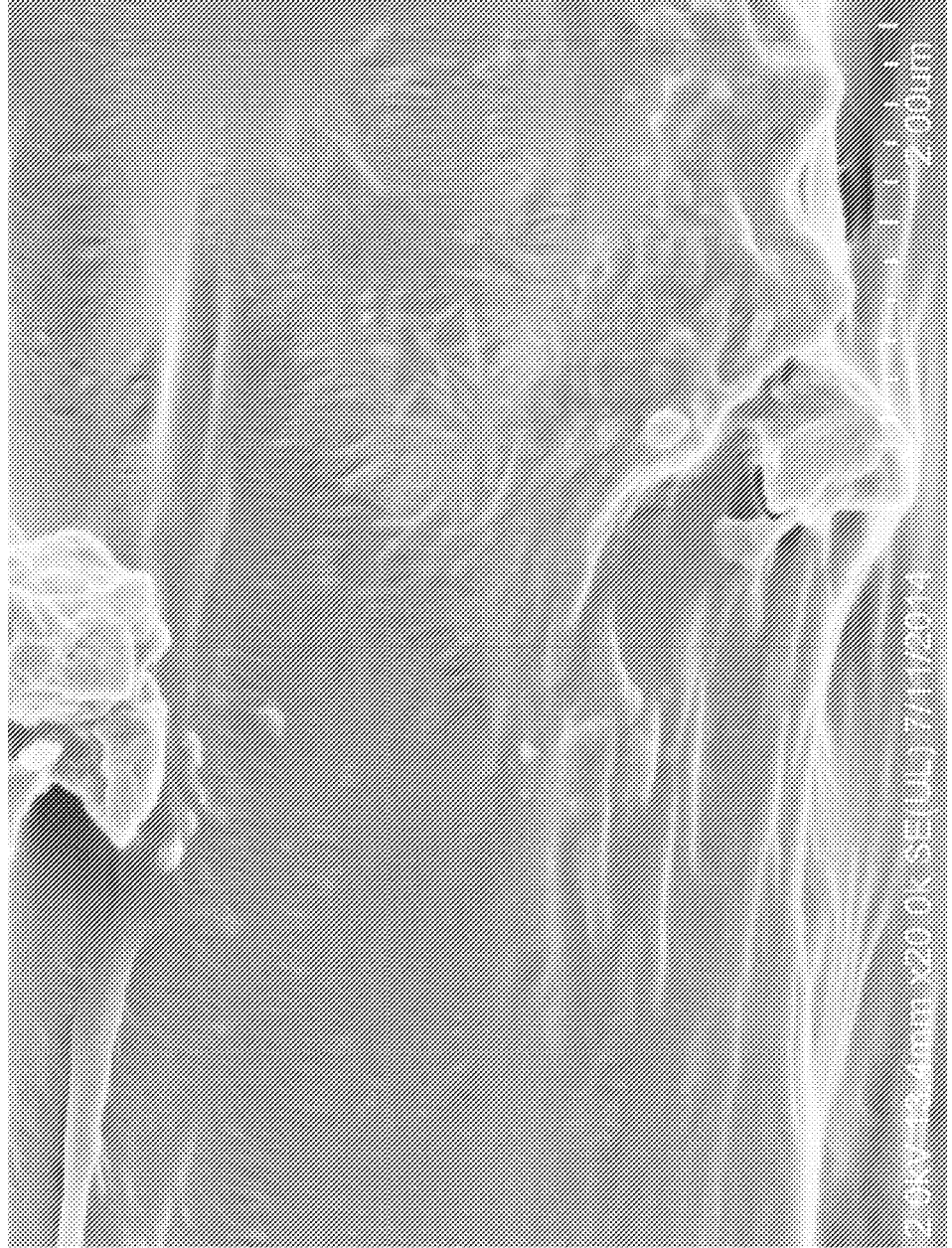


FIG. 17

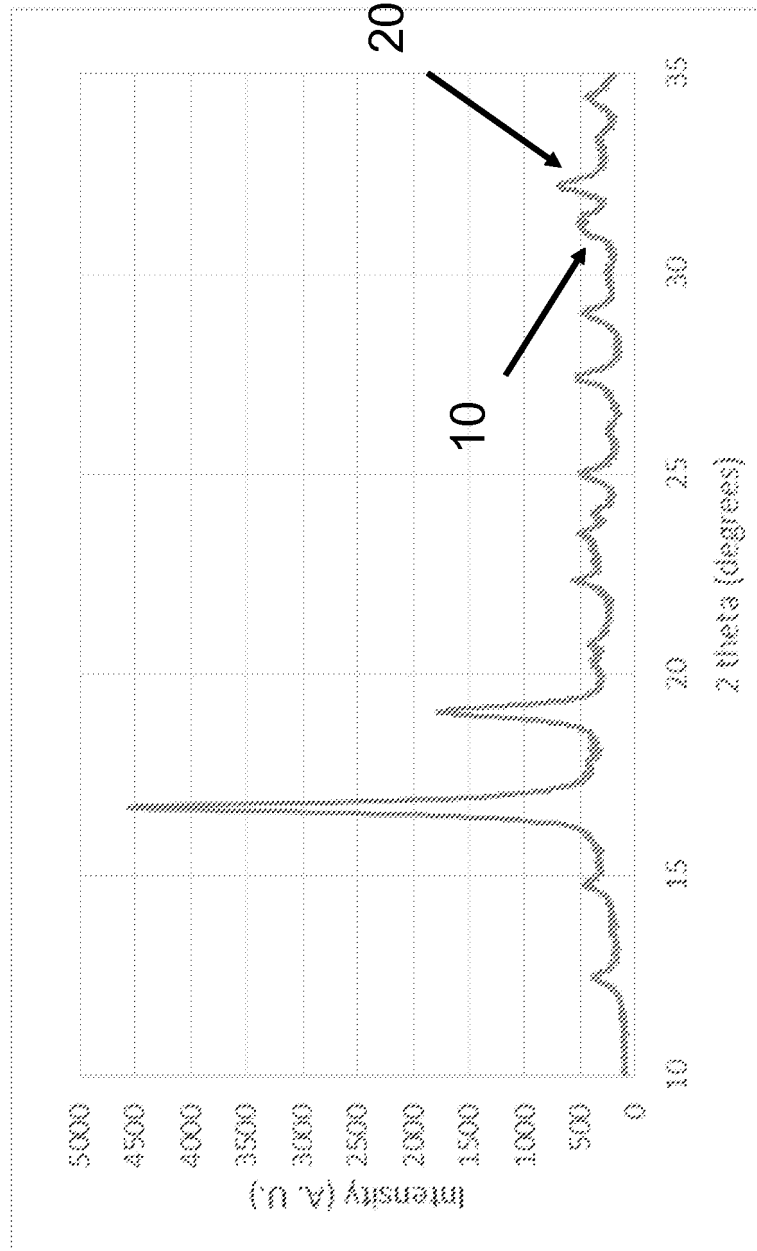


