

APPARATUS FOR ELECTROSTATIC DEPOSITION OF MATERIALS

Field of the Invention

The present invention relates to a method and apparatus used in electrostatic
5 deposition of materials.

Background

There are a number of applications that involve electrostatic deposition of materials, e.g. electrospinning or electrospraying. Electrospinning, i.e., electrostatic
10 spinning, is a process for manufacturing non-woven fiber fabrics. In a typical electrospinning process, an electrostatic field is applied to a capillary filled with a conducting fluid. The electrostatic field causes a suspended conical droplet of conducting fluid to form at the tip of the capillary. When the electrostatic field is sufficiently strong to overcome the surface tension of the droplet, the droplet
15 becomes unstable and a jet of fluid is ejected from the surface of the droplet. These resulting jets of fluids (i.e. fibers) are then collected on a target, for example, a plate. These fibers can be collected as an interconnected web of fibers on the plate. The resulting films/membranes from the web of fibers have very large surface area to volume ratios. Electrospun products can find wide applications in the industrial,
20 military, consumer, health care, and environmental areas. Recently, there has been increasing interest in exploiting this technology in the emerging area of bionanotechnology, which focuses on dimensions of fibers (at least in 1-D) in the nanometer scale, thus defined as nanofibers

Various issues relating to the electrospinning process, for example, obtaining
25 aligned nanofibers and increasing productivity during manufacturing remain challenges to be addressed. Fibers produced by electrospinning come normally in a non-woven fashion. In practice, obtaining aligned nanofibers or yarns, like in the mass production of conventional microfibers, is difficult because the spin line is generated in a very complex three-dimensional whipping manner rather than in a
30 straight line. However, for practical applications, having nanofibers arranged in an orderly array is desired in some circumstances. For example, it is often required to

have aligned fiber yarns as composite reinforcement in order to take advantage of its designable characteristics. The resultant composites have special strength/stiffness properties in a certain load-bearing direction due to the alignment of the fiber yarns. One such application is that of prosthetic vascular grafts where directional bias of fibers with respect to the tubular axis is required to mimetically obtain anisotropic vascular grafts with improved burst strength. Another application is that of forming nanofibrous scaffolds for tissue engineering.

Productivity is another critical issue in electrospinning process which needs to be resolved. Due to the thinness of nanofiber, it usually takes a few hours to a day to have a nanofibrous mat with hundreds of microns in thickness because of a low deposition rate of ca. 1g/hr. The low yield in manufacturing is one of the most important reasons which limit the industrialization and commercialization of this technology. One method of improving the production is to adopt the concept of multiple spinnerets. In such electrospinning apparatus, uniformity of fiber distribution is the main concern. Also, charge repulsion between jets ejecting from the different spinnerets becomes a problem to be addressed. In an article entitled "A Fundamental Investigation Of The Formation And Properties Of Electrospun Fibers" by Warner et al., published in the National Textile Center Annual Report, M98-D01, 1999, a rotary electrospinning apparatus with multiple spinnerets to improve productivity, is described. It was reported that the charge repulsion between jets was minimized with their design. However, maintaining consistent feed rates to all the spinnerets simultaneously was a problem.

The present invention has been made and is now reduced to practice with the knowledge of these concerns.

Summary

In accordance with a first aspect of the present invention, there is provided an apparatus for electrostatic deposition of a material comprising a plurality of spinnerets; a collector for collecting the material discharged from the respective spinnerets, a electrically conducting plate in electrical contact with the spinnerets, wherein, in use, an electric field is generated between the plate and the collector and around the spinnerets, and wherein, in use, a potential difference is created between the spinnerets and the collector, and wherein the spinnerets are moveable relative to the collector in a direction substantially perpendicular to a discharging direction of the spinnerets.

The plurality of spinnerets may be disposed in a staggered arrangement.

The plate may move with the spinnerets.

The spinnerets and the plate may be mounted on a holder. The holder may be moveable.

The spinnerets may be moveable in two directions substantially perpendicular to the discharging direction of the spinnerets.

The spinnerets may further be moveable in a direction substantially parallel to the discharging direction of the spinnerets.

An electric potential may be applied to the spinnerets and the collector is grounded.

An electric potential may be applied to the collector and the spinnerets are grounded.

The spinnerets may comprise syringe needles.

The collector may comprise a substantially planar structure.

The collector may comprise a rotatable drum or cylindrical frame structure.

