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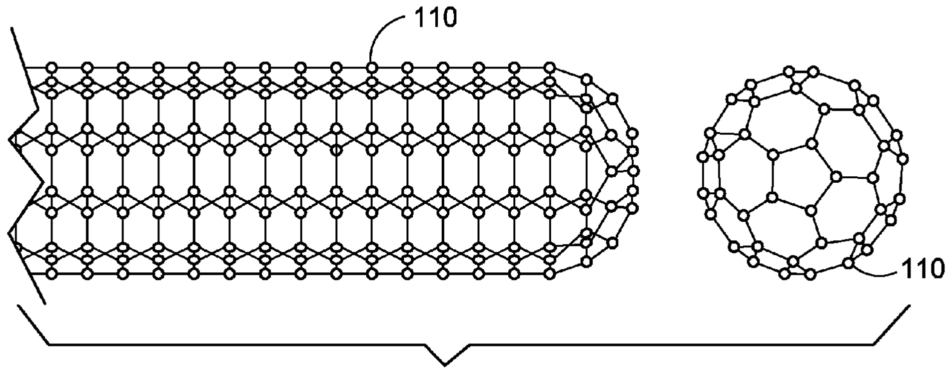
(54) **Title:** SYSTEM AND METHODS FOR SPINNING CARBON NANOTUBES INTO YARN, AND YARN MADE THEREFROM



(57) **Abstract:** A system and method for processing of carbon nanotubes (CNTs) to form a structured longitudinal arrangement, or base yarn, is disclosed. A CNT array having a multiplicity of CNTs arranged on a substrate and several methods for removal are further disclosed. Also included are a drafter for aligning and drafting the CNTs to form a sliver, a spinning apparatus, including at least one twist zone for providing rotation to the CNTs or sliver to produce a twisted, diametrically- condensed, longitudinal orientation of the CNT fibers; and take-up for collecting the yarn. Preferably the system for processing CNTs to form a structured longitudinal arrangement is a spinning process; more preferably, it is an electromagnetic (EM) spinning process.

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SYSTEM AND METHODS FOR SPINNING CARBON NANOTUBES INTO YARN, AND YARN MADE THEREFROM

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CROSS-REFERENCE

[0001] This patent application contains subject matter claiming benefit of the priority date of United States Provisional Patent Applications Serial No. 60/837,484 filed on August 14, 2006 and entitled METHOD OF SPINNING CARBON NANOTUBES INTO YARN, also Serial No. 60/845,380 filed on September 18, 2006 entitled SYSTEM AND APPARATUS FOR SPINNING CARBON NANOTUBES INTO YARN, in addition to Serial No. 60/845,430 filed on September 18, 2006, entitled SYSTEM AND METHOD FOR VACUUM PROCESSING OF CARBON NANOTUBES, accordingly, the entire contents of these provisional patent applications are hereby expressly incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention pertains generally to nanotechnology and textile arts. More specifically, the present invention pertains to systems and methods for drawing and drafting Carbon nanotubes (CNTs) and spinning the CNTs into yarn for use in commercial applications. The present invention, in a preferred embodiment, is particularly but not exclusively, a vacuum processing system coupled to an electromagnetic spinning apparatus for making yarn from CNTs, or other fiber strands.

Description of the Prior Art

[0003] Carbon nanotubes (CNTs) are often described as having perfect atomic structures wherein a graphene sheet is rolled up into the shape of a cylinder and capped with an end containing hexagonal and pentagonal rings. Fig. 1A illustrates side and end views of such a structure having walls one atom thick and a diameter on the order of 1-2nm. As is known, arrays of CNTs (or "CNT fibers") are grown on substrates. On or about the time of the present invention, CNT lengths on the order of about 1 to 4.5mm have been produced according to methods developed by Los Alamos National Laboratory as disclosed in published U.S. Patent Application, US 2007/0116631, entitled ARRAYS OF LONG CARBON NANOTUBES FOR FIBER SPINNING, invented by Qingwen Li, Yuntian T. Zhu, Paul Arendt, Raymond F. DePaula, James R. Groves. The resulting nanostructure has a length to diameter ratio exceeding 10,000.

[0004] Further as told by Li, et al., CNTs are at least one order of magnitude stronger than any other known material and have a theoretical strength of about 300 GPa. In practice, measured strengths have been up to about 150 GPa, and the strength may improve upon annealing. For comparison, Kevlar® and other aramid fibers currently used in bullet-proof vest have a strength of only about 3 GPa, and carbon fibers used for making space shuttles and other aerospace structures have strengths of only about 2-5 GPa. In addition to remarkable strength, CNTs also possess high elasticity and are excellent electrical and thermal conductors.

[0005] Also by way of background, CNT fibers (110) are processed for commercial use by spinning or twisting into yarn for additional processing into fabric, non-woven, and or composites. Fig. 1B illustrates typical yarn (130) twisted from fiber strands, such as cotton fiber (120). The resulting yarn (130), has turns either in the counterclockwise or clockwise direction, known as "S" twist or "Z" twist, respectively, as shown in Fig. 1C. The degree of twist in yarn may be expressed in turns per meter (tpm). More twist is required for increased strength up to an optimum twist wherein the fibers in the yarn become more perpendicular than parallel to the length of yarn. For base yarns made from CNTs, high twist rates are required on the order of 10,000 to 100,000 (tpm) wherein the diameter of the resulting base yarn is small and around 100nm. The base yarns are then cabled to make thicker yarns, or blended with other materials for commercial applications such as aerospace structures and personal body armor.

[0006] Existing technologies for inserting twist in fibrous structures to add strength rely on fiber lengths to be on the order of 2.5 cm or longer. By comparison, the long and dense arrays grown by techniques developed at Los Alamos are about 1 to 5 mm. Further, the diameter of yarn developed from conventional fibers is typically on the order of 0.1 to 1mm while CNT base yarn would be several orders of magnitude smaller. The linear speed of the yarn, comparable to the actual amount of yarn produced, is typically on the order of about 100-400 meters/min for conventional yarn for textile manufactures. The linear speed is also comparable to the rotational speed of the spinning apparatus. For the small diameter CNT fibers and base yarns, current ring and open end rotational systems are not adequate to insert the high twist rates need for CNT yarn production. Also a concern, yarn vibration in high speed production can produce erratic or uncontrolled motion resulting in production inefficiencies or stoppages. Accordingly, a need exists to develop yarn spinning techniques with very high rotational speeds (ω) and additional devices and methods to scale-up production making manufacturing commercially viable.

[0007] Also important in the yarn production process is what is known as drawing out or drafting a sliver prior to the twisting process. Initially, fibers may be grouped together in a mass loosely bonded known as web. Drafting the fibers typically will involve two or more mechanical rollers wherein a first set of rollers is rotating faster than a second set of rollers and thus the resulting sliver is being taken up faster than it is being delivered. Therefore, the result is that individual fibers are more parallel with respect to their longitudinal axes and strength is added to the softer mass. Further, the reduced cross-sectional area of the sliver will allow more turns per meter in the resulting base yarn thereby adding strength. The present invention seeks to induce novel methods and devices to draft slivers made from CNT fibers including a method to fine tune and adjust the drafting and the initial removal of the CNTs from the substrate.

[0008] Also important to the removal of fibers (110) contained in an array (210) from a substrate (211) as illustrated in Figs. 2A and 2B, is a prior art terminal speed limit of removal. As rows of CNTs are physically pulled from the substrate (211), they naturally align themselves into "ropes" held together by Van der Waals forces. Due to the high aspect ratio of around 10,000 to 1, length to diameter, the forces holding successive rows together is relatively minimal. Accordingly, current methods are only able to remove CNTs in the range of a few cm/min. An objective of the present invention is to provide structure and methods allowing for increasing the removal rate of the CNTs from the substrate to allow scale-up of production commercially viable.