FIG. 18

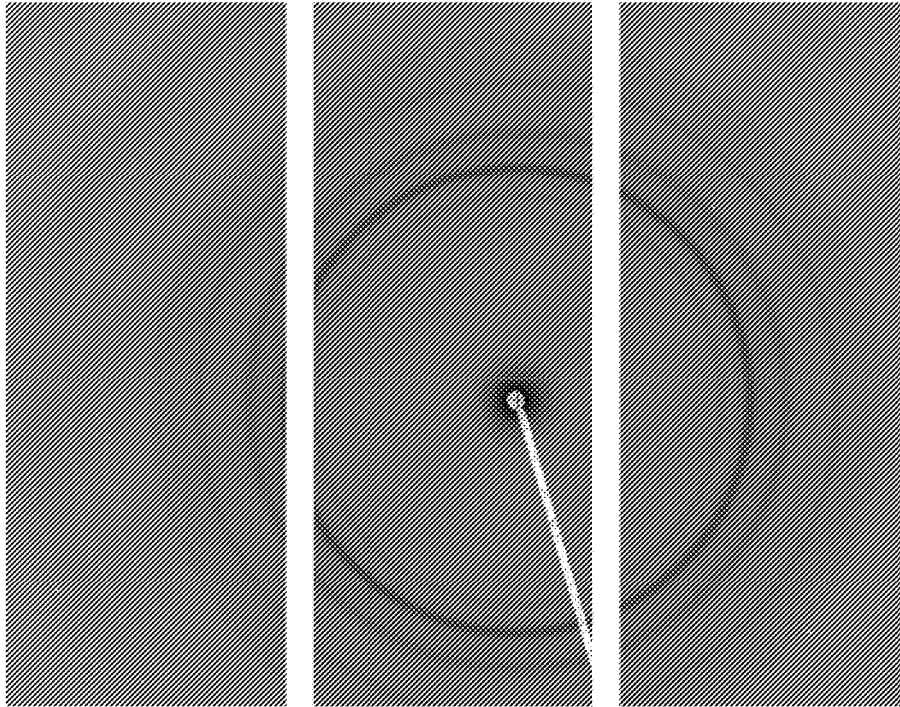


FIG. 19

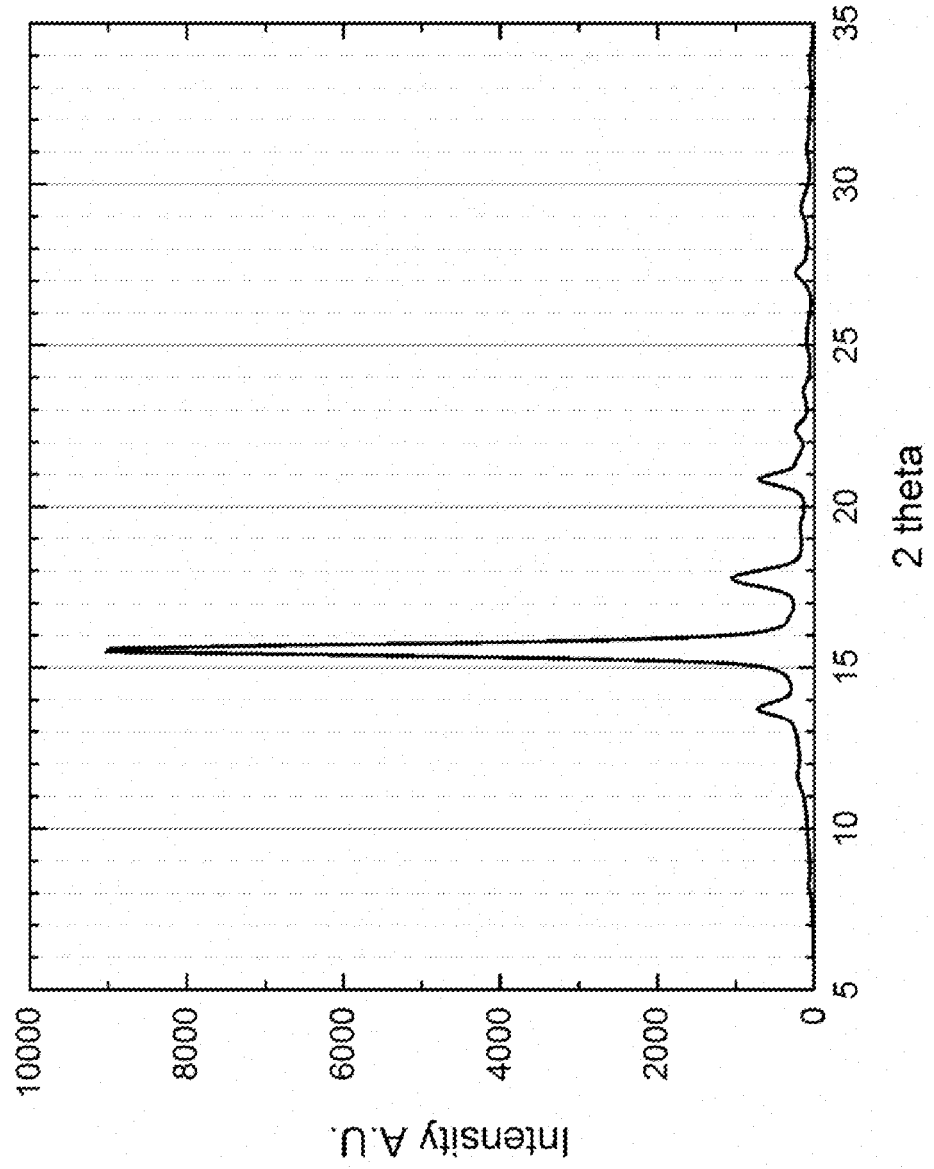


