

FIBER FORMATION BY ELECTRICAL-MECHANICAL SPINNING

FIELD OF THE INVENTION

[0001] The present invention relates to fiber formation, particularly to fibers of nano dimensions.

BACKGROUND OF THE INVENTION

[0002] Fibers of nano dimensions can be produced by streaming an electrostatically charged liquid such as a polymeric solution through a jet or needle with a very small orifice. Scaling up this process by using multiple needles suffers from the difficulty of electrically isolating these needles from each other. Consequently, needles typically must be at least one centimeter away from the nearest neighbor. In addition, the need to draw a Taylor cone from a single droplet on the end of each needle limits the maximum flow rate per needle and increases the number of needles that are needed to achieve large scale production.

[0003] Therefore, there is a need for a process to manufacture fibers of nano dimensions with high throughput without the need for multiple applicators. The present invention provides such a process.

SUMMARY OF THE INVENTION

[0004] The present invention provides a method of fiber production starting from a liquid material such as a polymer solution or a polymer melt. The liquid material is fed to an annular rotating member such as a disk or cup rotating around an axis concentric therewith. The rotating member has a relatively smooth continuous surface extending from the central area to a periphery. The liquid material is directed by centrifugal force radially from the central area to the periphery and is expelled from the periphery towards a target. Liquid material is electrically charged either by the rotating member or immediately after being expelled from the periphery of the rotating member by passing through an electric field. The target to which the fibers are directed is electrically grounded.

The difference in electrical potential between the charged fibers and the target, the viscosity of the liquid material and the size and speed of the annular member, the liquid delivery rate and the optional use of shaping air are adjusted relative to one another so that the liquid material is expelled in fibrous form. Also adjusting these variables affects the quality and quantity of the fibers.

DETAILED DESCRIPTION

[0005] Preferably, the continuous surface of the annular rotating member is the interior surface of a substantially cylindrical member such as a cup. The sides of the cup may be divergent such that the cup is in the form of a truncated cone. The annular spinning member rotates around an axis concentric therewith. The rotating member may be electrically charged to impart an electrical charge to the liquid material being fed to the rotating member. Alternatively, an electrical charge can be imposed on the liquid material as it is expelled from the rotating member in fibrous form by passing the fibers through an electric field. As the rotating member spins, the liquid material is centrifugally directed along the interior surface towards the periphery of the rotating member. Preferably, spinning points are located along the periphery of the rotating member. Examples of such spinning points are V-shaped serrations extending around the periphery, preferably extending outwardly and substantially parallel to the axis of rotation of the rotating member. The liquid material passes over the spin points and is expelled from the rotating member towards the grounded target. The rotating member may vary in size and geometry. The rotating member may be as a disk or rotating bell. The diameter of the rotating member may vary from 20 mm to 350 mm, such as 20 to 160, such as 30 to 80 mm. For fiber formation, the difference in electrical potential between the charged fibers and the target is preferably at least 5000 volts, such as within the range of 20,000 to 100,000 volts and 50,000 to 90,000 volts. If the electrical potential is insufficient, droplets and not fibers may be formed.

[0006] As the liquid material is expelled from the rotating member in fibrous form, the fibers are directed towards a grounded target where the fibers

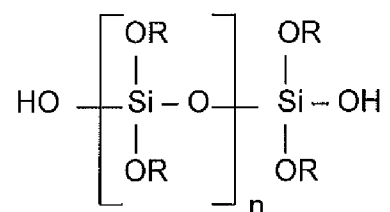
are collected. Alternately, the grounded target can be positioned behind a moving belt or conveyor where the fibers can be collected and removed from the target area. The distance to target can vary from 2 to 50 (5 to 130 cm), such as 2 to 30 inches (5 to 76 cm) such as 10 to 20 inches (25 – 51 cm). Preferably, with a rotating bell an air stream is propelled normally and concurrently against the expelled fibers so as to shape the fibers into a flow pattern concentric with the axis of rotation and towards the target. Typically air exits the rotary applicator via ports that surround the rotating member outside diameter. Air pressure measured at the entrance of the rotating member can typically be set at such as 1 – 80 PSIG (6.9×10^3 – 5.5×10^5 Pascals), such as 1 – 60 PSIG (6.9×10^3 – 4.1×10^5 Pascals) such as from 5 to 40 PSIG (3.4×10^4 – 2.8×10^5 Pascals). With a rotating disk, shaping air is usually not used.

