exhibit poor control over fiber alignment and 3D geometry. Neither the spatial distribution nor the fiber orientation inside the cloud is regulated. Poor control over the fiber cloud leads to poor control over deposition. In contrast, extrusion-3DP extrudes fibers through a moving nozzle that precisely controls the location of deposition and alignment of each portion of the fiber. However, extrusion-3DP has low throughput. While both techniques are capable of producing fibers over a large range of diameters, only extrusion-3DP can produce complex 3D structure, yet random-FD holds orders-of-magnitude advantage in throughput for fine fibers. The limit in throughput is intrinsic: to fill up the same volume, the length of the fiber required increases rapidly as the fiber diameter decreases. Extrusion 3DP has to trace the length of the fiber (e.g., > 100 km in length for some applications), while fiber deposition does not.

Accordingly, there is a need in the art for improved systems that enable production of complex 3D structure of small diameter fibers (e.g., fibers having diameters of less than 10 microns) with a high throughput.

SUMMARY

Some examples of the present invention include a rotary jet spinning system configured to manipulate the fiber motion through externally imposed gas (e.g., air flow) to form a directional stream of fibers. Some examples enable control of fiber alignment and have relatively high throughput.

In one aspect, the present disclosure refers to a system for focused directional deposition of one or more micron or nanometer polymeric fibers each having a diameter of less than 10 μm. The system includes a reservoir configured to hold a material including a polymer and rotatable about a rotation axis. The reservoir includes a first end; a second end opposite the first end; an outer sidewall extending from the first end to the second end, a shape of the reservoir including one or more apertures disposed radially inward from the outer sidewall of the reservoir that are configured to enable a gas to move through the reservoir from the first end to the second end; and one or more orifices formed in the outer sidewall, each of the one or more orifices configured for ejection of the material radially outward through the orifice as an ejected jet during rotation of the reservoir. The system also includes a plurality of gas flow sources, each configured to direct a flow of gas from upstream of the first end of the reservoir through the one or more apertures of the reservoir from the first end to the second end of the reservoir and downstream of the second end of the reservoir during rotation of the reservoir the plurality of gas flow sources collectively forming a combined gas flow in a first direction downstream of the second end of the reservoir that entrains and deflects the one or more ejected jets to form a focused stream

of the one or more micron or nanometer polymeric fibers in a first direction, the first direction having an orientation that is within 5 degrees of the rotation axis of the reservoir, and the plurality of gas flow sources having a converging orientation to form the combined gas flow in the first direction.

In some examples, the one or more gas flow sources comprise a plurality of gas flow sources having a converging orientation to form the combined gas flow in the first direction. In some examples, a gas flow rate of at least some of the plurality of gas flow sources relative to others of the gas flow sources is controllable to achieve a balanced combined gas flow. In some examples, a number of the plurality of gas flow sources and an arrangement of the plurality of gas flow sources are configured such that, at any single point in time during rotation of the reservoir, gas flow from all of the plurality of gas flow sources flows through an aperture of the one or more apertures of the reservoir or the gas flow from all of the plurality of gas flow sources is blocked by the reservoir. In some examples, the plurality of gas flow sources comprises three gas flow sources.

In some examples, a total gas flow rate from the one or more gas flow sources is controllable to change a distance from the reservoir at which the stream of the micron or nanometer dimension polymeric fiber has the tightest focus.

In some examples the first direction is within 2 degrees of the axis of rotation. In some examples, the first direction is substantially parallel to the axis of rotation.

In some examples, the focused stream of the one or more micron or nanometer dimension polymeric fibers has a stream width smaller than a diameter of the outer sidewall of the reservoir.

In some examples, the system further comprises a flow blocking structure disposed upstream of the plurality of gas flow sources and configured to reduce an effect of airflow upstream of the plurality of gas flow sources on focusing of the stream of the micron or nanometer dimension polymeric fiber. In some examples, the flow blocking structure is disposed upstream of the rotating reservoir and configured to at least partially block airflow from upstream of the rotating reservoir reducing an effect of airflow from upstream of the rotating reservoir on an interaction between airflow due to rotation of the reservoir and the flow of gas through the one or more apertures. In some examples, the flow blocking structure is stationary and does not rotate with the reservoir. In some examples, the flow blocking structure enables enhanced control of a structure of vortices generated by the flow of gas and the rotation of the reservoir thereby improving control of a lateral area of deposition of the micron or nanometer dimension polymeric fiber as the fiber travels toward a target.