FIG. 20

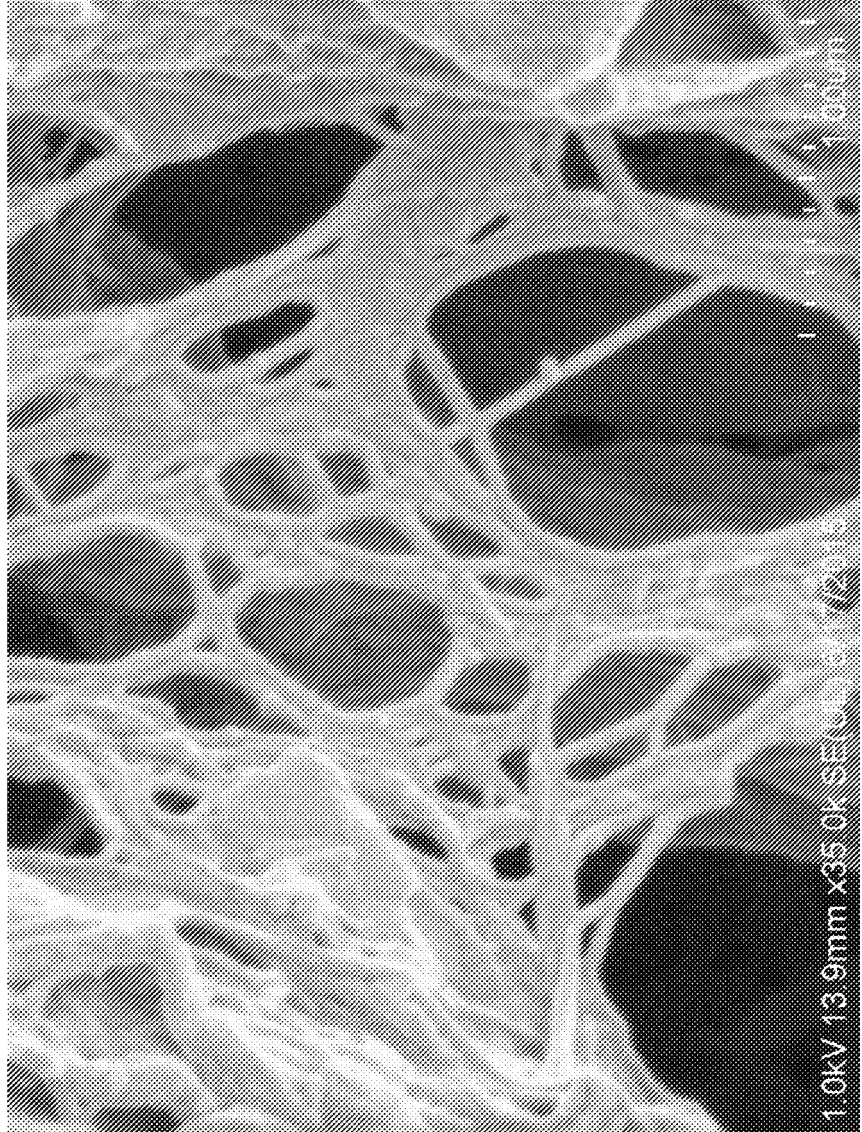


FIG. 21



FIG. 22