An axis of rotation of the drum or cylindrical frame structure may be substantially perpendicular to the discharging direction.

The material may comprise electrospun nanofibers.

The electrospun nanofibers may be collected in an aligned manner or in a randomly oriented manner.

The material may comprise electrosprayed droplets or particulates.

In accordance with a second aspect of the present invention, there is provided an apparatus for electrostatic deposition of a material comprising a plurality of spinnerets; a collector for collecting the material discharged from the respective spinnerets, a electrically conducting plate in electrical contact with the spinnerets, wherein, in use, an electric field is generated between the plate and the collector and around the spinnerets, and wherein, in use, a potential difference is created between the spinnerets and the collector, and wherein the spinnerets are moveable relative to the collector in a direction substantially perpendicular to a discharging direction of the spinnerets.

The plurality of spinnerets may be disposed in a staggered arrangement.

The method may comprise moving the spinnerets in two directions substantially perpendicular to the discharging direction of the spinnerets.

The method may further comprise moving the spinnerets in a direction substantially parallel to the discharging direction of the spinnerets.

An electric potential may be applied to the spinnerets and the collector is grounded.

5 An electric potential may be applied to the collector and the spinnerets are grounded.

The spinnerets may comprise syringe needles.

The collector may comprise a substantially planar structure.

The collector may comprise a rotatable drum or cylindrical frame structure.

10 An axis of rotation of the drum or cylindrical frame structure may be substantially perpendicular to the discharging direction.

The material may comprise electrospun nanofibers.

The electrospun nanofibers may be collected in an aligned manner or in a randomly oriented manner.

15 The material may comprise electrosprayed droplets or particulates.

Brief Description of The Drawings

Embodiments of the invention are described hereinafter with reference to the accompanying drawings in which:

20 Figure 1 is a schematic drawing of an electrospinning system in accordance with an exemplary embodiment of the present invention.

Figure 2 is an isometric view of an electrospinning apparatus, in accordance with an exemplary embodiment of the present invention.

25 Figure 3 is an isometric view of the movable multiple spinneret system of the electrospinning apparatus of Figure 2.

Figure 4 is an isometric view of the spinneret holder and the attached spinneret plate of the electrospinning apparatus of Figure 2.

Figure 5a is an isometric view of a cylindrical frame collector of the electrospinning apparatus of Figure 2.

30 Figure 5b is an isometric view of a drum collector, in accordance with an embodiment of the present invention.

Figure 6 is an isometric view of a drum collector of Figure 5b, together with a mounting base.

Figure 7a is an electron micrograph showing aligned nanofibers produced using the drum collector of Figure 5a.

5 Figure 7b is an electron micrograph showing randomly oriented nanofibers produced using the cylindrical drum collector of Figure 5b.

Detailed Description

Figure 1 shows a schematic drawing of an electrospinning system in accordance with an embodiment of the present invention. The electrospinning system comprises a syringe pump 10, a high voltage power supply 20, a movable multiple spinneret system 30 and a nanofiber collector 25. The syringe pump 10 feeds a conducting fluid used for forming nanofibers to the multiple spinneret system 30 through a series of tubes 12. The term "nanofiber" is used to represent one
 15 filament or a bundle of filaments having average diameter(s) less than about 1,000 nanometers (nm), for example, below 500 nm, preferably from about 1nm to 100nm. The material used for forming the nanofibers may be from any fiber-forming materials, such as general fiber-forming polymers, fiber-forming ceramic precursors, fiber-forming carbon precursors. Water-soluble polymers such as polyethylene oxide,
 20 polyvinyl alcohol, polyvinyl pyrrolidon, etc., and organic solvent soluble polymers such as polyamide, polycaprolactone, polylactic acid, etc. may also be used, from which a spinnable solution can be made for use in the electrospinning process.

A plurality of spinnerets in the form of syringe needles 31 are mounted on the multiple spinneret system 30. In the example embodiment, the spinneret system 30
 25 comprises three syringes 31. However, it will be appreciated that different numbers (≥ 2) of syringes may be used in different embodiments. Each of the syringes 31 is mounted to a spinneret holder 38 by means of plugs 32. The conducting fluid, for example a polymer solution, flows from the pump 10 through the series of tubes, into each syringe 31 via the plugs 32. The multiple spinneret system 30 is operable to
 30 move in a reciprocating manner, for example, from left to right, as indicated by the arrows 35 shown in Figure 1. A charge in the range of about 8 to 25 kV is applied to the spinnerets 31 in the example embodiment by the high voltage power supply 20.