[0007] The rotating member is connected to a drive means such as a rotating drive shaft connected to a member such as an electrical motor or air motor capable of spinning the rotary member at speeds of at least 500 rpm, such as 1000 to 100,000, and 3000 to 50,000 rpms typically with speeds of 10,000 to 100,000 rpms. If the speed of the rotating member is insufficient, fibers may not form and the liquid may be expelled from the rotary member as sheets or globs. If the speed of the rotating member is too high, droplets may form or fibers may break off.

[0008] Typically, the liquid material is passed through the interior of the drive shaft and fed to the rotating member. When the rotating member is cup-shaped, such as a rotating bell, the liquid material is fed through the closed end of the cup and in the central or base area of the cup. Typically, the liquid enters the closed end of the cup through a supply nozzle that may range in size from 0.5 to 1.5 mm. The liquid can then travel through the inside of the cup and exits on the surface of the cup through a center orifice or series of orifices onto the cup face.

[0009] The flow rate of liquid material to the rotating member is typically 1 ml/hour to 500 ml/minute, such as from 20 ml/hour to 50 ml/minute such as from 50 to 1000 ml/hour.

[0010] The liquid material that is spun into fibers in accordance with the invention is typically a polymer solution or melt. The polymers can be organic polymers such as polyesters, polyamides, polymers of n-vinyl pyrrolidone, polyacrylonitrile and acrylic polymers such as are described in published application U.S. 2008/0145655A1. Alternately, the liquid can be an inorganic polymer. Examples of inorganic polymers are polymeric metal oxides that contain alkoxide groups and optionally hydroxyl groups. Preferably, the alkoxide groups contain from 1 to 4 carbon atoms such as methoxide and ethoxide. Examples of such polymeric metal oxides are polyalkylsilicates such as those of the following structure:



where R is alkyl containing from 1 to 4, preferably from 1 to 2 carbon atoms, and n is 3 to 10.

[0011] Also, hybrid organic/inorganic polymers such as acrylic polymers and polymeric metal oxides can be employed. Examples of such organic/inorganic hybrid polymers are described in published application U.S. 2008/0207798A1. Also, inorganic materials such as inorganic oxides or inorganic nitrides or carbon or ceramic precursors, such as silica, alumina, Titania, or mixed metal oxides can be used.

[0012] The electrical conductivity of the liquid material can vary and should be sufficiently electrically conductive such that it can accept a charge build up but not to the point that electrical shorting occurs. With indirect charging, the electrical conductivity can be high since shorting is not a problem. The electrical conductivity can be adjusted by using appropriate amounts of salts such as ammonium salts and electrically conductive solvents such as alcohol-water mixtures.

[0013] The surface tension of the liquid material can vary. If the surface tension is too high, atomization and droplets rather than fibers may be formed.

[0014] The liquid preferably thickens as polymer concentration increases or polymer crosslinking occurs. In the case of a polymer solution, the viscosity of the solution can be controlled by controlling the molecular weight of the polymer, the concentration of the polymer in the solution, the presence of crosslinking of the polymer in solution, or by adding a thickening agent to the polymer solution such as polyvinyl pyrrolidone, polyvinyl alcohol, polyvinyl acetate, polyamides and a cellulosic thickener. If the viscosity of the solution is too high, i.e., at its gel point or above, it behaves more like a solid material and may not form a fiber and may build up as solid polymer on the surface of the rotating member. If the viscosity of the liquid is too low, atomization and not fiber formation may result.