In another aspect, the present disclosure refers to a method for formation and deposition of at least one micron or nanometer polymeric fiber having a diameter of less than 10 μm. The method includes rotating a reservoir holding a material comprising a polymer about a rotation axis to eject at least one jet of material from at least one orifice defined by an outer sidewall of the reservoir; directing a plurality of flows of gas through a portion of the reservoir radially inward of the outer sidewall, the plurality of flow of gas directed from an upstream first end of the reservoir to a downstream second end of the reservoir during rotation of the reservoir and ejection of the at least one jet of material to form at least one micron or nanometer polymeric fiber, the plurality of flows of gas entraining the one micron or nanometer polymeric fiber, converging and forming a combined gas flow in a first direction, and forming a focused fiber deposition stream of the at least one micron or nanometer polymeric fiber in athe first direction, the first direction having an orientation of within 5 degrees of the rotation axis of the reservoir; and collecting the focused fiber deposition stream on a target surface.

In some examples, the first direction is substantially parallel to the rotation axis of the reservoir.

In some examples, the at least one flow of gas comprises a plurality of flows of gas that converge and form a combined gas flow in the first direction. In some examples, a flow rate of at least some of the plurality of converging flows of gas relative to others of the plurality of converging flows of gas is controllable to achieve a balanced combined gas flow. In some examples, a total gas flow rate of the plurality of converging flows of gas is controllable to change a distance from the reservoir at which the focused fiber deposition stream of the at least one micron or nanometer dimension polymeric fiber has the tightest focus. In some examples, the plurality of gas flows comprises three gas flows.

In some examples, the focused fiber deposition stream has a substantially tangential orientation to the target surface during fiber collection.

In some examples, the method further comprises rotating the target surface during fiber collection.

In some examples, the method further comprises at least partially blocking flow of gas from upstream of the reservoir to reduce an effect of airflow upstream of the plurality of gas flow sources on focusing of the fiber deposition stream of the at least one micron or nanometer dimension polymeric fiber.

In some examples, the target surface is moved linearly during deposition of the fiber stream.

In some examples, the material in the reservoir comprises a solvent.

In some examples, the material in the reservoir comprises a polymer melt. In some examples, the method further comprises heating the reservoir.

Claims

1. A system for focused directional deposition of one or more micron or nanometer polymeric fibers each having a diameter of less than 10 μm, the system comprising:

a reservoir configured to hold a material including a polymer and rotatable about a rotation axis, the reservoir including:

a first end;

a second end opposite the first end;

an outer sidewall extending from the first end to the second end, a shape of the reservoir including one or more apertures disposed radially inward from the outer sidewall of the reservoir that are configured to enable a gas to move through the reservoir from the first end to the second end;

one or more orifices formed in the outer sidewall, each of the one or more orifices configured for ejection of the material radially outward through the orifice as an ejected jet during rotation of the reservoir; and

a plurality of gas flow sources, each configured to direct a flow of gas from upstream of the first end of the reservoir through the one or more apertures of the reservoir from the first end to the second end of the reservoir and downstream of the second end of the reservoir during rotation of the reservoir, the plurality of gas flow sources collectively forming a combined gas flow in a first direction downstream of the second end of the reservoir that entrains and deflects the one or more ejected jets to form a focused stream of the one or more micron or nanometer polymeric fibers in a first direction, the first direction having an orientation that is within 5 degrees of the rotation axis of the reservoir, and the plurality of gas flow sources having a converging orientation to form the combined gas flow in the first direction.

2. The system of claim 1, wherein a gas flow rate of at least some of the plurality of gas flow sources relative to others of the gas flow sources is controllable to achieve a balanced combined gas flow.

3. The system of claim 1, wherein a total gas flow rate from the plurality of gas flow sources is controllable to change a distance from the reservoir at which the stream of the micron or nanometer polymeric fibers has the tightest focus.