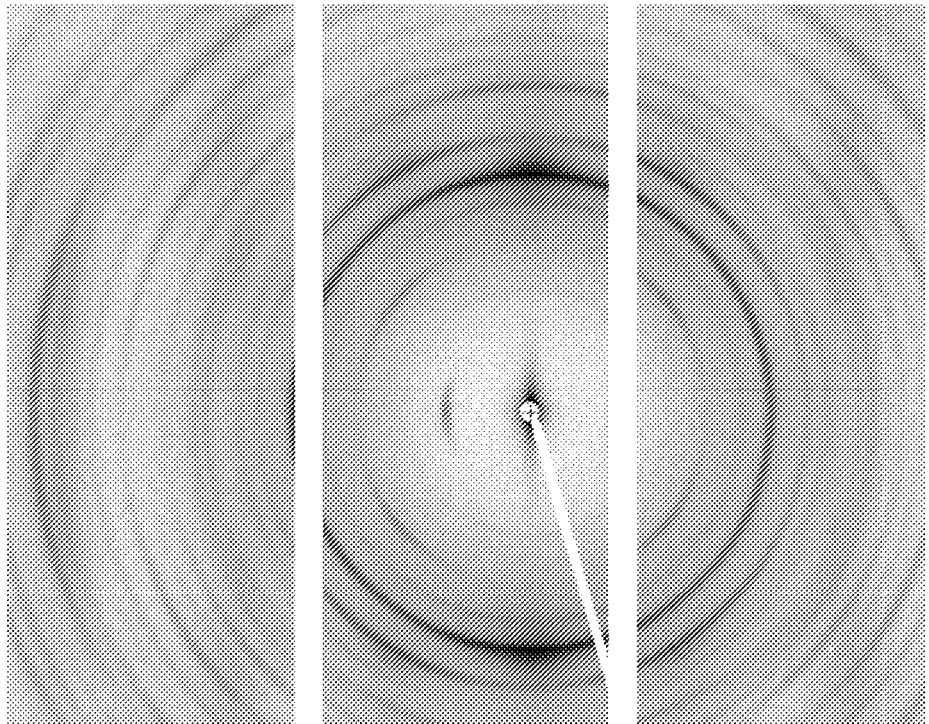


FIG. 23

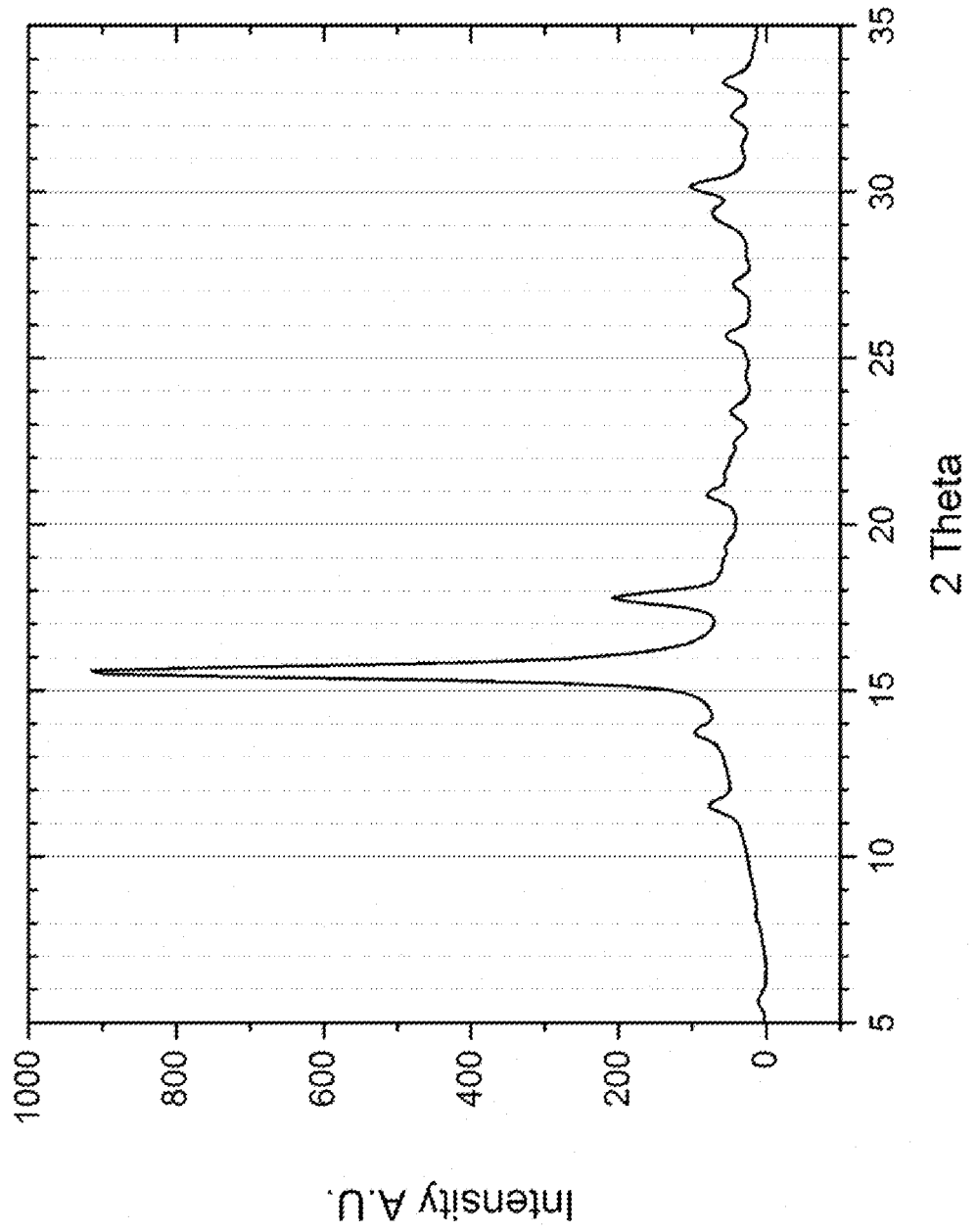