[0015] The fibers that are formed in accordance with the invention typically have diameters of up to 5,000 nanometers, such as 5 to 5,000 nanometers or within the range of 50 to 1200 nanometers such as 50 to 700 nanometers. Fibers can also have ribbon or flat face configuration and in this case the diameter is intended to mean the largest dimension of the fiber. Typically, the width of ribbon-shaped fibers is up to 5,000, such as 500 to 5,000 nanometers, and the thickness is up to 200, such as 5 to 200 nanometers.

[0016] In certain instances the nanofibers can be twisted around each other in a yarn-like structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIG. 1 is a schematic vertical cross-section through a centrifugal spinning apparatus in which the process of the invention may be practiced.

[0018] FIG. 2 is a bottom elevation of a spinning member in accordance with the process of the invention.

[0019] FIG. 3 is a section along line III-III of FIG. 2.

[0020] FIG. 4 shows photomicrographs at various magnifications of nanofibers prepared in accordance with Example 1.

[0021] FIG. 4a (comparative) shows photomicrographs at various magnifications of droplets prepared in accordance with Example 1a (comparative).

[0022] FIG. 5 is a chart showing how the variables of rotating member speed, shaping air and liquid flow effect fiber formation for the polymer solutions of Examples 1 and 1a (comparative).

[0023] FIG. 6 shows photomicrographs at various magnifications of nanofibers prepared in accordance with Example 2.

[0024] FIG. 6a (comparative) shows photomicrographs at various magnifications of droplets prepared in accordance with Example 2a (comparative).

[0025] FIG. 7 is a chart showing how the variables of rotating member speed, shaping air and liquid flow effect fiber formation for the polymer solutions of Examples 2 and 2a (comparative).

[0026] FIG. 8 shows photomicrographs at various magnifications of nanofibers prepared in accordance with Example 3.

[0027] FIG. 8a (comparative) shows photomicrographs at various magnifications of droplets prepared in accordance with Example 3a (comparative).

[0028] FIG. 9 shows photomicrographs at various magnifications of nanofibers in the form of a twisted yarn prepared in accordance with Example 4.

[0029] FIG. 10 shows photomicrographs at various magnifications of nanofibers prepared in accordance with Example 5.

[0030] With reference to FIG. 1, the apparatus 1 contains a cup-shaped rotating member 5 and an air plenum arrangement 7 through which air is directed to shape the fibrous stream 9 as it is directed towards the target 11. Positioned before the target is a conveyor 12 for removing the fibrous product from the apparatus 1. A container 13 for the liquid material 15 includes a suitable feed mechanism (not shown) for feeding the liquid material to the rotating cup 5 via a feed supply line 17 mounted concentrically with the axis 3. The supply line 17 has an exit in the rotating cup 5 adjacent to closed end.

Preferably, the feed supply line is located within a rotating drive shaft for rotating the cup-shaped rotary member 5. As shown in FIG. 1, a voltage is imposed on the rotating cup to impart a charge on the liquid material and the fibers that are expelled from the rotating cup.

[0031] With references to FIGS. 2 and 3, the rotating member 5 is cup-shaped having a planar base or closed end 21 and divergent walls 23 extending from the base 21. The base 21 has a central aperture 25 through which the feed supply line extends and fixing elements 27 by which the rotating cup 5 is mounted on the drive means for rotation around the axis 3. The interior surface 29 of the wall 23 is relatively smooth over the region extending from the base 21 to the edge 31 of the cup 5. The edge of the cup 5 is serrated such that there are spinning points 33 defined by V-shaped serrations 35 on the external periphery of the cup 5. V-shaped serrations 35 lie in a plane parallel to the base of the cup 5. In using apparatus 1, the cup 5 is spun at the desired rate and the liquid is fed to the rotating cup in the central area of the base of the cup and is directed to the periphery of the base 21 and across the interior surface 29 by centrifugal force. The liquid that is electrically charged flows across the interior surface 29 of the rotating cup through the spinning points 33 from which the liquid is expelled in fibrous form towards the grounded target 11.

[0032] The following examples are presented to demonstrate the general principles of the invention. However, the invention should not be considered as limited to the specific examples presented. All parts are by weight unless otherwise indicated.