4. The system of claim 1, wherein a number of the plurality of gas flow sources and an arrangement of the plurality of gas flow sources are configured such that, at any single point in time during rotation of the reservoir, gas flow from all of the plurality of gas flow sources flows through an aperture of the one or more apertures of the reservoir or the gas flow from all of the plurality of gas flow sources is blocked by the reservoir.

5. The system of any one of claims 1-4, wherein the plurality of gas flow sources comprises three gas flow sources.

6. The system of any one of claims 1-4, wherein the first direction is within 2 degrees of the axis of rotation.

7. The system of any one of claims 1-4, wherein the first direction is substantially parallel to the axis of rotation.

8. The system of any one of claims 1-4, wherein the focused stream of the one or more micron or nanometer polymeric fibers has a stream width smaller than a diameter of the outer sidewall of the reservoir.

9. The system of any one of claims 1-4, further comprising a flow blocking structure disposed upstream of the plurality of gas flow sources and configured to

reduce an effect of airflow upstream of the plurality of gas flow sources on focusing of the stream of the micron or nanometer polymeric fibers.

10. The system of claim 9, wherein the flow blocking structure is disposed upstream of the rotating reservoir and configured to at least partially block airflow from upstream of the rotating reservoir reducing an effect of airflow from upstream of the rotating reservoir on an interaction between airflow due to rotation of the reservoir and the flow of gas through the one or more apertures.

11. The system of claim 9 or claim 10, wherein the flow blocking structure is stationary and does not rotate with the reservoir.

12. The system of claim 9, wherein the flow blocking structure enables enhanced control of a structure of vortices generated by the flow of gas and the rotation of the reservoir thereby improving control of a lateral area of deposition of the one or more micron or nanometer polymeric fibers as the one or more micron or nanometer polymeric fibers travel toward a target.

13. The system of any one of claims 1-4. wherein the plurality of gas flow sources is configured to enable control of a rate of flow of the gas to focus a lateral area of deposition of the one or more micron or nanometer polymeric fibers as the one or more micron or nanometer polymeric fibers travel toward a target.

14. The system of any one of claims 1-4, further comprising a target rotation system configured to rotate a three dimensional target during deposition to deposit the one or more micron or nanometer polymeric fibers on more than one side of the target.

15. The system of any one of claims 1-4, wherein the system is configured to be hand held.

16. The system of any one of claims 1-4, further comprising a coagulation, precipitation or cross-linking reservoir configured to hold a bath for coagulation, precipitation or cross-linking of the ejected polymer material.

17. The system of any one of claims 1-4, further comprising a heat source for heating the polymer material prior to delivery to the reservoir or while in the reservoir.

18. The system of any one of claims 1-4, wherein the system is configured for co-deposition of fibers and further comprises:

a second reservoir configured to hold a second material including a second polymer and rotatable about a second rotation axis, the second reservoir including:

a first end;

a second end opposite the first end;

an outer sidewall extending from the first end to the second end, a shape of the second reservoir including one or more apertures disposed radially inward from the outer sidewall of the reservoir that are configured to enable a gas to move through the reservoir from the first end to the second end; and

one or more orifices formed in the outer sidewall, each of the one or more orifices configured for ejection of the second polymer material radially outward through the orifice as a second ejected jet during rotation of the second reservoir; and

a second plurality of gas flow sources, each configured to direct a flow of gas from upstream of the first end of the second reservoir through the one or more apertures of the second reservoir from the first end to the second end of the second reservoir and downstream of the second end of the second reservoir during rotation of the second reservoir, the second plurality of gas flow sources having a converging orientation such that the flows of from the second plurality of gas flow sources collectively forming a second combined gas flow in a second direction downstream of the second end of the second reservoir that entrains and deflects the second ejected

jet to form a second focused stream of one or more second micron or nanometer polymeric fibers in a second direction, the second direction having an orientation that is within 5 degrees of the rotation axis of the second rotation axis,

wherein the first direction and the second direction are oriented for deposition on a same collection surface.

19. The system of claim 18, wherein the system is configured for simultaneous deposition of one or more fibers of the first polymer and one or more fibers of the second polymer on the same collection surface.

