(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
11 July 2013 (11.07.2013)

W IPO | PCT

(10) International Publication Number
WO 2013/103844 Al

(51) International Patent Classification:
D04H 18/04 (2012.01)

(21) International Application Number:
PCT/US20 13/0203 19

(22) International Filing Date:
4 January 2013 (04.01 .2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/583,242 5 January 2012 (05.01 .2012) US

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(81) Designated States *(unless otherwise indicated, for every kind cf national protection available):* AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind cf regional protection available):* ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.1 7(H))*

— *as to the applicant's entitlement to claim the priority cf the earlier application (Rule 4.1 7(in))*

Published:

— *with international search report (Art. 21(3))*

(54) Title: METHOD OF FORMING NONWOVEN FABRICS UTILIZING REDUCED ENERGY

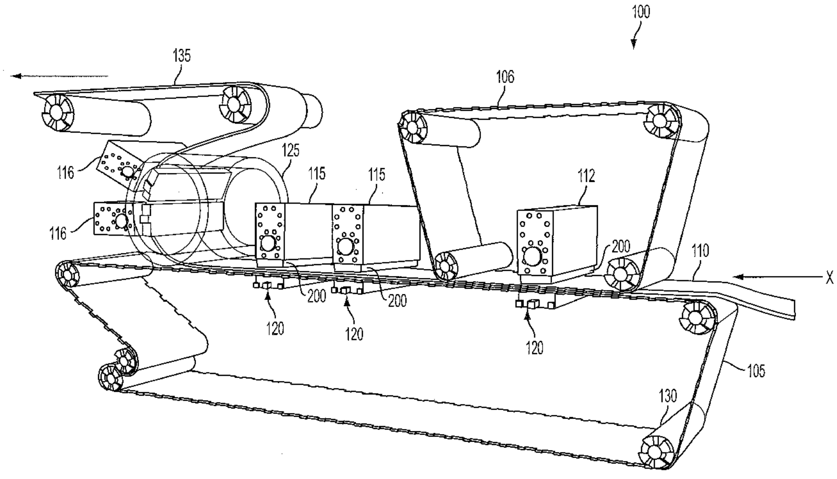

FIG. 1

(57) Abstract: A method for hydroentanglmg a fabric material moving in a processing direction to form a nonwoven fabric is provided, the method including subjecting the fabric material to one or more hydroentanglmg jet strips that include one or both of (i) at least one hydroentanglmg jet strip having a spacing between nozzle orifices of at least about 1200 microns; and (ii) a series of hydroentanglmg j et strips including a first hydroentanglmg jet strip and a second hydroentanglmg jet strip spaced apart in the processing direction, the first hydroentanglmg jet strip being upstream of the second hydroentanglmg jet strip in the processing direction and including a plurality of nozzle orifices having a first spacing between nozzle orifices that is greater than a second spacing between nozzle orifices of the second hydroentanglmg jet strip, the first spacing being at least about 1200 microns.

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METHOD OF FORMING NONWOVEN FABRICS UTILIZING REDUCED ENERGY

FIELD OF INVENTION

The present invention relates generally to hydroentanglement processes for producing nonwoven textiles, and more particularly to reducing the amount of energy necessary to hydroentangle fibers without compromising performance characteristics of the nonwoven textiles produced.

BACKGROUND OF THE INVENTION

Nonwoven fibrous networks are increasingly used as a substitute for conventional woven textiles due in part to their low cost of production. The nonwoven fibers are initially presented as unbound fibers or filaments, which may be natural or man-made. A key step in the manufacturing of nonwovens involves binding the various fibers or filaments together. The manner in which the fibers or filaments are bound can vary, and include both mechanical and chemical techniques that are selected in part based on the desired characteristics of the final product. One bonding method involves hydroentanglement, which utilizes fluid sprayed from jets that impinge upon a web of filaments, causing fiber twisting and entanglement.

Accordingly, hydroentanglement or "spunlacing" is a process used for mechanically bonding a web of loose fibers to directly form a fabric. The underlying mechanism in hydroentanglement is subjecting the fibers to a non-uniform pressure field created by successive banks of high-velocity fluid streams. The impact of the fluid streams with the fibers while the fibers are in contact with adjacent fibers displaces and rotates the adjacent fibers, thereby causing entanglement. During these relative displacements of the fibers, some of the fibers twist around others and/or interlock with other fibers to form a strong structure, due at least in part to frictional forces between the interacting fibers. The resulting product is a highly compressed and uniform fabric formed from the entangled fibers. Such a hydroentangled fabric is often highly flexible, yet very strong, generally outperforming woven and knitted fabric counterparts in performance. Thus, the hydroentanglement process is often capable of providing a high-speed, low-cost alternative to other methods of producing fabrics. Hydroentanglement machines can, for example, produce fabric between about 1 and about 6 meters wide at a rate as fast as about 700 meters of fabric or more per minute. In operation, the hydroentanglement process depends on particular properties of coherent high-speed fluid streams produced by directing pressurized water through orifices defined in strips engaged with manifolds for dispensing water at a selected pressure through the orifices to form the fluid streams.

In conventional hydro entangling systems, a single manifold strip defines a row of orifices of identical size for creating substantially identical fluid streams. In addition, it is typical to utilize a series of manifolds, wherein each presents a hydroentangling fluid stream driven by a higher pressure than the previous fluid stream. The hydroentanglement process utilizes closely-spaced fine, high-speed, columnar water jets described, for example, in U.S. Pat. Nos. 3,403,862; 3,485,706; 3,485,709; 3,486,168 and 3,620,903, the entire disclosures of which are hereby incorporated by reference. Typical jet orifices range in diameter from 80 to 150 microns and the orifices are typically spaced apart at a distance of about 500 to 600 microns. Hydroentanglement jet strips are available from, for example, Groz-Beckert and Nippon Nozzle. In order to provide uniformity of the product and enhance repeatability of the hydroentangling process, the jet streams emitted from the jet nozzles are intended to impact the fabric in a confined space as the jet streams lose their uniform continuity due to various physical aspects of the water jet streams, such as internal flow patterns, wall friction, cavitations and the like. A description of a hydroentangling jet strip device and related jet nozzles is provided in U.S. Pat. Nos. 7,303,465 and 7,467,446, the entire disclosures of which are herein incorporated by reference.