EXAMPLES

EXAMPLE A

[0033] An acrylic-silane polymer was prepared as follows.

[0034] With reference to Table 1 below, a reaction flask was equipped with a stirrer, thermocouple, nitrogen inlet and a condenser. Charge A was then added and stirred with heat to reflux temperature (75°C-80°C) under nitrogen atmosphere. To the refluxing ethanol, Charge B and Charge C were

simultaneously added over three hours. The reaction mixture was held at reflux condition for two hours. Charge D was then added over a period of 30 minutes. The reaction mixture was held at reflux condition for two hours and subsequently cooled to 30°C.

TABLE 1

	Example A
<u>Charge A (weight in grams)</u>	
Ethanol SDA 40B ¹	477.5
<u>Charge B (weight in grams)</u>	
Methyl Methacrylate	0.2
Acrylic acid	11.5
Silquest A-174 ²	134.4
2-hydroxyethylmethacrylate	45.8
n-Butyl acrylate	0.2
Acrylamide	7.2
Ethanol SDA 40B	206.5
<u>Charge C (weight in grams)</u>	
Vazo 67 ³	8.1
Ethanol SDA 40B	101.7
<u>Charge D (weight in grams)</u>	
Vazo 67	2.0
Ethanol SDA 40B	12.0
% Solids	21.3
Acid value (solution)	10.5

¹ Denatured ethyl alcohol, 200 proof, available from Archer Daniel Midland Co.

² gamma-methacryloxypropyltrimethoxysilane, available from GE silicones.

³ 2,2'-azo bis(2-methyl butyronitrile), available from E.I. duPont de Nemours & Co., Inc.

[0035] A hybrid organic-inorganic polymer was prepared as follows:

[0036] The ethanol solution of acrylic-silane polymer solution, prepared as described above, 200 grams, was poured into a jar, and deionized water (30 grams) was added. An ethanol solution of ethyl polysilicate (Silbond 40, Akzo Chemical, Inc) was added to the polymer solution along with polyvinylpyrrolidone (4 grams, Aldrich, Catalog 437190, CAS [9003-39-8], and MW 1,300,000). While warming the jar with hot tap water, the mixture was hand shaken, and hand stirred with a spatula until a homogeneous solution was obtained. After this solution was allowed to stand at room temperature for about 3.5 hours, its viscosity of was determined to be C⁺ by the method of ASTM-D1545.

EXAMPLE B

[0038] An acrylic-silane polymer was prepared as follows.

[0039] With reference to Table 2 below, a reaction flask was equipped with a stirrer, thermocouple, nitrogen inlet and a condenser. Charge A was then added and stirred with heat to reflux temperature (75°C-80°C) under nitrogen atmosphere. To the refluxing ethanol, Charge B and Charge C were simultaneously added over three hours. The reaction mixture was held at reflux condition for two hours. Charge D was then added over a period of 30 minutes. The reaction mixture was held at reflux condition for two hours and subsequently cooled to 30°C.

TABLE 2

	Example A
<u>Charge A (weight in grams)</u>	
Ethanol SDA 40B ¹	288.0
<u>Charge B (weight in grams)</u>	
Methyl Methacrylate	16.0
Acrylic acid	6.9
Silquest A-174 ²	81.1
2-hydroxyethylmethacrylate	0.1
n-Butyl acrylate	0.1
Glycidyl Methacrylate	11.6
Ethanol SDA 40B	124.5
<u>Charge C (weight in grams)</u>	
Vazo 67 ³	49.0
Ethanol SDA 40B	61.1
<u>Charge D (weight in grams)</u>	
Vazo 67	1.2
Ethanol SDA 40B	7.2
% Solids	18.5
Acid value (solution)	8.9

¹ Denatured ethyl alcohol, 200 proof, available from Archer Daniel Midland Co.

² gamma-methacryloxypropyltrimethoxysilane, available from GE silicones.

³ 2,2'-azo bis(2-methyl butyronitrile), available from E.I. duPont de Nemours & Co., Inc.