[0009] Figures 2A through 2C generally illustrate the steps by which CNTs (110) are made into yarn (230) for structural materials. Reference character (220) generally represents a spin zone (220) to twist the fiber into yarn (230). Fig. 2C further shows base yarns (230) cabled together to form thicker yarns (240) using a secondary spin zone (220a).

[0010] Moreover, in the textile industry, it is desirable to instantaneously gather information on the condition and properties of the spun yarn during the spinning process. In normal yarn production, visual inspections are used to monitor yarn quality and production. In the case of CNTs, the size of the fibers do not allow for visual inspection. Hence, a different inspection system is needed.

[0011] In light of the above, it is an object of the present invention to provide systems and methods to efficiently draw CNTs from their substrate arrays without breaking the fibers bonded to one another. It is another object of the present invention to provide a system and method of CNT removal that can be tuned or adjusted by a user. It is yet another object of the present invention to design a yarn spin zone apparatus suitable for high rotational speeds required to produce the twist rates desired for the yarn to be made from CNTs. It is still a further object of the present invention to provide a method to instantaneously inspect yarn made from CNTs during production. It is yet still an object of the present invention to provide a design for an electromagnetic spin zone that reduces core losses. It is yet another object of the present invention to provide an electromagnetic spin zone in addition to methods to improve conductivity of CNT fibers, or other fiber strands for improved twist rates.

BRIEF SUMMARY OF THE INVENTION

[0012] The present invention specifically addresses and alleviates the above mentioned deficiencies associated with the prior art. More particularly, the present invention is a yarn comprising: a multiplicity of carbon nanotubes (CNTs) helically twisted about a longitudinal axis to form a CNT twist rate, wherein the CNT twist rate is between about 10,000 turns per meter and 100,000 turns per meter. The yarn of the invention further comprises: an outer twist zone with respect to the longitudinal axis; an inner twist zone, wherein the CNTs of the outer twist zone and the inner twist zone are twisted in opposite directions with respect to the longitudinal axis.

[0013] The invention is further a system for drawing carbon nanotubes (CNTs) from a substrate comprising: an array of CNTs formed on the substrate about an axis; a vacuum device comprising a low pressure orifice, a high pressure orifice, and an intermediate pressure orifice, the low pressure orifice arranged at a distance (d) from the array of CNTs along the axis; wherein the low pressure orifice draws the CNTs from the substrate aligned substantially parallel to the axis.

[0014] The system is further characterized wherein the low pressure orifice comprises a size an a shape substantially relating to a change in pressure along the axis; the change in pressure substantially relating to a velocity gradient along the axis, wherein the velocity gradient is proportional to a CNT removal rate and a velocity of the CNTs along the axis which can be controlled by a user by selecting the low pressure orifice size and shape. Further in this embodiment, the distance (d) can be adjusted by a user to affect a removal rate of the CNTs from the substrate. Also according to this and other embodiments, conductive particles are introduced at the high pressure orifice, wherein the conductive particles combine with the CNTs to make a resulting mass that has a greater electrical conductivity than the CNTs alone.

[0015] Moreover according to this and other embodiments applicable to CNT or other fibers, the system is characterized wherein the vacuum device has a cavity, the cavity having a velocity gradient associated therewith, the velocity gradient able to strip electrons from an air mixture within the cavity creating a plasma mass, the plasma mass combining with the CNTs removed from the substrate making a resulting mass more electrically conductive.

[0016] In another aspect, the invention is a method for drawing carbon nanotubes (CNTs) from a CNT array on a substrate comprising the steps of: aligning a vacuum device low pressure orifice at a distance (d) to the CNTs; applying a velocity gradient to the CNT array to remove the CNTs using the low pressure orifice. This method further comprises varying a size and a shape of the low pressure orifice to affect the velocity gradient as chosen by a user; and varying the distance (d) to affect the velocity gradient as chosen by the user.

[0017] Further this method includes the steps of: introducing conductive particles to the vacuum device; combining the conductive particles to the CNTs within the vacuum device, making a combination that is more electrically conductive as compared to the CNTs alone. This method additionally includes: configuring the vacuum device to contain within a velocity gradient; stripping electrons from an air mixture within the vacuum device using the velocity gradient creating a plasma mass; combining the plasma mass to the CNTs within the vacuum device, making a combination that is more electrically conductive as compared to the CNTs alone.

[0018] In yet another aspect, the invention is a system for making a base yarn from carbon nanotubes (CNTs) comprising: a CNT array grown on a substrate; a mechanical roller to remove the CNTs from the CNT array; a vacuum device for drafting the CNTs into a sliver; and a first spin zone to impart a rotational force on the sliver to form a base yarn. Further, this embodiment is characterized wherein the CNTs are removed from the substrate in the form of a web, the system further comprising: a first set of rollers to draft the CNT web into a sliver; and a second set of rollers to further draft the CNT sliver.

[0019] The system in this particular embodiment is further characterized wherein the CNT web is a first CNT web, further comprising a convergence zone to direct the CNT web into the first set of rollers; and a second CNT web wherein the first and second CNT webs combine in the convergence zone. This system further comprises: a second spin zone to impart a rotational force in a reverse direction of that the first spin zone; and a spool to take up the base yarn. More specifically, the rotational force is imparted with a magnetic flux. Or optionally, the rotational force is imparted with forced air.

[0020] In another aspect, the invention is not only applicable to CNT fibers and comprises a method for forming yarn from electrically conductive fibers, the method comprising: providing the electrically conductive fibers (ECFs) upstream from a spin zone; directing the ECFs into the spin zone; twisting the ECFs, using a rotating magnetic field, producing a yarn having a twist rate associated therewith. This further comprises drafting the ECFs using a vacuum device prior to the directing and the twisting.

[0021] In still another aspect, the invention is an induction motor comprising: a center axis; a plurality of pole segments radially aligned about the center axis; a plurality of conductive wires wrapped around each of the plurality of pole segments, the plurality of pole segments and the conductive wires together forming a motor stator assembly; a rotor area located in an area closest to the center axis; a polyphase AC current applied to the plurality of conductive wires producing a rotating magnetic field in the rotor area, the rotor area having a multiplicity of electrically conductive carbon nanotube fibers (CNTs), the rotating magnetic field imparting a rotational force on the CNTs. Further the induction motor of the present invention is characterized wherein the pole segments comprise end portions; the end portions shaped with a point generally pointed though the center axis. Further to the induction motor the plurality of pole segments comprises powdered ferrite to minimize core losses. In addition, the induction motor is claimed wherein the rotor area contains a liquid medium having a density greater than the CNTs, wherein the liquid medium and the CNTs rotate together causing a centripetal force on the CNTs with respect to the center axis.

[0022] These, as well as other advantages of the present invention, will be more apparent from the following description and drawings. It is understood that changes in the specific structure shown and described may be made within the scope of the claims, without departing from the spirit of the invention.

[0023] While the apparatus and method has or will be described for the sake of grammatical fluidity with functional explanations, it is to be expressly understood that the claims, unless expressly formulated under 35 USC 112, or similar applicable law, are not to be construed as necessarily limited in any way by the construction of "means" or "steps" limitations, but are to be accorded the full scope of the meaning and equivalents of the definition provided by the claims under the judicial doctrine of equivalents, and in the case where the claims are expressly formulated under 35 USC 112 are to be accorded full statutory equivalents under 35 USC 112, or similar applicable law. The invention can be better visualized by turning now to the following drawings wherein like elements are referenced by like numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The novel features of this invention, as well as the invention itself, both as to its structure and its operation, will be best understood from the accompanying drawings, taken in conjunction with the accompanying description, in which similar reference characters refer to similar parts, and in which:

[0025] Figure 1A is an illustration of side and end views of an exemplary single-walled carbon nanotube (SWNT).