The number of water jets depends on the orifice density (also referred to as the orifice-to-orifice spacing). In general, the spacing of nozzles in traditional systems is about 500 to 600 microns, or approximately 1600 to 2000 orifices per meter. Often, the fibrous web passed through a hydroentangling system is pre-wetted by an initial manifold operating at low pressure, which also helps to get rid of air pockets in the fibrous material. The water delivered in a pre-wetting stage can also act as a lubricant and thereby enhance the subsequent intermingling of fibers. In a traditional system, the water pressure will gradually increase in successive manifolds. The hydroentangled fabric can also be passed through a de-watering system, for example air dryers, where excess water is removed with the help of a vacuum box attached below the belt holding the fabric and inside the drum to avoid submersion of the fabric and achieve better fiber entangling.

Hydroentanglement was initially established in the 1,950's and used as a low energy patterning process. In fact, hydroentanglement was primarily used solely as a finishing process for a previously bonded nonwoven material. This is because the hydroentanglement process yields the most textile-like product for nonwoven materials. Hydroentangled nonwoven fabrics are sometimes referred to as "spunlace" due to the "lace" like structures created by the hydroentangling manufacturing process. Hydroentangled nonwoven fabrics have textile-like features with similar feel and comfort.

Additionally, hydroentangling or spunlacing is also utilized for producing wipes, which are used in a variety of contexts as a consumer product, as well as in medical and other industries. The marketability of some wipes lies in specific functionality, which in turn depends on the bulk of the nonwoven substrate produced after hydroentangling.

It is commonly thought that in order to maintain a strong fabric, the fiber to fiber bonding forces must be maximized throughout the length of the fabric, thus necessitating densely packed jet nozzles along a jet strip to impart energy into the fabric for twisting and entangling the fibers. Operation of these densely packed jet nozzles utilizes large quantities of water. This large water requirement can negatively impact the environment around nonwoven manufacturing plants and can even limit production capabilities of certain plants where availability of sufficient water is a constant challenge.

Accordingly, there is a need to provide a method of producing a nonwoven product having desired qualities related to, for example, bulkiness, quilted appearance, and strength, that utilizes a hydroentangling bonding technique that minimizes the required energy and water input.

BRIEF SUMMARY OF THE INVENTION

Embodiments of the present invention relate to systems and methods for hydroentangling a fabric material moving in a processing direction to form a nonwoven fabric. In certain embodiments, the system advantageously utilizes less water and energy than traditional hydroentanglement systems and can still provide a nonwoven fabric with performance characteristics comparable to nonwoven fabrics formed using conventional systems. Specifically, an inventive aspect of a system described herein includes the use of jet strips having nozzles spaced apart greater than the standard 500-600 microns. Thus, a novel set of jet-strips described herein can be used to reduce the amount of energy expended and the amount of water consumed in a hydroentangling system. Although wider orifice spacing equates to a smaller impact force, wider orifice spacing also allows jet streams to achieve a deeper fiber penetration. Thus, by utilizing an elongate hydroentangling jet strip comprising a plurality of nozzle orifices spaced apart from one another an orifice spacing distance of at least 1200 microns along a length of the elongate hydroentangling jet strip, less energy is required while still maintaining the strength of the hydroentangled structure due to an increased depth of the bonding and the fibers intertwining along the path of the increased depth. Furthermore, using a jet strip with increased orifice spacing can result in a hydroentangled web with regions which are uncompressed, full with loft, bulk and volume and thereby exhibiting improved absorbency and insulating properties. Such a structure is highly desirable for wipes, insulation materials, filtration media, and other applications requiring bulk. Various system and method embodiments described herein can further be used for splitting or fibrillating multicomponent fibers in a more efficient way.

Specifically, embodiments of the present invention relate to a method for hydroentangling a fabric material moving in a processing direction to form a nonwoven fabric, the method comprising advancing the fabric material in the processing direction and subjecting the fabric material to fluid jet streams from one or more hydroentangling jet strips. The fluid jets are emitted from each hydroentangling jet strip at pressures sufficient to hydroentangle the fabric material. In an embodiment, the one or more hydroentangling jet strips operate at a fluid pressure of about 100 bar or greater. Each jet strip comprises a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction. In addition, one or more of the hydroentangling jet strips comprises one or both of (i) at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1200 microns; and (ii) a series of hydroentangling jet strips comprising a first hydroentangling jet strip and a second hydroentangling jet strip spaced apart in the processing direction, wherein the first hydroentangling jet strip is upstream of the second hydroentangling jet strip in the processing direction and comprises a plurality of nozzle orifices having a first spacing between nozzle orifices that is greater than a second spacing between the nozzle orifices of the second hydroentangling jet strip, the first spacing being at least about 1200 microns.

In an embodiment, the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1500 microns. In an embodiment, the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1800 microns. In an embodiment, the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 2000 microns. In an embodiment, the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 3000 microns. In an embodiment, the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 4000 microns.

In an embodiment of the present invention, the first spacing is at least about 1500 microns. In an embodiment of the present invention, the first spacing is at least about 1800 microns. In an embodiment of the present invention, the first spacing is at least about 2000 microns. In an embodiment of the present invention, the first spacing is at least about 3000 microns. In an embodiment of the present invention, the first spacing is at least about 4000 microns. In an embodiment of the present invention, the first spacing is at least about 1800 microns and the second spacing is less than about 1500 microns. In an embodiment of the present invention, the first spacing is at least about 2000 microns and the second spacing is less than about 1500 microns. In an embodiment of the present invention, the first spacing is at least about 2000 microns and the second spacing is about 600 microns.

In various embodiments of the present invention, the hydroentangling method further comprises a pre-wetting jet strip positioned to wet the fabric material with a fluid stream and positioned upstream of the one or more hydroentangling jet strips. In an embodiment, the pre-wetting jet strip operates at a fluid pressure of less than about 80 bar. Preferably, the pre-wetting jet strip operates at a fluid pressure of less than about 50 bar, and more preferably the pre-wetting jet strip operates at a fluid pressure of about 30 bar. A purpose of the pre-wetting jet strip is to saturate the fabric material prior to subjecting the material to the one or more hydroentangling jet strips.