[0040] Deionized water (30 grams) was pored into a jar, and polyvinylpyrrolidone (4 grams, Aldrich, Catalog 437190, CAS [9003-39-8], and MW 1,300,000) was added. The mixture was warmed on a hotplate to promote dissolution, and the resulting solution was allowed to stand at room temperature. The acrylic-silane polymer solution, 170 grams, was added to this aqueous polyvinylpyrrolidone solution. While heating the contents of the jar with warm

water on a hot plate, the mixture was hand shaken until a homogeneous solution was obtained. This organic polymer solution was allowed to stand at room temperature to cool before use.

EXAMPLE C

[0041] An inorganic sol gel polymer was prepared as follows.

[0042] Deionized water (36 grams) was placed in a jar, and polyvinyl alcohol (4 grams, Aldrich, Catalog 36311, CAS [9002-89-5], 96% hydrolyzed, and MW 85,000-100,000) was added to the water while stirring magnetically. This mixture was warmed to 80 °C in a hot water bath to affect dissolution. More deionized water (40 grams) was added to this warm aqueous polyvinyl alcohol solution while continuing to stir. To this warm, diluted aqueous polyvinyl alcohol solution was added colloidal silica dispersion (120 grams, MT-ST Silica, Nissan Chemical Industries, LTD., about 30% silica in methanol) while continuing to stir. Viscosity of this polyvinyl alcohol, silica solution was determined to be A* by the method of ASTM-D1545.

EXAMPLE D

[0043] A solution of polyacrylonitrile was prepared by dissolving 12 weight percent of polyacrylonitrile resin (Aldrich, Catalog 181315, CAS [25014-41-9], MW 150,000) in dimethylformaldehyde solvent while warming on a hot plate.

EXAMPLE 1

[0044] The polyacrylonitrile resin solution of Example D was loaded into a 300 ml positive pressure fluid delivery system. A rate of 300 milliliters per hour was fed through a 3/8 inch (9.5 mm) outside diameter teflon tube system to a rotary spray applicator via a 1.1 mm diameter fluid nozzle. The outlet of the nozzle was connected to a rotary bell cup 55 mm in diameter. The fluid nozzle inserts to the back of the bell cup where approximately 80-100% of the fluid exits through a circular slit of approximately 40mm diameter. The fluid then forms a thin sheet across the bell cup and spins off the edge of the rotary bell cup to form

fibers. This rotary bell was set to spin at a rate of 12,000 rpms. The bell cup edge geometry is configured with straight serrations. The perpendicular distance from the circular slit to the edge of the bell cup is approximately 7.85 cm. The bell cup referred to in this experiment is a Durr Behr Eco bell cup model N16010037 type. The bell shaping air was set at 25 psig (1.72×10^5 Pascals) at the back of the bell via a ½ inch (12.7 mm) outside diameter nylon tube. The rotary applicator was connected to a high voltage source with a 75,000 Volt indirect charge applied potential. The entire delivery tube, rotary applicator and collector were in a booth that allowed the environmental condition to maintain a relative humidity of approximately 55% to 60% at a room temperature of 70°F to 72°F (21°C – 22°C). Nanofibers were collected on the grounded target onto aluminum panels set at a target / collection distance of 15 inches (38 cm) from the rotary bell and were characterized by optical microscopy and scanning electron microscopy. The nanofibers were essentially cylindrical and had diameters of 600 to 1800 nanometers (nm). Some large diameter fibers were observed that appear to be assemblies of the smaller diameter fibers. The scanning electron micrograph is shown in Figure 4 and shows many fibers with little or no drops.

[0045] A Design Analysis was completed for the solution of Example 1 to determine application factors with respect to this solution. The application factors studied for this work were bell speed from 12K rpms to 28K rpms, target distance from 10 inches to 20 inches (25.4 – 50.8 cm), voltage from 60KV to 90KV, fluid delivery rate from 100ml/ hour to 300 ml/ hour and bell shaping air from 15psig to 35psig (1.03×10^5 – 2.41×10^5 Pascals). The results reported in Figure 5 showed that fluid delivery rate, shaping air, and bell speed were the most influential application factors followed by target distance and KV.