FIG. 24

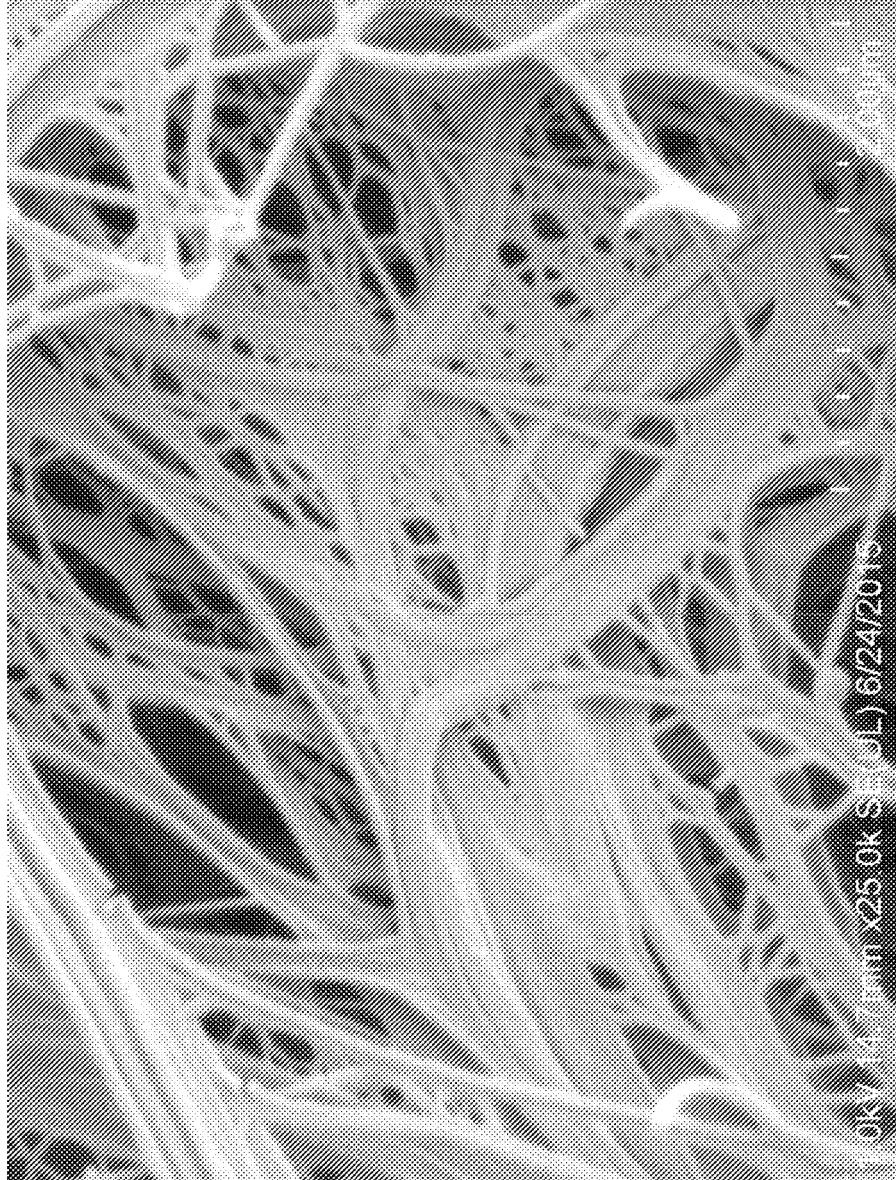


FIG. 25

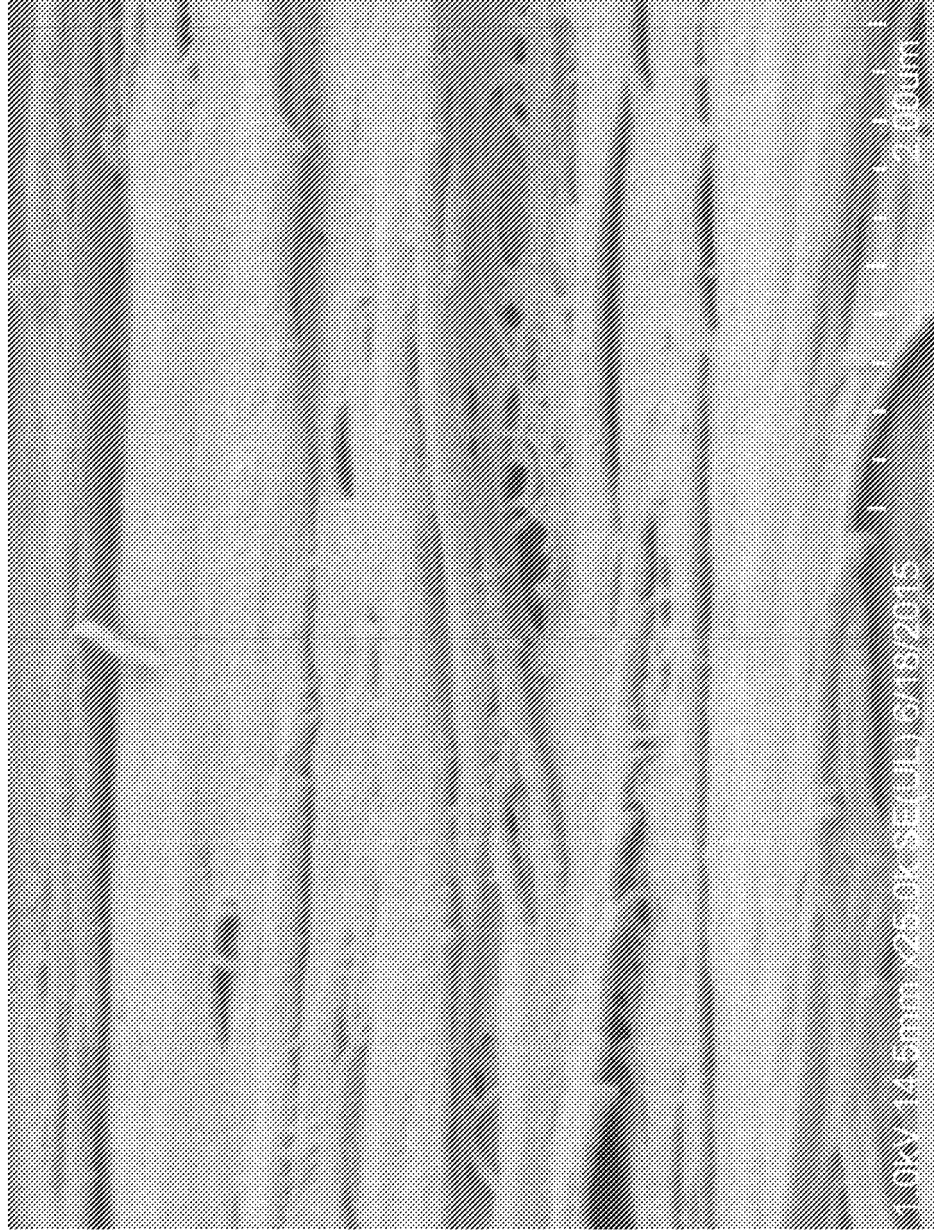