In a particular embodiment of the present invention, the hydroentangling method comprises subjecting the fabric material to fluid jet streams at a first fluid pressure from a pre-wetting jet strip in order to pre-wet the fabric material and subjecting the fabric material to fluid jet streams from a series of hydroentangling jet strips spaced apart in the processing direction and downstream from the pre-wetting jet strip, each hydroentangling jet strip operating at a second fluid pressure greater than the first fluid pressure. Additionally, each hydroentangling jet strip comprises a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction, wherein the series of hydroentangling jet strips comprises a first hydroentangling jet strip comprising a plurality of nozzle orifices having a spacing between nozzle orifices greater than about 1200 microns and a second downstream hydroentangling jet strip having a spacing between nozzle orifices of about 600 microns. Again, the pre-wetting jet strip can typically operate at a fluid pressure of less than about 80 bar while the hydroentangling jet strips can typically operate at a fluid pressure of about 100 bar or greater. In an embodiment, the first hydroentangling jet strip comprising a plurality of nozzle orifices has a spacing between nozzle orifices greater than about 1500 microns, greater than about 2000 microns, greater than about 3000 microns, or greater than about 4000 microns in various embodiments.

Various embodiments of the present invention also relate to a system for hydroentangling a fabric material moving in a processing direction to form a nonwoven fabric, the system comprising one or more hydroentangling jet strips, each hydroentangling jet strip comprising a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction. The one or more hydroentangling jet strips comprise one or both of (i) at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1200 microns (e.g., at least about 1500 microns, at least about 1800 microns, at least about 2000 microns, etc.); and (ii) a series of hydroentangling jet strips comprising a first hydroentangling jet strip and a second hydroentangling jet strip spaced apart in the processing direction, wherein the first hydroentangling jet strip is upstream of the second hydroentangling jet strip in the processing direction. Furthermore, the first hydroentangling jet strip comprises a plurality of nozzle orifices having a first spacing between nozzle orifices that is greater than a second spacing between nozzle orifices of the second hydroentangling jet strip, the first spacing being at least about 1200 microns (e.g., at least about 1500 microns, at least about 1800 microns, at least about 2000 microns, etc.). Embodiments of the system can incorporate any of the embodiments of the jet strips noted above.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings pertinent to this invention are briefly described as follows:

FIG. 1 is a non-limiting schematic illustration of an embodiment of a hydroentangling unit employed for hydroentangling the nonwoven webs.

FIG. 2 is a non-limiting schematic illustration of an embodiment of a jet strip mentioned in FIG. 1.

FIGs. 3A-F are non-limiting top-view schematic illustrations of jet strips with varying jet spacing of the nozzles.

FIG. 4 is a non-limiting schematic illustration of the depth of fiber penetration after water jet impact.

FIG. 5 is a non-limiting schematic illustration of an embodiment of a test-stand hydroentangling unit employed for impinging water jet(s) onto a nonwoven fabric.

FIGs. 6A-B are non-limiting optical cross-sectional views of a nonwoven web before and after water jet impingement.

FIGs. 7A-C are non-limiting top view, schematic illustration of nozzle plates used in the test-stand hydroentangling unit of FIG. 5.

FIGs. 8A-C are non-limiting illustrations of the differences between web structures obtained after water jet impact using (a) a single jet, (b) two jets, and (c) three jets.

FIG. 9 is a non-limiting graph illustrating depth of fiber penetration for single jet impact at 100 and 200 bar pressure.

FIG. 10 is a non-limiting graph illustrating % fiber penetration for single, two, and three jet hydroentangled webs.

FIG. 11 is a non-limiting graph illustrating a comparison of depth of fiber penetration with varying number of jets at two different pressures.

FIGs. 12A-B are non-limiting schematic illustrations of the depth of fiber penetration when hydroentangling a web with a single jet.

FIGs. 13A-B are non-limiting schematic illustrations of the depth of fiber penetration when hydroentangling a web with three jets.

FIGs. 14A-B are non-limiting three-dimensional images illustrating a single jet hydroentangled web and showing (a) jet impact region and (b) non-jet impact region.

FIGs. 15A-B are non-limiting three-dimensional images illustrating the grouping of fibers and strands for a two jet hydroentangled web.

FIGs. 16A-B are non-limiting three-dimensional images illustrating the grouping of fibers and strands for a three jet hydroentangled web.

FIGs. 17A-B are non-limiting graphs plotting (a) jet impact force per meter of manifold and (b) fiber penetration as nozzle spacing is increased.

FIGs. 18A-E are non-limiting optical cross-sectional images of nonwoven webs hydroentangled at 100 bar pressure with jet strips with various nozzle spacings, S.

FIGs. 19A-E are non-limiting optical cross-sectional images of nonwoven webs hydroentangled at 200 bar pressure with jet strips with varied nozzle spacing S.

FIG. 20 is a non-limiting image illustrating the water jet marks after two passes under a jet strip at 100 bar pressure and with an orifice spacing of 4800 microns.

FIGs. 21A-B are non-limiting optical cross-sectional images of nonwoven webs hydroentangled as per conditions mentioned in Example 3.

FIG. 22 is a non-limiting graph illustrating the increased thickness or bulkiness exhibited by a nonwoven material hydroentangled with jet strips having nozzles spaced at 4800 microns versus jet strips having nozzles spaced at the standard 600 microns.

FIG. 23 is a non-limiting graph illustrating the increased consistency of the surface of a nonwoven hydroentangled with a jet strip incorporating the wider spaced nozzles.

FIGs. 24A-E are non-limiting images illustrating the increase in bulkiness achieved with jet strips incorporating wider spaced nozzles.

DETAILED DESCRIPTION

The present inventions will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, these inventions may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout. As used in this specification and the claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise.

As used herein, jet strips are sometimes differentiated by reference to a "hydroentangling" jet strip as opposed to a "pre-wetting" jet strip. In a typical hydroentangling system, a first jet strip is used to simply wet the fibrous material by delivering water jets at a pressure that is insufficient to achieve significant entangling of the fibers (e.g., a pressure of less than about 80 bar, more often less than about 50 bar). This is referred to herein as a pre-wetting jet strip. After treatment by a pre-wetting jet strip, hydroentangling systems typically subject the fibrous material to one or more higher pressure water jet strips adapted to entangle the fibers, which are referred to herein as hydroentangling jet strips. These jet strips operate at pressures of, for example, at least about 100 bar or at least about 200 bar (e.g., about 90 to about 250 bar). Reference to increases in jet strip orifice spacing herein are primarily directed to the hydroentangling jet strips. Consequently, orifice spacing of the pre-wetting jet strip is not particularly limited in the present invention.