[0046] In Figure 5 “BS” refers to Bell Speed”. “SA” refers to Shaping Air. “FF” refers to Fluid Delivery Rate.

[0047] The values of the vertical axis are the product of the thickness of the nanofiber mat that is formed multiplied by the ratio of nanofiber to drops.

The thickness of the mat is given a subjective value of 1 to 10 and the ratio of nanofibers to drops is given a subjective value of 1 to 6.

[0048] The higher the number of the value on the vertical axis, more volume of good fibers is generated.

EXAMPLE 1A (Comparative)

[0049] In this example, the procedure of Example 1 was repeated with the following differences:

Bell Speed	28,000 rpms
Target collector distance	10 inches (25.4 cm)
Fluid delivery rate	200 ml/hour

[0050] Nanofibers were attempted to be collected on the grounded aluminum target onto aluminum panels set at a part / collection and were characterized by scanning electron microscopy as shown in Figure 4a. The electron microscopy shows very little fiber formation and many wet drops.

EXAMPLE 2

[0051] The hybrid organic – inorganic polymer solution of Example A was spun into nanofibers in accordance with the procedure of Example 1, but using a Dur Behr Eco bell cup model N16010033. The nanofibers were characterized by optical microscopy and scanning electron microscopy. The nanofibers were somewhat flat-faced with cross-sectional dimensions that ranged from 700 nanometers (nm) to 5000 nm. The scanning electron micrograph is shown in Figure 6 and shows many fibers with little or no wet drops.

EXAMPLE 2A (Comparative)

[0052] In this example, the procedure of Example 2 was generally followed with the following differences:

Bell Speed	28,000 rpms
Target/collector distance	10 inches (25.4 cm)
Fluid delivery rate	200 ml/hour

Nanofibers were attempted to be collected on the grounded aluminum panel target and were characterized by scanning electron microscopy as shown in Figure 6A. This electron microscopy shows very little fiber formation and many wet drops.

[0053] A Design Analysis as described in Example 1 was completed for the solution of Example 2. The application factors studied for this work were bell speed from 12K rpms to 28K rpms, target distance from 10 inches to 20 inches (25.4 – 38.1 cm), voltage from 60KV to 90KV, fluid delivery rate from 100 ml/hour to 300 ml/hour and bell shaping air from 15 psig to 35 psig (1.03×10^5 – 2.41×10^5 Pascals). The results reported in Figure 7 showed that fluid delivery rate, shaping air, bell speed and target distance were the most influential followed by KV. Figure 7 uses the same terminology as used in Figure 5.

EXAMPLE 3

[0054] The inorganic sol gel polymer solution of Example C was spun into nanofibers in accordance with the procedure of Example 2 using a fluid delivery rate of 100 milliliters per hour, a spin rate of 28,000 rpms, a voltage of 90,000 volts and a target collector distance of 20 inches (50.8 cm). The bell shaping air was set at 15 psig (1.03×10^5 Pascals) at the back of the bell. Nanofibers were collected on the grounded aluminum panel target and were characterized by optical microscopy and scanning electron microscopy.

[0055] The nanofibers were essentially cylindrical and had diameters of 100 to 700 nm. Some of the fibers appeared to have small beads along the linear axis that had not drawn into a fiber. The scanning electron micrograph is shown in Figure 8 and shows many small fibers with little drop formation.

EXAMPLE 3A (Comparative)

[0056] In this example, the procedure of Example 3 was repeated with the following differences:

Bell Speed	12,000 rpms
Fluid flow rate of	300 ml/hour

Target collector distance 10 inches (25.4 cm)
Shaping air 35 psig (2.4×10^5 Pascals)

[0057] Nanofibers were attempted to be collected on the grounded aluminum target and were characterized by scanning electron microscopy as shown in Figure 8A. The electron microscopy shows little fibers with wet drops.