However, it is noted that the voltage will depend on the polymer used and concentration of the polymer. Negative voltages may also be applied if necessary. A grounded collector 25 is positioned below the syringes 31 to create an electric field between the charged syringes 31 and the collector 25. The electric field causes tiny jets e.g. 34 of polymer solution (i.e. nanofiber) to be ejected from the tip of each syringe 31. The polymer jets e.g. 34 are deposited onto the collector 25, and form a web of interconnected nanofibers on the collector 25. The collector 25 may be of various shapes, for example, a rectangular frame, a cylindrical frame or a cylindrical drum. During the fiber collection process, the collector 25 can be made to rotate at high speed if e.g. a cylindrical frame or drum is used, or can be stationery, if e.g. a rectangular frame is used.

Figure 2 shows an isometric view of an electrospinning apparatus 18 in accordance with another embodiment of the present invention. The electrospinning apparatus 18 comprises a movable multiple spinneret system 130 and a collector system 71. The collector system 71 comprises a collector driving means 72 and a collector 70. In the example embodiment, plate 79 was grounded. In other applications, the polarity can be switched, that is plate 79 may connect with the high voltage, and plate 36 (Figure 3) may connect to ground. In other modifications, collector 70 can also be charged to a potential which is different from plate 79 by using a brush-like connector to connect to shaft 108 (Figure 5b) and using no conducting materials to fabricate the support 76.

The movable multiple spinneret system 130 is mounted to a base plate 90 by a mounting frame 60. The movable multiple spinneret system 130 is supported by the mounting frame 60. The mounting frame 60 comprises two support poles 62 and two bars 64. The support poles 62 are mounted substantially orthogonal to the base plate 90. The support poles 62 are spaced at a distance apart. The distance between the two support poles 62 is such that the mounting frame 60 can accommodate the overall length of the multiple spinneret system 130. The height of the support poles 62 depends on the vertical distance required between the multiple spinneret system 130 and the collector system 71. A shoulder block 63 is disposed on the other end of each of the support poles 62. Each shoulder block 63 is generally square in shape. The two bars 64 are mounted one on top of the other. Each of the bars 64 is generally elongate in shape. The bars 64 are mounted to the support poles 62 via the shoulder blocks 63. When mounted, the longitudinal axis of each of the bars 64 is generally perpendicular to the longitudinal axis of the support poles 62 (i.e. parallel to

the base plate 90). The multiple spinneret system 130 is mounted to the mounting frame 60 via two mounting bars 66. The mounting bars 66 are generally cylindrical in shape and each mounting bar 66 protrudes orthogonally from a side face 63a of each of the shoulder blocks 63.

5 Figure 3 shows an isometric view of the multiple spinneret system 130 of the electrospinning apparatus 18 of Figure 2. The multiple spinneret system 130 comprises a spinneret holder 138 movably mounted to a spinneret holder mounting frame 47. The spinneret holder mounting frame 47 is generally rectangular in shape and elongate. The spinneret holder mounting frame 47 is in turn mounted at its two
10 ends to the mounting frame 60 (Figure 2). Each of the two mounting bars 66 (Figure 2) of the mounting frame 60 (Figure 2) fit into a hole 51 on each end of the spinneret holder mounting frame 47. A guide rod 42 is mounted to the spinneret holder mounting frame 47, with its longitudinal axis substantially parallel to the spinneret holder mounting frame 47.

15 As shown in Figure 4, the spinneret holder 138 is a generally cube-shaped block, having a flange 138 extending from a first face. The flange 138a is adapted to receive a spinneret plate 36. The spinneret plate is mounted to the bottom surface of the flange 138a by means of screws e.g. 139, syringes (not shown) are mounted on the underside of spinneret carrier 132. The carrier 132 is mounted to a spinneret
20 plate 36. The carrier 132 is positioned substantially in the middle of the spinneret plate 36. The arrangement of the syringes (not shown) on the carrier 132 are identified by the positions of the four holes 32a on the carrier 132. In this embodiment, there are four syringes (not shown). However, it will be appreciated that different numbers (≥ 2) of syringes may be used in different embodiments. The
25 syringes (not shown) are arranged in two offset lines. It was found that disposing the syringes in a staggered arrangement, such as in two offset lines in the example embodiment, facilitated creating a more even electric field around the syringes. The repulsion force between the polymer jets are believed to be minimized in such arrangements, resulting in the polymer fiber being deposited on the collector and not
30 "fly" away. As a follow-on effect, this is believed to also help in the increase of the throughput. An even electric field is also believed to help to produce a fiber mat, in which the fiber is more evenly spread out on the collector.