It should be understood that various embodiments of the present invention provide an advantageous design for a system comprising at least one elongate hydroentangling jet strip (see element 200, FIG. 2, for example), wherein the spacing S between nozzle orifices is greater than about 600 microns, and more preferably greater than about 1200 microns. In one embodiment, a plurality of elongate hydroentangling jet strips may be provided wherein the orifice spacing S may vary between two or more elongate hydroentangling jet strips. Specifically, an inventive aspect of a manufacturing process and associated system described herein includes the use of jet strips having nozzles spaced apart greater than the standard 600 microns. These jet strips included nozzles spaced from, for example, about 1200 microns to about 4800 microns. These jet strips are typically attached to non-oscillating heads, although use of oscillating jet strips could be used without departing from the invention.

As used herein, the term "fiber" is defined as a basic element of textiles which has a high aspect ratio of, for example, at least about 100 times. In addition, "filaments/continuous filaments" are continuous fibers of extremely long lengths that possess a very high aspect ratio. "Staple fibers" are cut lengths from continuous filaments. The term "multicomponent fibers" refers to fibers that comprise two or more polymers that are different by physical or chemical nature including bicomponent fibers. The term "fabric material" as used herein in reference to fibrous materials, webs, mats, batts, or sheets refers to fibrous structures in which fibers are aligned in an undefined or random orientation. The term "hydroentangled" as applied to a nonwoven fabric herein defines a web subjected to impingement by a curtain of high speed, fine water jets, typically emanating from a nozzle jet strip accommodated in a pressure vessel often referred to as a manifold or an injector. This hydroentangled fabric can be characterized by reoriented, twisted, turned and entangled fibers.

The fibers hydroentangled according to the present invention can vary, and include continuous filament and staple fibers having any type of cross-section, including, but not limited to, circular, rectangular, square, oval, triangular, and multilobal. In certain embodiments, the fibers can have one or more void spaces, wherein the void spaces can have, for example, circular, rectangular, square, oval, triangular, or multilobal cross-sections. The fibers may be selected from single-component (*i.e.*, uniform in composition throughout the fiber) or multicomponent fiber types including, but not limited to, fibers having a sheath/core structure and fibers having an islands-in-the-sea structure, as well as fibers having a side-by-side, segmented pie, segmented cross, segmented ribbon, or tipped multilobal cross-section.

A jet strip with orifice spacing greater than 600 microns requires less fluid to operate and therefore less energy than a jet strip with orifice spacing of about 600 microns. Although impact force of a jet strip with wider orifice spacing is decreased, the bond depth penetration increases as orifice spacing increases. Therefore, a system incorporating jet strips with orifice spacing greater than, for example, about 1200 microns is capable of forming a hydroentangled fabric with characteristics comparable to a hydroentangled fabric formed from a system incorporating only jets strips with orifice spacing of about 600 microns, but at reduced water and energy consumption. Furthermore, a hydroentangling system comprising jet strips with orifice spacing greater than about 1200 microns is able to form bulkier nonwoven fabrics that have applicability in many industries where increased absorbency is desired.

Conventionally, jet strips with spacing on the order of 600 microns between adjacent nozzle orifices is used in multiple banks or injectors to achieve sufficient entangling. It is established herein that this is not necessary and that wider spacing between nozzle orifices can be utilized to achieve deep hydroentangling. Furthermore, if the final fabric is required to have a consolidated structure that is more tightly entangled, this can be achieved by a "finishing" jet strip. A finishing jet strip has a nozzle orifice spacing adapted to achieve a look similar to hydroentangled fabrics formed in systems utilizing conventional jet strips (e.g., a nozzle orifice spacing of about 600 microns).

Various embodiments of the present invention provide a method for hydroentangling a sheet of fabric material moving in a processing direction to form a hydroentangled nonwoven fabric. In an embodiment the method comprises advancing the fabric material in a processing direction. The advancing step may be accomplished using a conveyor belt configured for carrying the fabric material. The fabric material (and the nonwoven fabric resulting therefrom) may also be advanced by being taken up on a series of drums that may carry the finished nonwoven fabric to a dryer or other downstream processing step. The method further comprises subjecting the fabric material to a first plurality of fluid streams. As described herein with respect to various system embodiments, the first plurality of fluid streams may be generated by a corresponding first row of nozzle orifices. The first plurality of fluid streams may thus be spaced apart from one another along a width of the fabric material substantially perpendicular to the processing direction. The first plurality of fluid streams may be configured for impacting the fabric material with a first force intensity to form a hydroentangled fabric.

Various method embodiments of the present invention further comprise subjecting the nonwoven fabric to a second plurality of fluid streams disposed downstream from the first plurality of fluid streams in the processing direction. The second plurality of fluid streams are laterally offset at a selected distance from the first plurality of fluid streams along the width of the fabric material, such that the second plurality of fluid streams impact the fabric material with a second force intensity. In an embodiment, the second force intensity can be less than the first force intensity. In an alternative embodiment, the second force intensity can be greater than the first force intensity.

In an embodiment, the method and related system further comprises subjecting the fabric material to a pre-wetting plurality of fluid streams disposed upstream from the first plurality of fluid streams in the processing direction. The pre-wetting plurality of fluid streams are laterally offset at a selected distance from the first plurality of fluid streams along the width of the fabric material 110 (as shown in FIG. 1), such that the pre-wetting fluid streams impact the fabric material with a pre-wetting force intensity. In an embodiment, the pre-wetting force intensity is less than the first force intensity and is configured for wetting the fabric material. In an embodiment, the pre-wetting force intensity is too low to significantly hydroentangle the fabric material.

In an embodiment of the current invention, a fiber web is hydroentangled on only one surface using at least one manifold engaging at least one jet strip. The jet strip comprises a plurality of orifices spaced along length L of the jet strip, such that orifice spacing S is greater than approximately 600 microns. A nonwoven fabric with enhanced bulk can thereby be produced where the bulk can be controlled by the orifice spacing S. In another embodiment, a fiber web is hydroentangled on both surfaces using a plurality of manifolds, each engaging at least one hydroentangling jet strip. In certain embodiments, the hydroentangling jet strips operate at a pressure of at least about 100 bar, at least about 150 bar, or at least about 200 bar. A typically pressure range for hydroentangling is about 90 bar to about 300 bar, although higher pressures could be used without departing from the invention.