EXAMPLE 4

[0058] The polyacrylonitrile resin solution of Example D was spun into fiber in accordance with the procedure of Example 1 using a voltage 86,000. Fibers were collected on the grounded aluminum panel target and were characterized by optical microscopy and scanning electron microscopy. Large fibers collected on the panel. One large fiber was removed from the panel and was evaluated microscopically as shown in Figure 9. A low resolution optical image (left-most image) indicated that the large fiber might be an assembly of smaller fibers. Scanning electron microscopy (center image) revealed that these large fibers are a twisted yarn 100 microns in diameter comprised of several much smaller fibers. The yarn is formed as the smaller fibers rotate from the spinning bell cup. Higher magnification (right-most image) revealed that these smaller fibers are nano-scale in diameter within the yarn.

EXAMPLE 5

[0059] The organic polymer solution of Example B was spun into fibers in accordance with the procedure of Example 1 with the following differences:

Fluid flow rate 200 ml/hour
Shaping air 35 psig (2.41×10^5 Pascals)
Target collector distance 20 inches (50.8 cm)

The nanofibers were somewhat flat-faced with cross-sectional dimensions and had diameters of 300 to 700 nm. The scanning electromicrograph is shown in Figure 10. The micrograph shows many small fibers with little drop formation.

[0060] The invention is now set forth in the following claims.

WHAT IS CLAIMED IS:

1. A method of fiber production from a liquid material comprising
 - a. feeding the liquid material to a rotating annular member having an interior surface extending to an open end and a periphery around the open end,
 - b. directing the liquid material by centrifugal force along the interior surface towards the periphery of the rotating member, and
 - c. expelling the liquid material from the periphery towards a target in fibrous form;wherein the liquid material is electrically charged and the target is grounded.
2. The method of claim 1 in which the rotating annular member has a base or closed end and walls having the interior surface extending from the base or closed end to an open end and a periphery around the open end.
3. The method of claim 2 in which the liquid material is directed by centrifugal force along the base and across the interior surface of the walls toward the periphery of the rotating member.
4. The method of claim 1 in which the liquid material is in the form of a polymer solution or a polymer melt.
5. The method of claim 4 in which the polymer solution or polymer melt comprises an organic polymer, an inorganic polymer or a hybrid organic/inorganic polymer.
6. The method of claim 1 in which the fibers have a diameter of 5 to 5,000 nanometers.

7. The method of claim 3 in which the fibers have a diameter of 50 to 1200 nanometers.
8. The method of claim 1 in which the nanofibers are twisted together in the form of a twisted yarn.
9. The method of claim 3 in which the annular member is in the form of a truncated cone.
10. The method of claim 3 in which the rotating member is positioned in the front end of a hollow drive shaft that rotates therewith.
11. The method of claim 10 in which a feed tube for the liquid material extends through the hollow drive shaft and into the central area of the rotating member for the supply of liquid material to the rotating member.
12. The method of claim 3 in which the rotating member has spinning points located on its periphery.
13. The method of claim 12 in which the spinning points are V-shaped serrations.
14. The method of claim 13 in which the serrations extend outwardly from the periphery of the rotating member and are substantially parallel to the axis of rotation.
15. The method of claim 3, which further includes propelling an airstream normally against the expelled fibers so as to shape the fibers into a flow pattern concentric with the axis of rotation of the rotating member and towards the target.

16. The method of claim 15 in which the air stream is generated at a pressure of 1 to 60 PSIG (6.9×10^3 - 4.1×10^5 –Pascals).
17. The method of claim 3 in which the fibers are collected on the target.
18. The method of claim 17 distance from the periphery of the rotating member to the target is from 2 to 30 inches (5 – 76 cm).
19. The method of claim 1 in which the fibers are collected on an intermediate surface located between the target and the rotating member.
20. The method of claim 1 in which the rotating member is rotating at a speed of 1000 to 100,000 revolutions per minute.
21. The method of claim 1 in which the electrical potential between the expelled liquid material and the grounded target is at least 5000 volts.