[0026] Figure 1B illustrates an example of how fiber, in general, is twisted to form yarn.

[0027] Figure 1C further illustrates generally how yarn is twisted and the direction of twist.

[0028] Figures 2A through 2C generally illustrate the process by which CNTs are drawn from a substrate and twisted together to form base yarn, wherein several base yarns are further cabled together to form a thicker yarn suitable for commercial applications.

[0029] Figure 3A is a schematic illustration of an exemplary vacuum drawing device of the present invention.

[0030] Figure 3B is a perspective view of a similar apparatus as shown in Fig. 3A also illustrating the low pressure vacuum orifice of the present invention having different shapes to achieve a predetermined velocity gradient.

[0031] Figures 3C and 3D illustrate alternative embodiments of the low pressure orifice of the present invention.

[0032] Figure 4A-C are drawings to be viewed in succession, illustrating an embodiment for making base yarn of the present invention.

[0033] Figure 5A is a perspective illustration of an induction motor configured to serve as a spin zone of the present invention

[0034] Figure 5B is a top plan view of the induction motor of Fig. 5A.

[0035] Figure 6 is a stress vs. strain curve for yarn made from CNTs

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0036] Referring initially to Figure 3A, a preferred embodiment of the present invention is illustrated and generally designated system (300). Shown is a system for removing an array (210) of

CNTs (110) from a substrate (211). Vacuum device (350) contains low pressure (310), high pressure (330) and intermediate pressure (320) orifices, with corresponding pressures associated therewith P_1 P_3 P_2, where $P_1 < P_2 < P_3$. As an example $P_2=P_{ATM}$. More specifically, in a preferred embodiment, P_1 is vacuum pressure at 0 psi, P_1 is in the range of 14 to 30 psi, and P_3 is around 30 psi, with all pressures being absolute. At the openings of the high pressure (330) and low pressure (310) orifices are corresponding air velocities, V_3 and V_1. Arrow (360) indicates the direction of flow corresponding to V_3. The invention is able to control the velocity gradient along axis (340) particularly by varying the size and shape of the low pressure orifice (310), as illustrated in Figs. 3B-3D. Also, distance (d) can be varied to control the velocity at the leading edge of the CNT array (210). Air velocities V_1 and V_3 are in the range of 100 to 332 m/s.

[0037] Initially, as the CNTs (110) are removed from the substrate (211), it is desirable for the CNTs (110) to remain parallel during preprocessing before they are spun into a base yarn (Fig. 4C). Additionally, it is helpful for fiber processing to control speed of production and therefore velocity (V_1) and further the velocity gradient along axis (340). When CNTs (110) are removed from a substrate (211), it is preferable to provide a vacuum orifice diameter less than or approximately equal to the length of the CNTs (110), in order to ensure that the CNTs (110) align as they approach the vacuum orifice (310). Managing the orifice diameter is functionally preferred, in particular where the CNT or fiber length is substantially similar. Combining multiple substrates can also be achieved and may be facilitated by controlling the vacuum via a predetermined orifice size.

[0038] System (300) overcomes an issue in the prior art where if the CNTs (110) are removed too rapidly, the relatively weak forces holding successive rows of CNTs together will break. In the past the removal rate has been very slow on the order of a few cm/min that is not very practical for commercial yarn production. By designing a velocity gradient and an appropriate orifice diameter, the present invention not only draws the CNTs from the substrate, but also drafts the CNTs. Drafting the CNTs will pull the parallel CNTs closer together where Van der Waals forces between CNTs will cause them the stick together. The result is that the CNTs can be removed at a much higher rate. By way of example, but not limitation, for a 1 mm diameter circular cross-section orifice (310), and a vacuum producing a pressure differential of 14 psi, the vacuum force and corresponding air velocity is operable to exceed 100 m/s at a distance three times the orifice diameter at the leading edge of the CNT substrate. As stated, other than orifice (310) diameter and distance (d), other speed variables include vacuum force (pressure differential) and shape of the orifice (as shown in Figs. 3B-3D).

[0039] The present invention additionally contemplates adding conductive particles (361) at high pressure orifice (330). The conductive particles (361) will combine with the CNTs to form a resulting mass that is more conductive. These particles (361) could be mechanically inert for example, nanospheres. These nanospheres could be electrically conducting such as copper. They could also have a high permeability such as ferrite spheres. The conducting particles (361) would be more dense than the CNTs (110) facilitating removal later. While in the small bore (520) of the spin zone, the rotational acceleration would force the particles to the outer region of the spin zone and separate the particles from the CNTs. The spheres (361) could then be recycled. A conducting liquid could also be employed. The liquid being more dense would compact the CNTs in the spin zone. As required in the industry, higher strength yarns are compacted while being spun. Further along in the yarn production, as the CNTs sliver is spun using an electromagnetic spin zone (440, Figs. 5A-B), the yarn made therefrom would be spun more tightly and therefore have a higher strength. Low pressure conducting Plasma with possibly non-oxidizing gases (362) would similarly serve to increase conductivity of a resulting mass as it mixes with the CNTs. Plasma (362) is formed within vacuum cavity (363) when the velocity gradient causes the air inside to be stripped of its electrons.

[0040] It shall be further appreciated that systems and methods of the present invention could be employed in the textile arts to other fibrous strands. More specifically, the conductive particles could be added to fibers significantly less conductive as compared to CNTs, and later the fibers could be spun using an electromagnetic spinning apparatus. Likewise employing a plasma could be applicable to other fibers. CNTs (110) may be more generally labeled as electrically conductive fibers (ECFs).

[0041] Referring to Figs. 4A-4C, alternative combinations and embodiments are illustrated. The drawings should be viewed successively, with demarcation lines A-A and B-B connecting Fig 4A to Fig. 4B, and Fig. 4B to Fig. 4C respectively. It shall be noted that vacuum device (350) is comparatively located further downstream in the yarn production process than in the Fig. 3 example.

Vacuum (350) now serves to draft and align the sliver (413) to the spin zone (440). It shall be further appreciated that a vacuum force (350) could be located downstream of the spin zones (440, 441). Also note that high (330), intermediate (320) and low pressure (310) ports are configured differently as compared to Fig. 3A.

[0042] Initially, Fig 4A illustrates CNT array (210) having CNTs mechanically drafted therefrom using roller (415). A CNT web (410) results from this process and the web is drawn more closely together using convergence zone (420). Optionally, an additional web (411) (or multiple webs) drawn from another substrate could be combined in convergence zone (420). First roller (430) drafts the incoming cluster of fibers (412) into a sliver (413). This drafting, causing the fibers to be more elongated, will ultimately result in higher twist rates and a stronger base yarn (480). Second set of rollers (431) further drafts sliver (413) wherein second rollers (431) rotate faster than first set of rollers (430).

[0043] As previously stated, vacuum (350) in this embodiment, further drafts and aligns sliver (413) to first spin zone (440) in Figs 4B to 4C. Spin zones (440, 441) could be electromagnetic (as in Figs 5A-5B) or use a high pressure air vortex to impart a rotational force on the sliver (413). In a particular embodiment, first spin zone (440) is configured to only spin the outer fibers (460) of sliver (413) while second spin zone (441) is configured to spin inner fibers (461) in the opposite direction of first spin zone (440). The resulting base yarn (480) will have a false twist and a zero net twist about axis (450). Methods of the present invention are employed to achieve twist rates of about 10,000 to 100,000 turns per meter. Base yarn (480) is taken in by spool (470) and it is to be further appreciated that base yarn (480) could be cabled with other base yarns, similar to Fig. 2C. Alternatively, CNTs could be blended with other materials throughout the process, to form materials with different structural properties. These materials could be any high strength engineering material such as carbon fibers, glasses, and aramid fibers. Natural materials such as cotton, hemp and others may also be used. The percentages of any added fiber would be determined per the specific application.