When entangled only on one surface, upon impingement, water jets re-register the jet marks creating and maintaining a quilt like structure. For example, a web may be hydroentangled by using hydroentangling jet strips having an orifice spacing of 4800 microns in a plurality of banks followed by a final bank engaging a hydroentangling jet strip with an orifice spacing of 600 microns. The final bank is used to "finish" the fabric instead of using 5 banks of 600 microns spacing. This will result in a similar fabric (in terms of appearance and performance) at much lower amounts of energy.

In an embodiment of the present invention, a plurality hydroentangling jet strips of varied orifice spacing is utilized. For example, a hydroentangling jet strip with increased orifice spacing S_1 is utilized at a first hydroentangling manifold station. The increased orifice spacing S_1 preferably ranges from approximately 1200 microns to approximately 4800 microns. Subsequent to the initial depth bonding at a first hydroentangling manifold station, a second hydroentangling manifold station is used. The second hydroentangling manifold station engages a second jet strip with orifice spacing S_2. In an embodiment, S_2 is about 600 microns. In certain embodiments, $S_2 =$ Si or $S_2 <$ Si or $S_2 >$ Si. In a preferred embodiment, the second hydroentangling jet strip is positioned downstream of the first hydroentangling jet strip in the processing direction and the second nozzle orifice spacing S_2 is less than the first nozzle orifice spacing Si. It is important to note that the first hydroentangling jet strip is not necessarily adjacent to the second hydroentangling jet strip. The methods and systems disclosed herein can incorporate any number of hydroentangling jet strips. In various embodiments wherein a series of hydroentangling jet strips is used and varying orifice spacing is used, it is advantageous for one hydroentangling jet strip positioned upstream to have a larger spacing between nozzle orifices (e.g., greater than about 1200 microns or greater than about 1500 microns) than at least one hydroentangling jet strip positioned downstream, regardless of whether these two jet strips are adjacent to one another. For example, in certain embodiments, the methods and systems of the invention involve multiple passes through jet strips having the same orifice spacing (e.g., each jet strip with an orifice spacing greater than about 1200 microns or greater than about 1500 microns) followed by multiple passes through jet strips with a different orifice spacing (e.g., about 600 microns).

In a preferred embodiment, a hydroentangling system comprises three or more hydroentangling manifolds. A first manifold engages a first jet strip with orifice spacing S_1 of about 4800 microns. A second downstream manifold engages a second jet strip with orifice spacing S_2 of about 2400 microns. A third manifold (preferably downstream from the second manifold) engages a third jet strip, also referred to as a finishing jet strip, with orifice spacing S_3 of about 600 microns.

In various embodiments of the present invention, the hydroentangling system comprises a pre-wetting manifold station positioned upstream from the first hydroentangling manifold and configured such that the jet streams emanated from the pre-wetting manifold only wet (instead of significantly hydro entangle) the fabric material passed through the system. In an embodiment, the pre-wetting manifold engages a pre-wetting jet strip with orifice spacing S_W. In an embodiment, the pre-wetting manifold engages a pre-wetting jet strip with orifice spacing S_W of approximately 600 microns. In an embodiment, a pre-wetting jet strip operates at a pressure of less than about 80 bar (e.g., less than about 50 bar or less than about 40 bar).

In certain embodiments, two or more components of a multicomponent fiber used in the hydroentangling system of the invention can be separated from each other *(e.g.,* by fibrillation or splitting). For example, in one embodiment, an islands-in-the-sea fiber is used wherein the fiber can be fibrillated to separate the islands and sea component. See, for example, U.S. Pat. Nos. 7,883,772 and 7,981,226, both to Pourdeyhimi *et al.,* which are incorporated by reference herein.

Various embodiments of the system and methods described herein can be used to split multicomponent fibers while utilizing less energy. Structures such as segmented pie and islands-in-the-sea require significant hydroentangling energy to form micro-denier structures. A set of collimated jet streams can cause fiber splitting and subsequent fiber entanglement. The result is a micro-denier, soft, strong, durable nonwoven hydroentangled material. If the multicomponent fibrous structure is subjected to too high of energy initially, the fibers on the surface will split, but leave the rest of the fibers intact. The inventors have determined that with traditional systems comprising a plurality jet strips all with orifice spacing of 600 microns, no more than about 60% of the fibers are split. This leads to poor performance, delamination and loss of durability. However, if a system comprising a plurality of jet strips, wherein at least one initial jet strip has an orifice spacing S of at least 1200 microns is utilized, a higher percentage of the fibers can be split. Furthermore, less energy is required to operate such a system. By utilizing at least one jet strip with a wider orifice spacing S of at least 1200 microns, the fibrous structure is said to be "pre-entangled" prior to fiber splitting/fibrillation. As discussed above, a jet strip with increased orifice spacing is able to achieve an increased bond depth penetration, thereby deeply bonding and securing the individual fibers with a lower impact force. Fibers are more readily split when they are not free to move, i.e., when they are pre-entangled.

As shown in FIG. 1, for example, various embodiments of the present invention provide a system for hydroentangling a sheet of fabric material 110 moving in a processing direction X to form a nonwoven fabric 135. The system comprises at least one hydroentangling manifold 115 engaged with at least one elongate hydroentangling jet strip 200. As shown in FIG. 2, for example, a jet strip 200 comprises a plurality of orifices 201 arranged in at least one row 205 spaced apart along the length **L** of the jet strip 200. Each orifice can be spaced from an adjacent orifice a distance S, as measured from the center of a first orifice to the center of a second, adjacent orifice. Additionally, each orifice 201 can have a diameter **d.** Reference to spacing between nozzle orifices herein refers to center-to-center spacing S as shown in FIG. 2. High pressure fluid streams (e.g., water) are emitted through the orifices such that the fluid streams impact the fabric 110 in a local manner.

It should be further understood that an individual nozzle orifice in the present invention can, in various embodiments, be configured in a "cone-down" or "cone-up" position. Furthermore, a plurality of nozzle orifices 201 comprising a row 205 can be arranged in a staggered configuration or a substantially straight line.