Returning now to Figure 3, a guide flange 39 protrudes from the top surface of the spinneret holder 138. The spinneret holder 138 has a guide hole 40 through

which the guide rod 42 fits. The guide hole 40 has a larger diameter than the guide rod 42 to allow movement of the spinneret holder 138 along the guide rod 42. The spinneret holder 138 is disposed between two limit switches 46 on the guide rod 42. The limit switches 46 limit the extent to which the spinneret holder 138 moves along the guide rod 42 during the electrospinning. The distance between the two limit switches 46 can be adjusted, depending on the required dimensions of the nanofiber mat/membrane. When mounted to the spinneret holder mounting frame 47, the guide flange 39 of the spinneret holder 138 is positioned in a recess 52 in the spinneret holder mounting frame 47. A spinneret drive mechanism 48 moves the spinneret holder 138 reciprocally from left to right along the guide rod 42. The spinneret drive mechanism 48 comprises a motor 48a, a wheel 48b and a belt 48c. The belt 48c makes a loop round an axle of the motor 48a and the wheel 48b. The spinneret holder 138 is fixed to the belt 48b, such that when the motor 48a is turned on, the belt 48c is driven round the loop, carrying the spinneret holder 138 as it moves. When the spinneret holder 138 touches one of the limit switches 46, the motor 48a changes its direction and causes the spinneret holder 138 to move in the opposite direction along the guide rod 42. Similarly, when the spinneret holder 138 reaches the limit switch 46 on the opposite end of the guide rod 42. This results in the reciprocating movement of the spinneret holder 138 from left to right. The reciprocating movement of the spinneret holder 138 during the electrospinning process helps to improve the evenness / uniformity of nanofiber distribution on the collector 70 (Figure 2).

Returning now to Figure 2, the spinneret holder 138 is made of a non-conducting material. This is to avoid short circuits. On the other hand, the spinneret plate 36 is made of a conductive material, for example, aluminium alloy. This is to enable an electric potential to be applied between the spinneret plate 36 and the collector 70 during the electrospinning process.

A high voltage is applied to the spinneret plate 36 by a high voltage power supply (not shown) during the electrospinning process. This results in a uniform electric field created near the spinnerets. This uniform electric field helps to stabilize the polymer jets upon leaving the syringes (not shown). The uniform electric field also reduces the range of jet deviation from the spinneret axis due to charge repulsion of the charged polymer jets. This allows most of the polymer jets emanating from the syringes (not shown) to be deposited on the collector 70 rather than its surroundings.

In this embodiment, the collector driving means 72 is a motor and the collector 70 is a cylindrical frame collector. The collector motor 72 and the cylindrical frame collector 70 are mounted to the base plate 90 by a pair of mounting brackets 74 and a collector mounting frame 76, respectively. The collector system motor 72
 5 comprises a motor axle 75 extending from one end of the collector motor 72. The motor axle 75 is coupled to an axle 77 of the cylindrical frame collector 70. The cylindrical frame collector 70 is positioned below the multiple spinneret system 130, such that during the electrospinning process, the electrospun nanofibers can be deposited onto the cylindrical frame collector 70.

10 During the electrospinning process, the spinneret driving mechanism 48 moves the multiple spinneret system 130 reciprocally in a direction that is substantially paralleled to the axis of rotation of the cylindrical frame collector 70. The collector motor 72 can rotate the cylindrical frame collector 70 at various speeds, typically in the range of 2000rpm to 3000rpm, in order to facilitate the alignment of
 15 the nanofibers.

Figure 5a shows an isometric view of the cylindrical frame collector 70. The cylindrical frame collector 70 comprises the axle 77 and one disc 82 at each end of the cylindrical frame collector 70. The axle 77 protrudes from the discs 82. One end of the axle 77 has a coupling element 83 (Figure 2) for coupling the axle 77 to the
 20 axle 75 (Figure 2) of the collector motor 72 (Figure 2) bearings 84, one at each disc 82, enable the cylindrical frame collector 70 to rotate when it is driven by the collector motor 72 (Figure 2). A plurality of rods 80 are arranged around the collector axle 77.