[0044] Also, instead of spooling the base yarn, it is contemplated that the base yarn (480) will be about the same size as individual cotton fibers. Therefore, the base yarn could alternatively be cut at around one inch intervals similar to cotton fibers (120) and then integrated to existing textile systems.

[0045] Referring to Figs 5A and Figs. 5B, an induction motor (440) of present invention is illustrated. In this particular embodiment, induction motor (440) will provide a true twist, different from spin zones (440, 441) of Fig. 4C. Motor (440) has a polyphase AC current supplied to the stator windings (532). The applied current results in a rotating magnetic field of constant magnitude in the space occupied by the rotor (520). The field rotates at synchronous speed determined by the frequency and phase of the AC current, and the number of poles in the stator winding (532). In this example, a pair of pole segments (533) about center axis (450) make up a stator pole. In place of a typical rotor, the CNTs sliver (413) will serve as the rotor conductor. As the rotating magnetic field cuts the conductor in the rotor (413), voltages are induced and current flows. These currents experience a sideways force due to the magnitude of the stator (530) magnetic field. The resulting torque will pull it in the same direction of rotation as the stator field.

[0046] The invention embodiment of Figs. 5A-5B is an improvement over existing spin zones having a conventional rotor, because a rotor spinning at such high speeds (10^5 Hz) will cause the outer surface to have a velocity greater than the speed of sound. In practice, this has caused problems of instability. Because the CNT rotor (413) is so small, the surface velocity stays below the speed of sound and it can spin relatively faster.

[0047] A preferred embodiment of motor 440 uses a four phase system. Pole segments (533) contain end portions (531) that are pointed in shape to help direct the rotating magnetic field to the small diameter CNT web (413). A power ferrite is used over an iron laminate on pole segments (533) to help protect against eddy current and core loses to allow the rotating magnetic field to keep changing at high speeds.

[0048] Advantageously, the low density property of the CNTs (110) will allow the CNTs (110) to float in most liquids. Spinning the CNTs in a liquid having a higher density than the CNTs (110) will cause the CNTs (110) to converge or pack into the center of the rotational axis (450). Therefore in a particular embodiment, liquid may occupy the rotor area (520). A conducting liquid, in particular, may be used where the spin is produced electromagnetically. In this design the rotational chamber (520) is kept small to reduce pressures created by centripetal acceleration.

[0049] Referring now to Fig. 6, the stress vs. strain properties of yarn made from CNTs (110) is illustrated. Since it has been observed that the resistance of CNT yarn (480) should follow the stress vs. strain curve, the present invention seeks to provide a method of non-destructive testing by measuring the resistance of the resultant yarn during testing. Hence, essentially working backward, a peak strain and yield strength of the yarn (480) could be determined.

[0050] More specifically, as stated in the yarn spinning industry, it is desirable to instantaneously gather information on the condition and properties of the spun yarn (480) during the spinning process. In normal yarn production, visual inspections are used to monitor yarn quality and production. In the case of CNTs, the size of the fibers do not allow for visual inspection. A different inspection system is required, preferably one that includes process metrics and that does not rely entirely on (or at all on) visual inspection of finished product.

[0051] In one method of making the CNT yarn according to the present invention, the method relies on the electrical conducting properties of the CNTs. This system utilizes the unique electrical conducting properties of the CNTs to manipulate the fibers to twist around themselves to form the yarn. The electrical resistance in the longitudinal direction of the yarn provides manufacturing information on the diameter, packing density and twist rate, even during production of the yarn, which provides inputs to yarn control systems and methods for ensuring uniformity and quality of strength and other yarn properties, preferably in real-time feedback on the machine during the operation of the method. The system and methods are also operable to detect defects and approaching defects such as thin places, thick places, or material composition, with corrective or other adjustments being made as part of the preferred process of making the CNT yarn.

[0052] Dynamic resistance methods using time-dependent electrical current operate to allow more precise observation of the structural properties of the CNT yarns in real time during the production and post analysis.

[0053] Dynamic inspection can be measured by inducing electrical current into the fabricated yarn and monitoring the eddy current relaxation generated from the applied time-dependent magnetic field. These measurements will detect variations in the structural properties of the CNT yarn (480) by comparing against known measurements. An alternate method of the present invention is to measure the capacitance of two plates with the yarn passing between the plates. Still further, an alternate method would be to measure the capacitance of a coaxial capacitor where the conducting CNT yarn becomes the center conductor of the coaxial capacitor and comparing against known values.

[0054] These electrical properties of the CNT can be applied to measure stress-strain behavior of the CNT yarn. This system is operable to provide a non-destructive method for measuring properties such as peak strain to monitor and control critical CNT yarn strength properties.

[0055] Many alterations and modifications may be made by those having ordinary skill in the art without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiments have been set forth only for the purposes of example and that it should not be taken as limiting the invention as defined by the following claims. For example, notwithstanding the fact that the elements of a claim are set forth below in a certain combination, it must be expressly understood that the invention includes other combinations of fewer, more or different elements, which are disclosed above even when not initially claimed in such combinations.

[0056] While the particular System and Methods for Spinning Carbon Nanotubes into Yarn, and Yarn Made Therefrom as herein shown and disclosed in detail is fully capable of obtaining the objects and providing the advantages herein before stated, it is to be understood that it is merely illustrative of the presently preferred embodiments of the invention and that no limitations are intended to the details of construction or design herein shown other than as described in the appended claims.

[0057] Insubstantial changes from the claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of the claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

CLAIMS

What is claimed is:

1. A yarn (480) comprising:

a multiplicity of carbon nanotubes (CNTs) (110) helically twisted about a longitudinal axis (450) to form a CNT twist rate, wherein the CNT twist rate is between about 10,000 turns per meter and 100,000 turns per meter.

2. The yarn of claim 1, further comprising:

an outer twist zone (460) with respect to the longitudinal axis; and

an inner twist zone (461), wherein the CNTs of the outer twist zone and the inner twist zone are twisted in opposite directions with respect to the longitudinal axis.

3. A system (300) for drawing carbon nanotubes (CNTs) (110) from a substrate (211) comprising:

an array of CNTs (210) formed on the substrate about an axis (340); and

a vacuum device (350) comprising a low pressure orifice (310, 310b-d), a high pressure orifice (330), and an intermediate pressure orifice (320), the low pressure orifice arranged at a distance (d) from the array of CNTs along the axis;

wherein the low pressure orifice draws the CNTs from the substrate aligned substantially parallel to the axis.

4. The system of claim 3, wherein the low pressure orifice comprises a size an a shape substantially relating to a change in pressure along the axis; the change in pressure substantially relating to a velocity gradient along the axis, wherein the velocity gradient is proportional to a CNT removal rate and a velocity of the CNTs along the axis which can be controlled by a user by selecting the low pressure orifice size and shape.

5. The system of claim 3, wherein the distance (d) can be adjusted by a user to affect a removal rate of the CNTs from the substrate.

6. The system of claim 3, wherein conductive particles (361) are introduced at the high pressure orifice, wherein the conductive particles combine with the CNTs to make a resulting mass that has a greater electrical conductivity than the CNTs alone.

7. The system of claim 3, wherein the vacuum device has a cavity(363), the cavity having a velocity gradient associated therewith, the velocity gradient able to strip electrons from an

air mixture within the cavity creating a plasma mass (362), the plasma mass combining with the CNTs removed from the substrate making a resulting mass more electrically conductive.