In one embodiment, the fibrous material 110 which is subjected to water jet impingement is fed through a plurality of water jets via an endless conveyor belt 105. This belt 105 can be made of polymeric materials or stainless steel and can also be characterized by fine perforations and patterns. The conveyor belt is also referred to as a forming or supporting surface. Drums 130 can be used to move the belt 105 through the hydroentangling system 100.

The embodiment of a hydroentangling system 100 shown in FIG. 1 includes at least one hydroentangling manifold 115 (also referred to as a "bank"). A manifold is, for example, a pressure vessel or container extending along the width of the hydroentangling machine that is capable of accommodating a jet strip. A hydroentangling jet strip operates at a pressure sufficient to hydroentangle the fibrous material 110. Embodiments of the present invention can further comprise a pre-wetting manifold 112 that engages a pre-wetting jet strip that operates at a lower pressure which is sufficient only to pre-wet the fibrous material 110 and not sufficient to significantly hydroentangle the fibrous material.

A chamber inside a manifold emanates at least one fluid stream at a required pressure in a direction or plane which is substantially perpendicular to the machine direction X. In an embodiment, a pressure gauge (not shown) can be used to monitor pressure of an emanated fluid stream. An embodiment of a hydroentangling system 100 further comprises a de-watering system, for example air dryers, where excess fluid is removed with the help of a vacuum box 120 attached below the belt 105 to avoid submersion of the fabric and achieve better fiber entangling. The system can further include apron 106 that moves across the top face of the fibrous material around the location of the first manifold.

In various embodiments of the present invention, pressurized fluid streams impinge the face of the fabric 110 as the fabric 110 passes under a manifold 115. An embodiment of a hydroentangling system 100 comprises a plurality of manifolds 115 used to impinge the face of the fabric material 110. As used herein, the term "pass" defines a single run of the fabric material through a system 100. In an embodiment of a hydroentangling system 100, fabric material 110 can undergo a plurality of passes through the system. In various embodiments, the fibrous web material 110 may be subjected to multiple manifolds or banks 115 and/or passes on a single side.

In an alternative embodiment where bulk is not desired, or registering of the various jet streams is not critical, additional impingement and penetration may be carried out on the back-side of the fibrous web material 110 with a plurality of jet streams engaged with at least one backside manifold 116. In an embodiment, a large drum 125 can be used to roll the fabric material 110 such that the backside of the fabric material 110 is exposed to a jet strip 200 engaged with a backside manifold 116. Such a production system is also useful for hydro-splitting nonwovens comprised of multicomponent filaments. The additional backside jet streams facilitate breaking the various filaments at a different surface than the surface impinged by the at least one frontside manifold 115. However, when bulk is an objective of the finished product the nonwoven web 110 is only subjected to water jet streams on a single side.

In an embodiment, a manifold is capable of engaging a jet strip 200 (also referred to as a "nozzle strip"). Various hydroentanglement system and method embodiments described herein provide a first elongate hydroentangling jet strip 200 defining at least one nozzle orifice 201 that generates a corresponding fluid stream. Various embodiments (such as that shown in FIG. 1, for example), comprise at least one additional jet strip 200. Embodiments of the present invention can comprise a plurality of hydroentangling jet strips 200. In an embodiment, a jet strip 200 is approximately 25 mm wide, 1 mm thick and has a length **L** spanning the width of the hydroentangling machine. Depending on the desired end-use of the hydroentangled material 135, length **L** can range between 1.2 to 7 m, although the length can vary without departing from the invention.

A jet strip 200 is characterized by a plurality of surface perforations also referred to as orifices or nozzles of required diameters and perforated at intervals along the length **L** of a jet strip 200. A plurality or curtain of water jets emanates from the nozzle orifices 201 and causes the fibers of the fibrous web 110 to be mechanically bonded by turning, twisting, inter-twining and penetrating the surface fibers into the thickness, which thereby forms a high-strength, flexible hydroentangled fabric 135.

FIGS. 3(a) to 3(f) serve to illustrate exemplary jet strips that could be used with the present invention and particularly highlight that orifice diameters can be varied in the present invention (within a single jet strip row or varied between adjacent jet strip rows), and these figures also provide various examples of changes in orifice spacing. As shown in FIG. 3(a), for example, various embodiments of jet strip 200 comprise a first row 205 of a plurality of nozzle orifices. A first orifice 202 has diameter $\mathbf{di}$. In an embodiment, a second orifice 204 has diameter $\mathbf{d_2}$. In various embodiments, $\mathbf{di=d_2}$, $\mathbf{di<d_2}$, or alternatively $\mathbf{di>d_2}$. As illustrated in FIG. 3(b), for example, various embodiments of jet strip 200 comprise a first row 205 of a plurality of orifices and a second row 210 of a plurality of orifices. As illustrated in FIG. 3(c), for example, embodiments of jet strip 200 comprise a plurality of orifice rows. As illustrated in FIGs. 3(a)-3(f), for example, diameters of each nozzle orifice in a single row, or across a plurality of rows, can remain the same or vary.

Furthermore, a plurality of orifices 201 in a jet strip can have orifice spacing S. The term "orifice spacing", "orifice-to-orifice distance", or "pitch" is the distance S measured between two successive centers of orifices 201 in a same row of a nozzle strip 200. As illustrated in FIGs. 3(d) and 3(e), for example, various embodiments of a jet strip 200 comprises a plurality of nozzle orifices 201 evenly spaced along length **L** of jet strip 200. In an alternative embodiment, spacing S between nozzle orifices comprising a single row is altered. As illustrated in FIG. 3(f), for example, various embodiments of a jet strip 200 comprise a first row 205 of a plurality of nozzle orifices with orifice spacing Si and a second row 210 of a plurality of nozzle orifices with orifice spacing S_2. In various embodiments, Si=S_2, S!<S_2, or alternatively Si>S_2.

In many traditional embodiments of a jet strip 200, adjacent nozzle orifices 201 in a single row are evenly spaced by a distance S of about 600 microns. In an embodiment of the system described herein, adjacent nozzle orifices 201 in a single row of at least one jet strip are spaced by a distance S of at least about 1200 microns. In certain embodiment, adjacent nozzle orifices 201 in a single row of at least one jet strip are spaced by a distance S of at least 1500 microns. In an embodiment, adjacent nozzle orifices 201 in a single row are approximately spaced by a distance S of at least 2400 microns. In an embodiment, adjacent nozzle orifices 201 in a single row are approximately spaced by a distance S of at least 4800 microns. Subjecting the fibrous web 110 to jet strips with increased spacing S can increase bulkiness and consistency in the registering of the respective jet streams for creating a "quilted" composition. Furthermore, less water and energy is required to operate a jet strip with increased spacing S.