20. A method for formation and deposition of at least one micron or nanometer polymeric fiber having a diameter of less than 10 μm, the method comprising:

rotating a reservoir holding a material comprising a polymer about a rotation axis to eject at least one jet of material from at least one orifice defined by an outer sidewall of the reservoir;

directing a plurality of flows of gas through a portion of the reservoir radially inward of the outer sidewall, the plurality of flows of gas directed from an upstream first end of the reservoir to a downstream second end of the reservoir during rotation of the reservoir and ejection of the at least one jet of the material to form at least one micron or nanometer polymeric fiber, the plurality of flows of gas entraining the at least one micron or nanometer polymeric fiber, converging and forming a combined gas flow in the first direction, and forming a focused fiber deposition stream of the at least one micron or nanometer polymeric fiber in the first direction, the first direction having an orientation of within 5 degrees of the rotation axis of the reservoir; and

collecting the focused fiber deposition stream on a target surface.

21. The method of claim 20, wherein the first direction is substantially parallel to the rotation axis of the reservoir.

22. The method of claim 20, wherein a flow rate of at least some of the plurality of flows of gas relative to others of the plurality of flows of gas is controllable to achieve a balanced combined gas flow.

23. The method of any one of claims 20-22, wherein a total gas flow rate of the plurality of flows of gas is controllable to change a distance from the reservoir at which the focused fiber deposition stream of the at least one micron or nanometer polymeric fiber has the tightest focus.

24. The method of claim 20, wherein the plurality of gas flows comprises three gas flows.

25. The method of claim 20, wherein the focused fiber deposition stream has a substantially tangential orientation to the target surface during fiber collection.

26. The method of claim 20, further comprising rotating the target surface during fiber collection.

27. A method of forming a three dimensional tissue scaffold comprising performing the method of any one of claims 20 to 22 where the target surface is a three dimensional shape for a tissue scaffold.

28. The method for forming the three dimensional tissue scaffold of claim 27, further comprising rotating the target for deposition on more than one side of the three dimensional shape.

29. The method of any one of claims 20-22, further comprising at least partially blocking flow of gas from upstream of the reservoir to reduce an effect of airflow upstream of the plurality of gas flow sources on focusing of the fiber deposition stream of the at least one micron or nanometer polymeric fiber.

30. The method of any one of claims 20-22, wherein the target surface is moved linearly during deposition of the fiber.

31. The method of any one of claims 20-22, wherein material in the reservoir comprises a solvent.

32. The method of any one of claims 20-22, wherein the material in the reservoir comprises a polymer melt.

33. The method of claim 32, further comprising heating the reservoir.

34. The method of any one of claims 20-22, wherein the at least one ejected jet contacts a bath prior to being collected on the target surface.

35. The method of claim 34, wherein the bath comprises a cross-linking agent.

36. The method of claim 34, wherein the at least one ejected jet precipitates in the bath forming the at least one micron or nanometer polymeric fiber.

37. The method of claim 34, wherein the at least one ejected jet coagulates in the bath forming the at least one micron or nanometer polymeric fiber.

38. The method of any one of claims 20-22, wherein the at least one micron or nanometer polymeric fiber is deposited for reinforcement of a composite material.

39. The method of any one of claims 20-22, wherein the at least one micron or nanometer polymeric fiber is deposited on one or more items of food.

40. The method of any one of claims 20-22, further comprising:

rotating a second reservoir holding a second material comprising a second polymer about a second rotation axis to eject at least one jet of second material from at least one orifice defined by an outer sidewall of the second reservoir;

directing at least one second flow of gas through a portion of the second reservoir radially inward of the outer sidewall, the at least one second flow of gas directed from an upstream first end of the second reservoir to a downstream second end of the second reservoir during rotation of the second reservoir and ejection of the at least one jet of second material to form at least one micron or nanometer polymeric fiber of the second polymer, and the at least one second flow of gas entraining the at least one micron or nanometer polymeric fiber of the second polymer and forming a second focused fiber deposition stream; and

collecting the second focused fiber deposition stream on the target surface.

41. The method of claim 40, wherein the collection of the first focused fiber deposition stream overlaps in time with the collection of the second focused fiber deposition stream.