8. A method for drawing carbon nanotubes (CNTs) (110) from a CNT array (210) on a substrate (211) comprising:

aligning a vacuum device (350) low pressure orifice (310, 310b-d) at a distance (d) to the CNTs; and

applying a velocity gradient to the CNT array to remove the CNTs using the low pressure orifice.

9. The method of claim 8, further comprising:

varying a size and a shape of the low pressure orifice to affect the velocity gradient as chosen by a user; and

varying the distance (d) to affect the velocity gradient as chosen by the user.

10. The method of claim 8, further comprising:

introducing conductive particles (361) to the vacuum device;

combining the conductive particles to the CNTs within the vacuum device, making a combination that is more electrically conductive as compared to the CNTs alone.

11. The method of claim 8, further comprising:

configuring the vacuum device to contain within a velocity gradient;

stripping electrons from an air mixture within the vacuum device using the velocity gradient creating a plasma mass (362); and

combining the plasma mass to the CNTs within the vacuum device, making a combination that is more electrically conductive as compared to the CNTs alone.

12. A system (400) for making a base yarn from carbon nanotubes (CNTs) (110) comprising:

a CNT array (210) grown on a substrate;

a mechanical roller (415) to remove the CNTs from the CNT array;

a vacuum device (350) for drafting the CNTs (211) into a sliver(413); and

a first spin zone (440) to impart a rotational force on the sliver (413) to form a base yarn (480).

13. The system of claim 12, wherein the CNTs are removed from the substrate in the form of a web (410), the system further comprising:

a first set of rollers (430) to draft the CNT web into a sliver (413); and

a second set of rollers (431) to further draft the CNT sliver.

14. The system of claim 13, wherein the CNT web is a first CNT web, further comprising a convergence zone (420) to direct the CNT web into the first set of rollers; and a second CNT web (411) wherein the first and second CNT webs combine (412) in the convergence zone.

15. The system of claim 12 further comprising:

a second spin zone (441) to impart a rotational force in a reverse direction of that the first spin zone; and

a spool (470) to take up the base yarn.

16. The system of claim 12 wherein the rotational force is imparted with a magnetic flux.

17. The system of claim 12 wherein the rotational force is imparted with forced air.

18. A method for forming yarn (480) from electrically conductive fibers (110) comprising:

providing the electrically conductive fibers (ECFs) upstream from a spin zone (440);

directing the ECFs into the spin zone; and

twisting the ECFs, using a rotating magnetic field, producing a yarn having a twist rate associated therewith.

19. The method of claim 18, further comprising drafting the ECFs using a vacuum device (350) prior to the directing and the twisting.

20. An induction motor (440) comprising:

a center axis (450);

a plurality of pole segments (533) radially aligned about the center axis;

a plurality of conductive wires (532) wrapped around each of the plurality of pole segments, the plurality of pole segments and the conductive wires together forming a motor stator assembly (530);

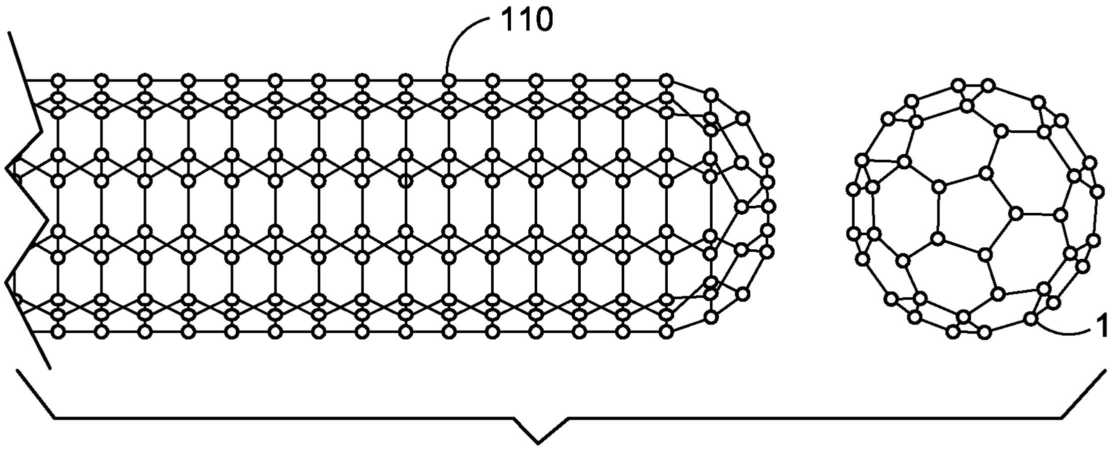
a rotor area (520) located in an area closest to the center axis; and

a polyphase AC current applied to the plurality of conductive wires producing a rotating magnetic field in the rotor area, the rotor area having a multiplicity of electrically conductive carbon nanotube fibers (CNTs) (413), the rotating magnetic field imparting a rotational force on the CNTs.

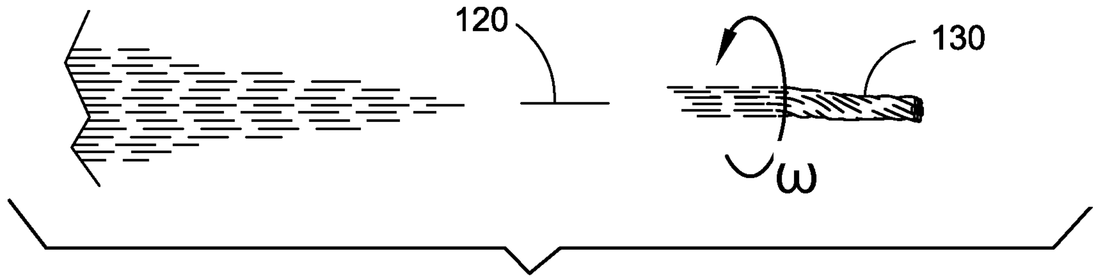
21. The induction motor of claim 20, wherein the pole segments comprise end portions (531), the end portions shaped with a point generally pointed though the center axis.

22. The induction motor of claim 20, wherein the plurality of pole segments comprise powdered ferrite to minimize core losses.

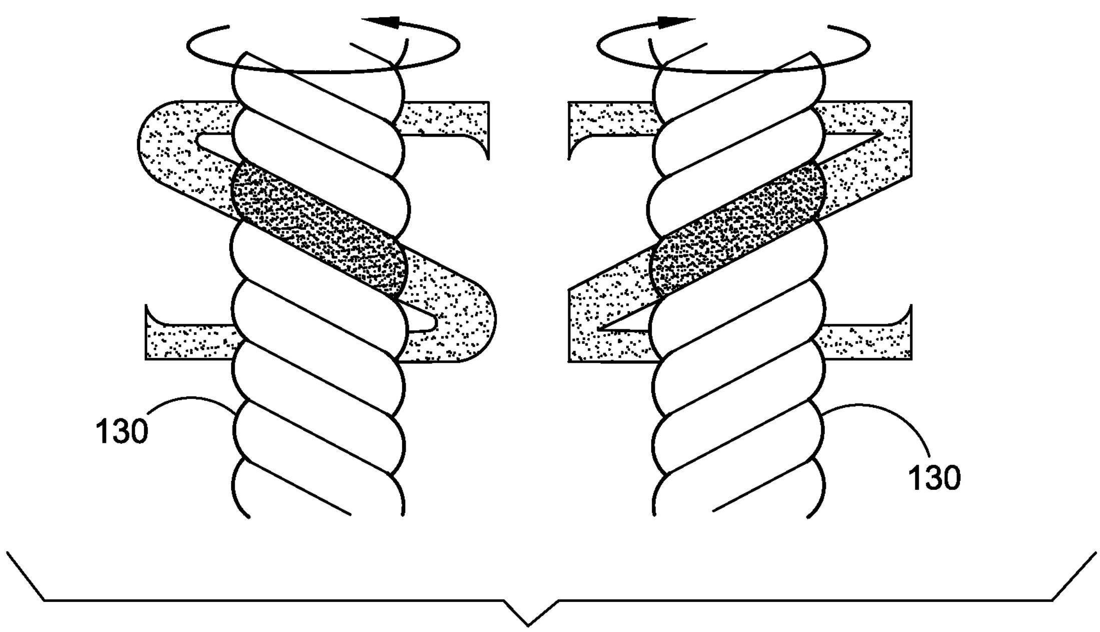
23. The induction motor of claim 20, wherein the rotor area contains a liquid medium having a density greater than the CNTs, wherein the liquid medium and the CNTs rotate together causing a centripetal force on the CNTs with respect to the center axis.