FIG. 26

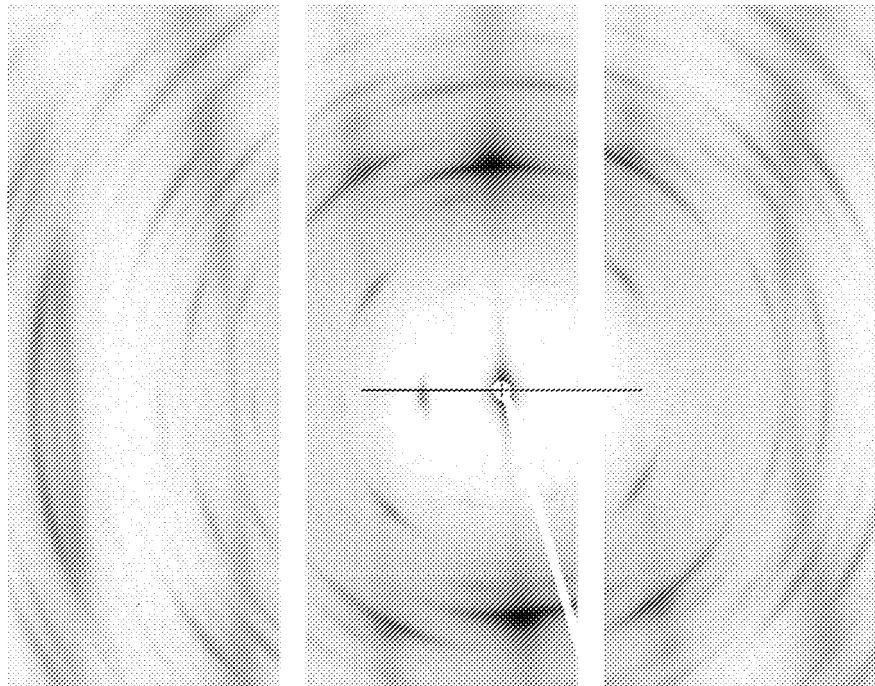


FIG. 27