During the electrospinning process, the polymer jets (i.e. nanofibers) are collected substantially perpendicularly to the rods 80 of the cylindrical frame collector
 25 70. It has been found that the cylindrical frame collector 70 facilitates creating an electric field during the spinning process which favors the formation of aligned nanofibers. The rotation of the cylindrical frame collector 70 also enables the nanofiber to stretch from one rod to the next. This stretching effect further assists the alignment of the nanofibers. Aligned nanofibers produced using the cylindrical frame
 30 collector 70 are shown in Figure 7a.

Figure 5b shows an isometric view of a cylindrical drum collector 100 in accordance with another embodiment of the invention. The drum collector 100 comprises a cylindrical drum 102, an axle 104 protruding horizontally from both sides of the cylindrical drum 102. A coupling notch 108 is positioned near an end of the

axle 104. The coupling notch 108 allows the cylindrical drum collector 100 to be coupled to the axle 75 (Figure 2) of the collector motor (Figure 2).

Figure 6 shows an isometric view of the cylindrical drum collector 100 partially attached to the collector mounting frame 76. The collector mounting frame 76 comprises a pair of "L" shaped brackets 87. In this embodiment each bracket 87 comprises a base 88 and a support 85 that extends generally perpendicularly from the base 88 to form the "L" shaped bracket. In the example embodiment, plate 89 was grounded. A bearing 110 on each end of an axle 104 of the cylindrical drum collector 100 rests on a semicircular depression 85c in a top surface of the of the support 85. A pair of pins 85b are disposed on the top surface of the support 85. A clamp 86 having a semicircular depression 86a to accommodate the shape of the bearing 110, is removably mounted to the support 85 by fitting the pins 85b on the top surface of the support 85 into a pair of corresponding holes 86b on the clamp 86, as shown in Figure 6. This configuration allows interchangeability between different types of collectors.

It should be appreciated that collectors of other configurations in different embodiments. For example, a stationary rectangular frame collector may be used to obtain randomly oriented fibers, as shown in Figure 7b. In example embodiments, randomly oriented fibers were obtained for relative speeds between the stationary collector and the movable spinnerets of less than about 5m/s. At higher relative speeds, oriented fibers can be obtained, i.e. similar to using a stationary spinnerets and a collector rotating at high rpm.

In the forgoing manner, an apparatus and methods for electrospinning are disclosed. Only several embodiments are described, however, it will be apparent to ones skill in the art in view of this disclosure that numerous changes and/or modifications may be made without departing from the scope of the invention.

The interchangeability of the collectors allow randomly oriented fibers as well as aligned fibers to be produced with the same apparatus.

For example, in the embodiment described above, eight stainless steel rods are assembled around the collector axle in the cylindrical frame collector. The cylindrical frame collector can be constructed with more or fewer rods than current eight rods to obtain different sizes of aligned nanofibers and nanofibrous

membranes, depending on what is required. In particular, placement of a stationary one-frame structure can be used for collecting aligned nanofibers.

5 Fibers produced with the apparatus described above are mostly circumferentially oriented. However, it is possible to have electrospun fibers aligned in other directions by re-arranging the rods on the cylindrical frame collector at other angles with respect to the rotating axis of the cylindrical frame.

10 In another exemplary embodiment, other types of spinnerets (instead of the syringe needles) can be used. For example, the spinnerets can be integrated into the multiple spinneret system as a spinneret head with round holes or other shapes of exit orifice.

15 In another exemplary embodiment, multiple spinnerets can be made to rotate during electrospinning. This helps to improve the uniformity of the distribution of nanofibers. In one such embodiment, the multiple spinnerets may rotate about a z-axis and move reciprocally along an x-axis while the collector rotates about the x-axis.

Apart from polymer solutions, other types of material, for example, polymer melts can also be used. Polymer melts can be obtained by adding a heating system to melt the polymers before the polymers are being electrospun.

20 The apparatus of the present invention can be used in other types of applications, other than for the electrospinning of polymer nanofibers and production of nanofiber membranes / mats. For example, the electrospinning apparatus can also be used for the electrospraying of tiny droplets of chemicals or particulates to achieve fast and even distribution of chemicals and solutions. The droplets of chemicals or particulates may be deposited onto membranes, fabrics, sheet materials, bulk materials and any other suitable material of different kinds and shapes. One example
25 application of such an embodiment would be in clothing e.g. for military personnel to detect and filter out toxic or dangerous chemical particles.