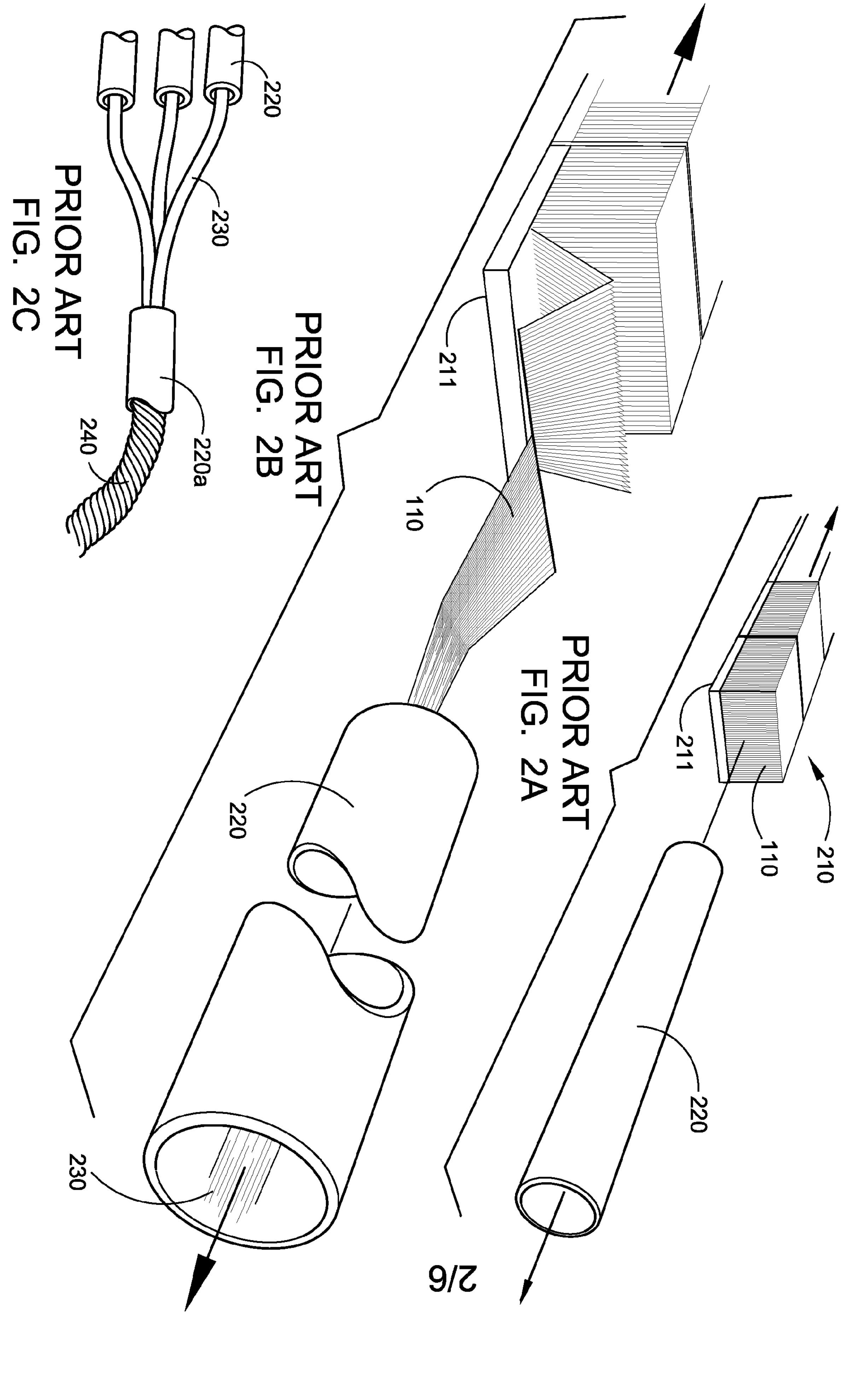
PRIOR ART
FIG. 1A



PRIOR ART
FIG. 1B



PRIOR ART
FIG. 1C



PRIOR ART
FIG. 2C

PRIOR ART
FIG. 2B

PRIOR ART
FIG. 2A

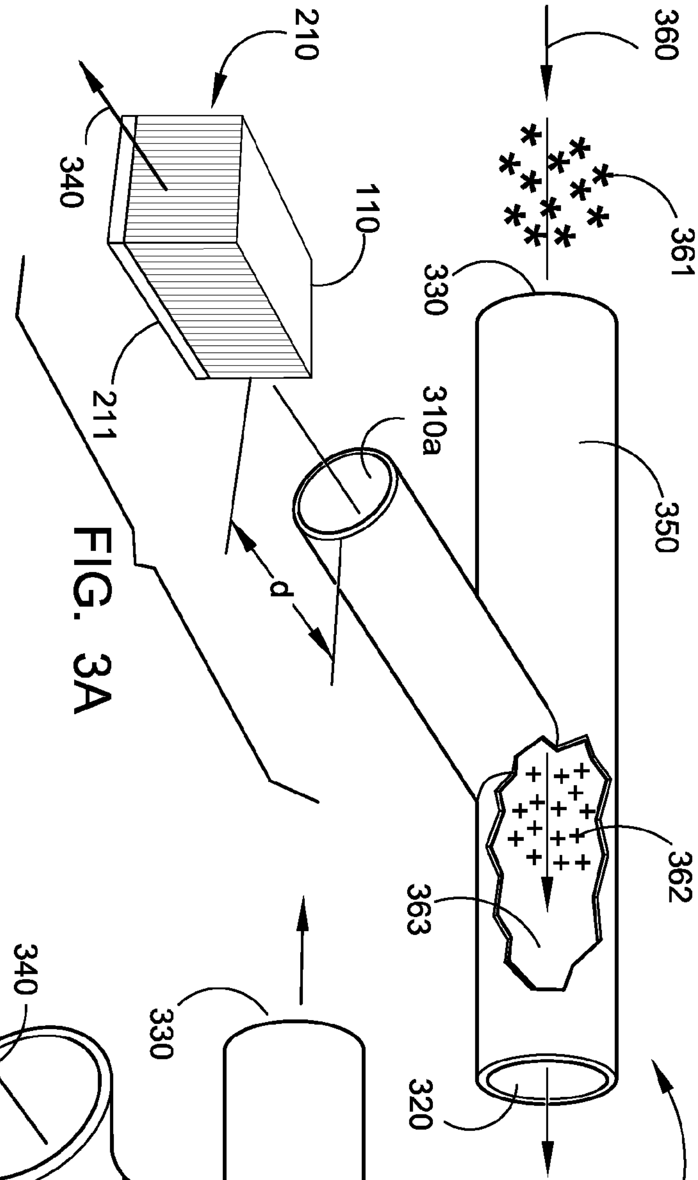


FIG. 3A