Commonly, in a jet strip, the pitch or spacing between the orifices defines the jet density. In a traditional embodiment where orifice spacing is 600 microns, the process requires a relatively high energy in bonding the webs to obtain a well-bonded uniform, regular substrate 135. Also, a higher number of orifices produces high water consumption throughout the process, requires a greater amount of energy to obtain the desired pressures at higher flow rates, and also increases the task of re-cycling and filtering the used water. Thus, a novel set of jet-strips described herein can be used to reduce the amount of energy expended and the amount of water consumed in a hydroentangling system. In various embodiments of a hydroentangling system, for example, nozzle strips have an orifice density ranging from 200 - 1600 orifices per meter indicating a decrease in the number of water jet streams as the orifice-to-orifice spacing increases. This implies a reduction in amount of fluid flowing through the orifices, also defined as mass flow rate *(m),* and subsequently a decrease in the amount of energy required by the system.

When a water jet emanates from a nozzle plate with nozzle inlet diameter d_n, it remains collimated through a certain length having a glassy appearance. Prior development in hydroentangling technology has established the diameter of constricted water jets, d_j as

$$d_j = \sqrt{C_d} d_n$$

where $C_d \approx 0.62$ which is the discharge coefficient of a sharp-edge capillary nozzle generating a constricted water jet with nozzle inlet diameter d_n. Using the diameter of constricted water jet d_j, the mass flow rate through a nozzle can be calculated as follows:

$$m = \frac{\pi}{4} \rho d_j^2 V$$

where $p = 998.2kg I m^3$, representing the density of water at room temperature. Pi is the pressure in Pa, and V_l is in m/s. Note that 1 bar is equal to 10^5 Pa. Thereby, the above mentioned set of equations can be used to calculate the flow rate of water through each of the nozzle strips used in an embodiment of a hydroentangling system.

Furthermore, the impact force, F of a liquid jet is linearly related to its velocity, V, and flow rate, m. In turn, the flow rate, m, is directly proportional to gauge pressure. As mentioned, p is defined as the liquid's density. Therefore the following equations can be used to calculate impact force F of a liquid jet stream:

$$F\ a\ \mathrm{mV}, \text{ where } m = \frac{\pi}{4} pd^2 V$$

Bernoulli's equation is used to calculate the velocity of a constricted water jet, which is given as:

$$V = \sqrt{2\frac{P}{\rho}}$$

From the above equations, we conclude $Fa?$.

Therefore, wider orifice spacing equates to a smaller impact force. However, wider orifice spacing also allows for deeper fiber penetration as explained below. Thus, by utilizing wider spaced nozzle jets, such as greater than about 1200 microns, for example, less energy is required while still maintaining the strength of the hydroentangled structure due to an increased depth of the bonding and the fibers intertwining along the path of the increased depth.

Nozzle orifice spacing S affects percent fiber penetration. As illustrated in FIG. 4, for example, due to the impact of a water jet on a fibrous material 110, fibers from the surface 405 are carried along the jet and reach deep inside the textile substrate 410. The distance between the fibers on the surface of the web to the point where the fibers penetrate inside the bulk of the web at the jet impact region is defined as the depth of fiber penetration. Accordingly, the fiber penetration relative to the thickness of the web, measured using ASTM D 5729, for example, is defined as % *fiber penetration* and is calculated using the following equation:

$$\% FiberPenet\ ration = T_2 l T_1 \times 100, \text{ where}$$

T_1 - Web thickness after water jet impact (mm); and

T_2 - Depth of fiber penetration (mm).

Optical cross-sectional views of hydroentangled fabrics can be used to reveal the transfer of surface fibers into the bulk of the web at a jet impact point. It is noted that there is no surface fiber penetration at a non-jet impact region. When high speed water jets hit the surface of a web, the jets carry the directly impacted fibers along their path and also drag peripheral fibers in the vicinity of the jet impact region along their path as well. Increased orifice spacing corresponds to deeper bonding penetration. The jet impact regions exhibit the interlocking of fibers by twisting, turning and bending with each other and of course fiber penetration. The increase in depth of fiber penetration in thickness direction also indicates that the interaction between fibers coming under the influence of adjacent water jets is reduced as orifice spacing is increased. Hydroentanglement systems incorporating jet strips with increased orifice spacing provide for more flexibility of the fibers upon impact of the water jets. This flexibility is characterized by the fibers being enabled to penetrate deep into the web, thus enhancing the interlocking action by supplying fibers disposed within the structure with energy to bond by twisting. This construction provides for a "depth" bonding of the nonwoven fibers versus the mere surface bonding of the prior art.

In the case of a single jet, surface fibers penetrate deep inside the web at the jet impact region as the high-speed water jet pushes the surface fibers deep into the bulk of the web. Since the fibers are not held by any other force except inter-fiber friction, there is better fiber movement along the jet direction and the inter-fiber friction is negligible when compared to the applied impact force. On the other hand, when a plurality of jet streams are closely spaced, the depth of fiber penetration is lower because adjacent jets on either side of a first jet hold and restrain the two ends of a fiber while the middle jet acts on pushing the fiber down. Due to no freedom of movement for the fiber, the fiber movement is restrained and effective fiber penetration is reduced.

In various embodiments, an exemplary fiber length is about 2500 microns. Therefore, as orifice spacing in a jet strip is increased above 600 microns, adjacent jet streams are less able to hold and restrain the ends of a fiber and the percent of fiber penetration increases.