Claims

1. An apparatus for electrostatic deposition of a material comprising:
a plurality of spinnerets;
a collector for collecting the material discharged from the respective
5 spinnerets,
a electrically conducting plate in electrical contact with the spinnerets,
wherein, in use, an electric field is generated between the plate and
the collector and around the spinnerets, and
wherein, in use, a potential difference is created between the
10 spinnerets and the collector, and
wherein the spinnerets are moveable relative to the collector in a direction
substantially perpendicular to a discharging direction of the spinnerets.
- 15 2. The apparatus as claimed in claim 1, wherein the plurality of spinnerets are
disposed in a staggered arrangement.
3. The apparatus as claimed in claims 1 or 2 wherein the plate moves with the
spinnerets.
- 20 4. The apparatus as claimed in claim 3, wherein the spinnerets and the plate
mounted on a holder.
5. The apparatus as claimed in claim 4, wherein the holder is moveable.
- 25 6. The apparatus as claimed in any one of claims 1 to 5, wherein the spinnerets
are moveable in two directions substantially perpendicular to the discharging
direction of the spinnerets.
- 30 7. The apparatus as claimed in any one of claims 1 to 6, wherein the spinnerets
are further moveable in a direction substantially parallel to the discharging direction
of the spinnerets.

8. The apparatus as claimed in any one of claims 1 to 7, wherein an electric potential is applied to the spinnerets and the collector is grounded.

5 9. The apparatus as claimed in any one of claims 1 to 7, wherein an electric potential is applied to the collector and the spinnerets are grounded.

10. The apparatus as claimed in any one of claims 1 to 9, wherein the spinnerets comprise syringe needles.

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11. The apparatus as claimed in any one of claims 1 to 10, wherein the collector comprises a substantially planar structure.

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12. The apparatus as claimed in any one of claims 1 to 10, wherein the collector comprises a rotatable drum or cylindrical frame structure.

13. The apparatus as claimed in claim 12, wherein an axis of rotation of the drum or cylindrical frame structure is substantially perpendicular to the discharging direction.

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14. The apparatus as claimed in any one of claims 1 to 13, wherein the material comprises electrospun nanofibers.

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15. The apparatus as claimed in claim 14, wherein the electrospun nanofibers are collected in an aligned manner or in a randomly oriented manner.

16. The apparatus as claimed in any one of claims 1 to 13, wherein the material comprises electrosprayed droplets or particulates.

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17. A method of electrostatic deposition of a material comprising:
moving a plurality of spinnerets relative to a collector in a direction substantially perpendicular to a discharging direction of the spinnerets; generating an electric field around the spinnerets; utilising an electrically conducting plate in electrical contact with the spinnerets, and generating the electric field between the plate and the
35 collector.

18. The method as claimed in claim 17, wherein the plurality of spinnerets are disposed in a staggered arrangement.

5 19. The method as claimed in claim 17 or 18, comprising moving the spinnerets in two directions substantially perpendicular to the discharging direction of the spinnerets.

10 20. The method as claimed in any one of claims 17 to 19, further comprising moving the spinnerets in a direction substantially parallel to the discharging direction of the spinnerets.

15 21. The method as claimed in any one of claims 17 to 20, wherein an electric potential is applied to the spinnerets and the collector is grounded.

22. The method as claimed in any one of claims 17 to 21, wherein an electric potential is applied to the collector and the spinnerets are grounded.

20 23. The method as claimed in any one of claims 17 to 22, wherein the spinnerets comprise syringe needles.

24. The method as claimed in any one of claims 17 to 23, wherein the collector comprises a substantially planar structure.

25 25. The method as claimed in any one of claims 17 to 24, wherein the collector comprises a rotatable drum or cylindrical frame structure.

26. The method as claimed in claim 25, wherein an axis of rotation of the drum or cylindrical frame structure is substantially perpendicular to the discharging direction.

30 27. The method as claimed in any one of claims 17 to 26, wherein the material comprises electrospun nanofibers.

28. The method as claimed in claim 27, wherein the electrospun nanofibers are collected in an aligned manner or in a randomly oriented manner.

29. The method as claimed in any one of claims 17 to 28, wherein the material
5 comprises electrosprayed droplets or particulates.