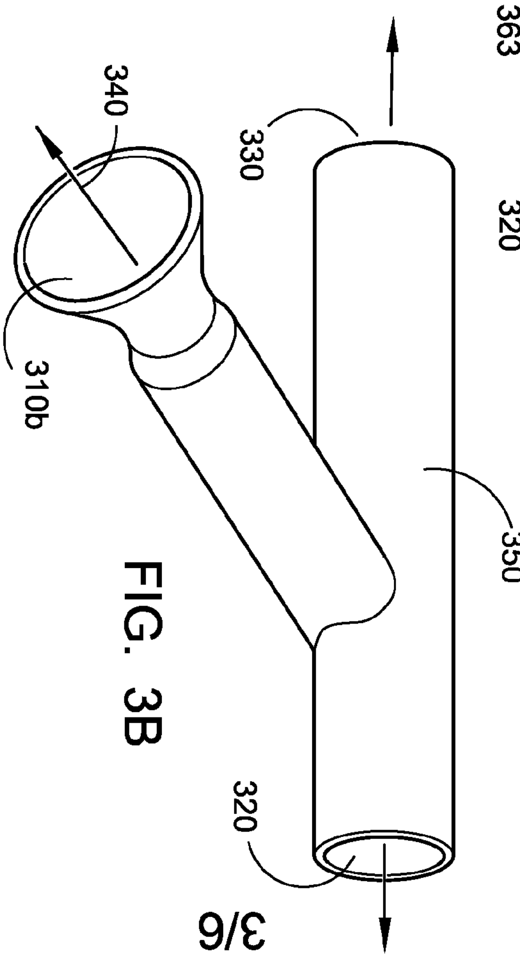


FIG. 3B

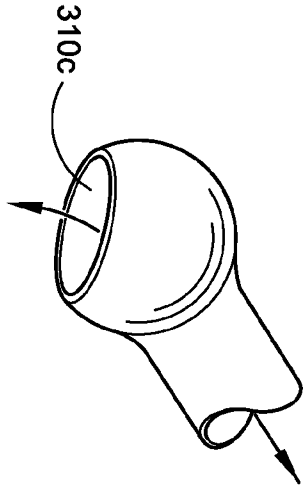


FIG. 3C

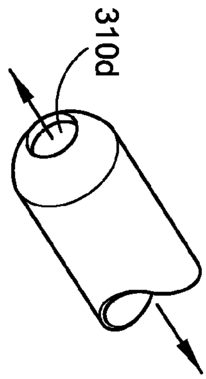


FIG. 3D

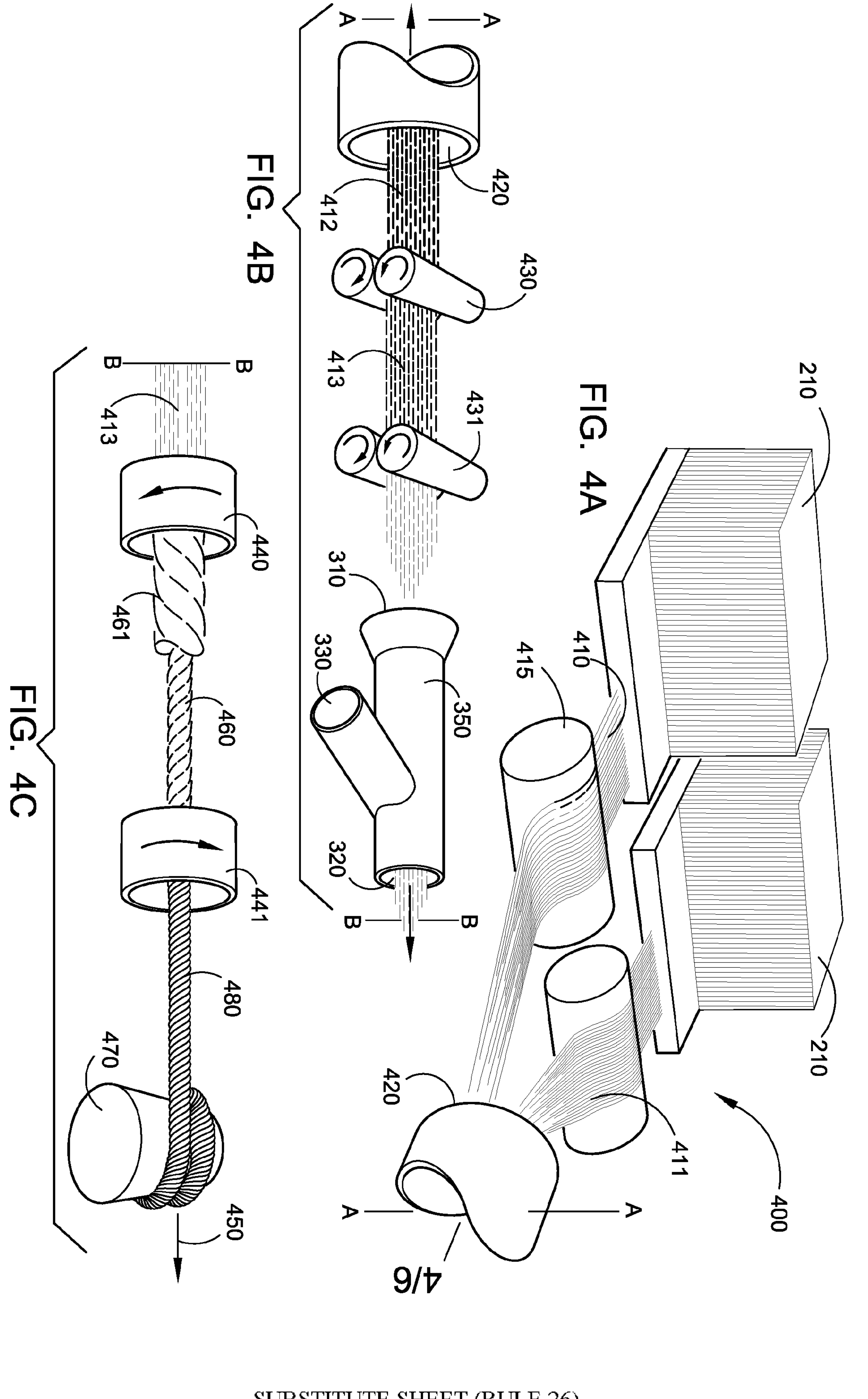


FIG. 4A

FIG. 4B