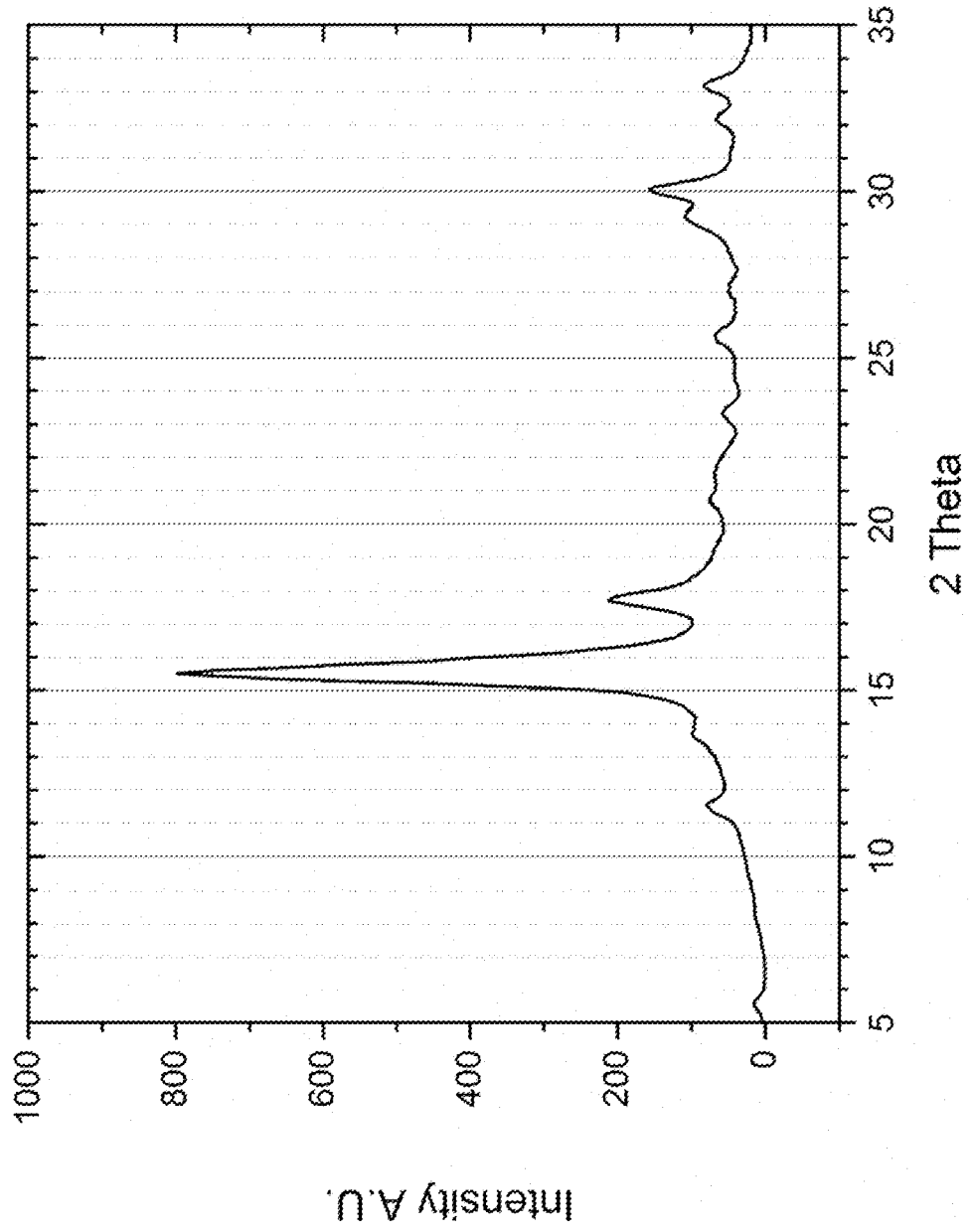
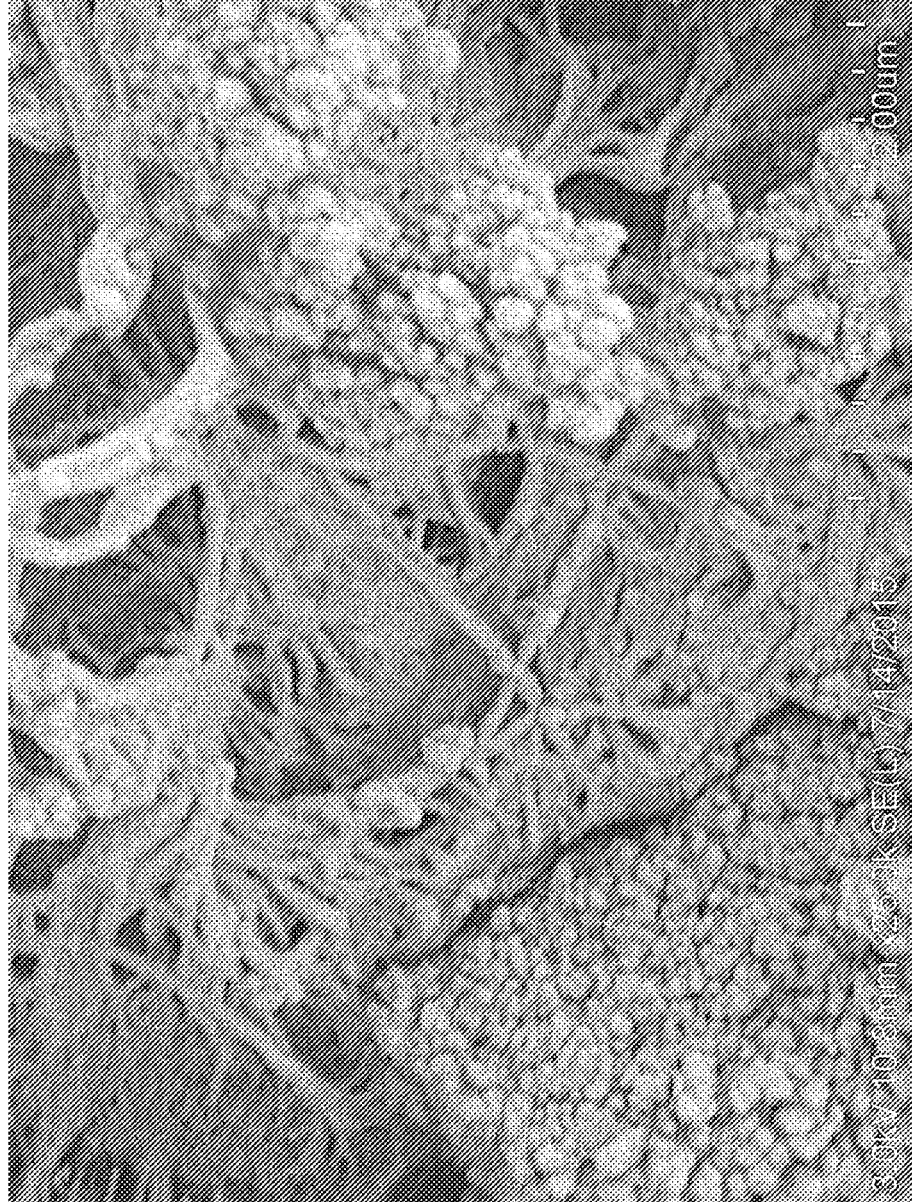


FIG. 28



FIG. 29



REFERENCES CITED IN THE DESCRIPTION

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