FIG. 4C

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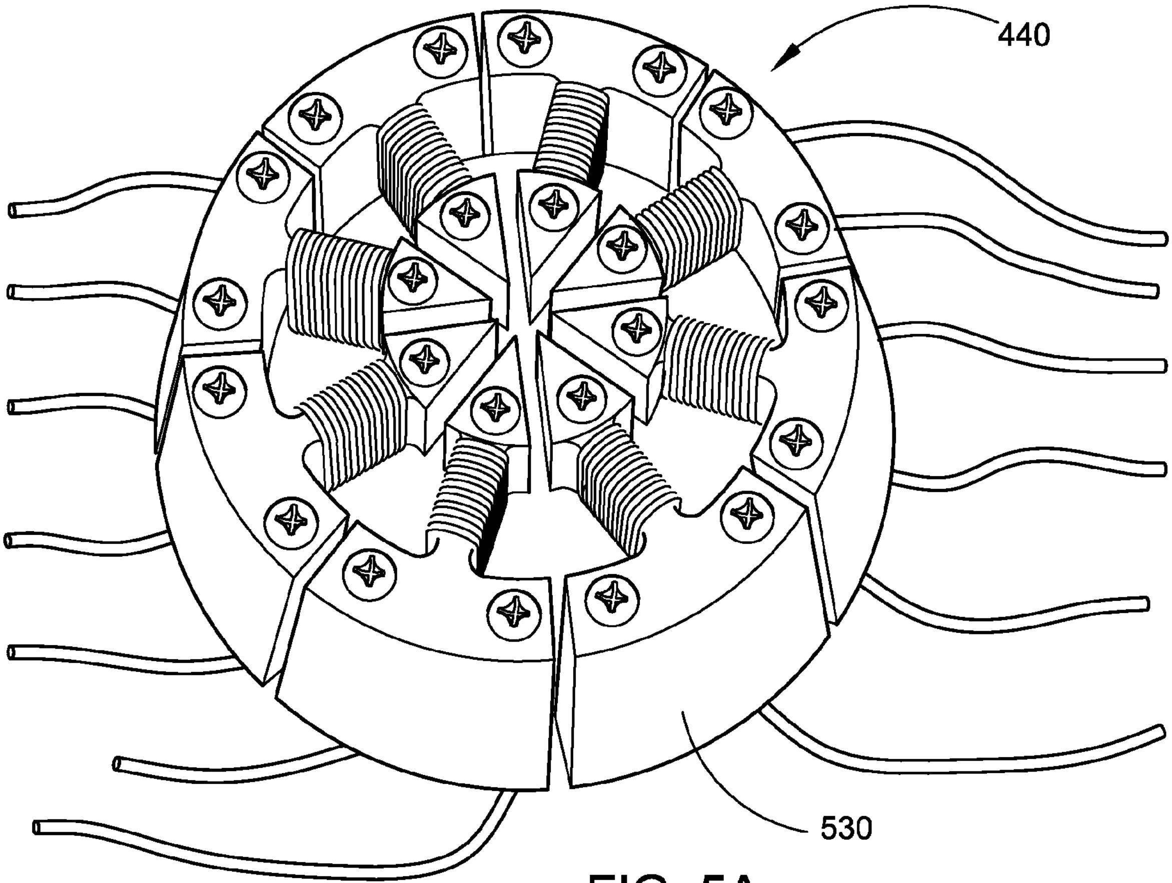

FIG. 5A

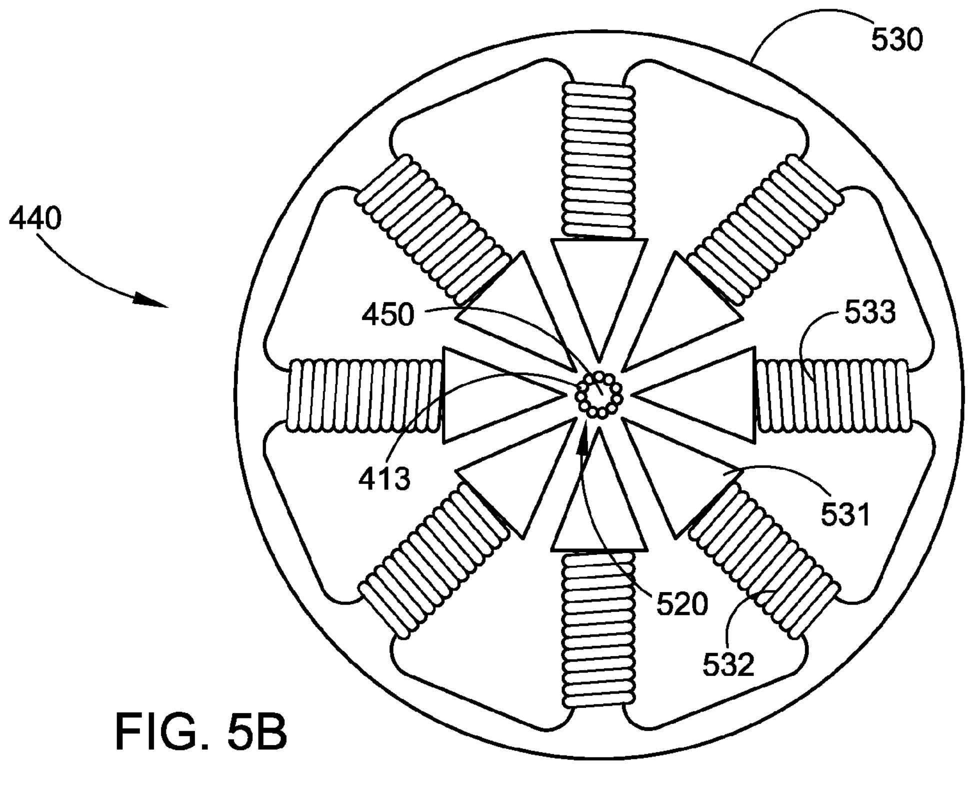

FIG. 5B

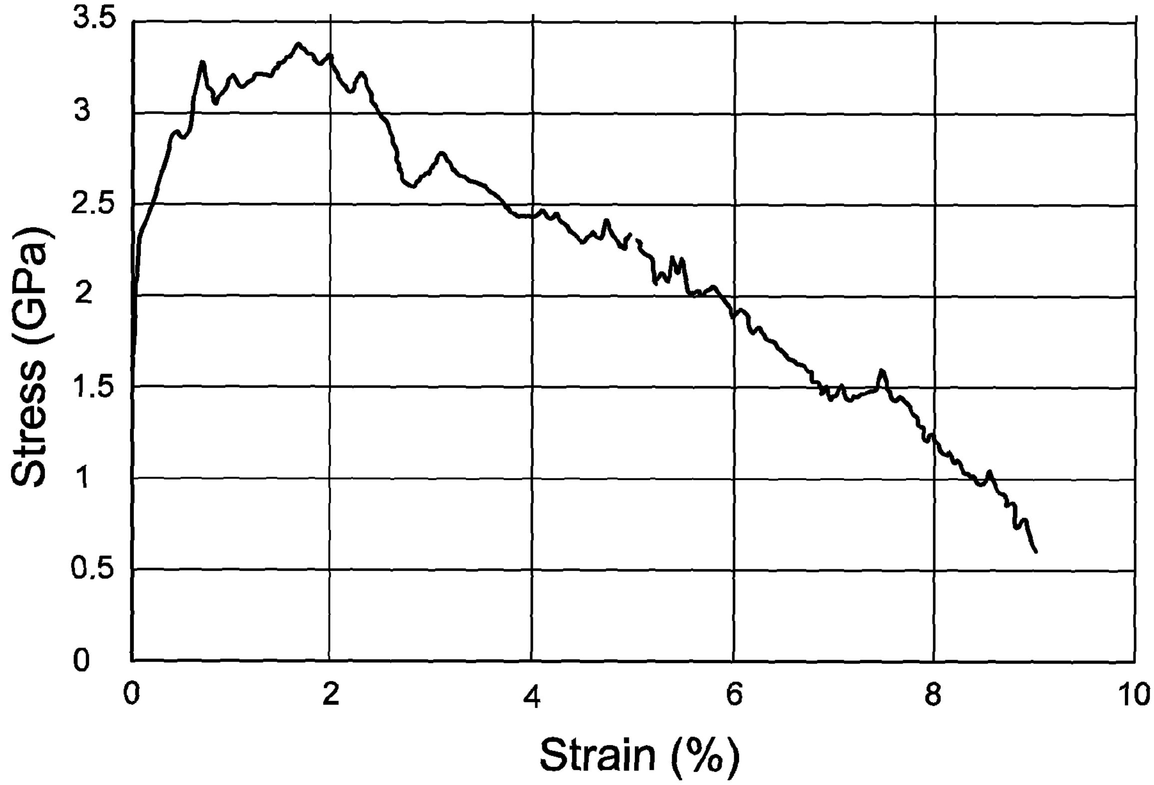

FIG. 6