Apart from deeper fiber penetration with increase in orifice spacing S, hydroentangled webs also exhibited a "quilt like" structure as a result of jet impingement with wider orifice spacing. For orifice spacing of, for example, about 2400 and about 4800 microns, the energy imparted by the water jets is sufficient to rebound off of the mesh utilized in forming the web and produces a mirror "quilt". By contrast, a "quilt" construction is not formed for similar water jets spaced at 600 microns, for example. When high speed water jets hit the surface of a web, the jets carry the directly impacted fibers along their path and also drag peripheral fibers in the vicinity of the jet impact region along their path as well. Therefore, when a curtain of jets impact the surface of a web, the fibers move into the web and either penetrate deeper with a wider orifice spacing, or their mobility is arrested due to more closely spaced jet streams. In addition, the impact of jet streams also compresses the web at the point of jet impact wherein the amount of compression depends on how closely the jets are positioned. If the jets are closely spaced as in the conventional hydroentangling jet strip with a nozzle density of 1600 per meter (i.e., orifice spacing of 600 microns) for example, then the web is compressed more than a web impacted by jet streams more widely spaced. Upon jet impact, both the level of compression and the amount of surface fiber transfer, both of which determine the final thickness and degree of entanglement, are affected by the orifice spacing S. Specifically, the impact force of fluid streams per meter of fibrous web material decreases as orifice spacing S increases. As the spacing between the jets is increased, fibers were entangled by forming a knot-like structure which compresses the web at the jet impact region. Moreover, between the clustered entangled regions of a web hydroentangled with the widest orifice spacing, there are regions which are uncompressed, full with loft, bulk and volume and thereby exhibiting improved absorbency and insulating properties. Such a structure is highly desirable for wipes and other applications requiring bulk.

EXPERIMENTAL

Several examples are discussed below demonstrating certain embodiments of the invention. The examples demonstrate the effect of nozzle strips having wide orifice spacing on the properties of hydroentangled nonwoven fabrics and on the amount of hydroentangling energy required. The testing conducted in the examples is briefly described below.

To examine the quantitative effects of the embodiments of the present invention in improving nonwoven fabric strength, the tear resistance of certain inventive nonwoven examples was evaluated in the processing direction and compared to corresponding tear strength of a control fabric. The tear test measures the force required to tear a textile specimen in which a tear is initiated prior to testing. More particularly, according to ASTM D2261-96 "Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure (Constant- 65 Rate-of-Extension Tensile Testing Machine)," a rectangular specimen (75 mmx200 mm) of the nonwoven fabric is precut in the center of the long edge to form a two-tongued or "trouser-shaped" specimen. One tongue is clamped into the lower jaw of the machine and the other is clamped into the upper jaw. During the measurement, the distance between the jaws increases and the force applied to the fabric, due to the movement of the jaws, propagates the tear. During the tear test, the force required to move the clamps is also recorded. The results can be normalized with the average resistance of the control fabric for better comparison.

As one skilled in the art will appreciate, it is important that hydroentangled fabrics maintain their strength against tensile load. It is important to ensure that amending the tear resistance of the fabrics does not damage their tensile properties. For this reason, certain embodiments of the nonwoven fabric of the invention were examined using the tensile test methods outlined in ASTM D 5035-95 entitled "Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method)". This test reports the force required to tear a textile specimen in the tensile direction. In accordance with this method, a rectangular specimen (25 mm x 150 mm) of the nonwoven fabric is mounted on the upper and lower jaw of a tensile testing machine with its long dimension parallel to the direction of force application. The distance between the jaws is increased until the break of the fabric occurs, caused by the force applied to the specimen. The force required to break the textile specimen and the elongation of the specimen are reported during the measurement.

Enhanced bulk of the hydroentangled material is another important characteristic achieved by various embodiments of the present invention. Certain product samples were tested for their thickness. Thickness is the measure of distance between the opposing surfaces of the nonwoven material and is measured using thickness test methods outlined in ASTM D 5729-97 entitled "Standard Test Method for Thickness of Nonwoven Fabrics."

Additionally, the basis weight of the samples was examined using test methods outlined in ASTM D 3776/D 3776M-09ae2 entitled "Standard Test Method for Mass Per Unit Area (Weight) of Fabric." This test reports a measure of mass per unit area and is measured and expressed as grams per square meter (g/m^2).

In addition, air permeability of certain samples was examined using test methods outlined in ASTM D 737-04 entitled "Standard Test Method for Air Permeability of Textile Fabrics." This test method reports a measure of air flowing through the fabric sample in a give area.

Absorbency of certain samples was measured using a Gravimetric Absorbency Testing System (GATS). This test indicates the lateral wicking ability of a fabric, or the ability of the material to take-up liquid spontaneously in the direction perpendicular to its plane.

Finally, the specific energy of certain samples was measured using a calculation based on the Bernoulli equation that ignores viscous losses throughout the system. Having the manifold's pressure, P, the jet velocity is:

$$V = \sqrt{2\frac{P}{\rho}}$$

Where p = Density of the water in room temperature, assumed to be 998 *kg/m*^{3}. The pressure P is expressed in Pa and *Vis* in *m/s.* Note that 1 bar is equal to 10^5 Pa.

The rate of energy transfer by waterjets is calculated as follows:

$$\dot{E} = \frac{\pi}{8} p d^2 C_d V^3$$

Where d is the diameter of the orifice capillary section and expressed in m. C_d is the coefficient of discharge (described below and set to be ~ 0.62), and $\dot{E}$ $_{1S}$ the energy rate in *J/s.*

Specific energy expressed in*j/kg* of fabric is calculated using the following equation:

$$SE = \frac{\dot{E}}{\dot{M}}$$

Where $\dot{M}$ is the mass flow rate of the fabric in *kg/s* and is calculated as follows:

$$\dot{M} = Sample\ Width \times Basis\ Weight \times Belt\ Speed$$

Sample width is expressed in *m*, Basis Weight is expressed in *kg/m*^{2}, and Belt speed is expressed in *m/s.* Therefore, *SE* is expressed in Joules (or kilo Joules) per kilogram of fabric. The total energy transferred to the fabric is therefore, dependent on jet pressures used, the line speed and the basis weight of the web used.

Example 1

A hydroentangling test apparatus used in this example is shown in FIG. 5. This illustrated apparatus 300 was employed for carrying out a preliminary study of this invention and producing a control sample for comparison with alternative configurations which become the subject of the invention. This test apparatus 300 comprises a high-pressure pump system (not shown in the figure) engaging a filtration system (not shown) and water supply 320, a pressure vessel or manifold 305 operating up to a pressure of 400 bar, a motor (not shown) which drives a stainless-steel drum with fine mesh 325, a feed roller 308, and wind-up rollers 309. A pressure gauge 306 measured pressure within the manifold 305. The entire apparatus 300 is supported on a stand with a leveling screw 315 that can adjust the height of the drum from the nozzle exit 330 fixed in the manifold 305. The nozzle plate used for this study can be accommodated in a flange 335 mounted under the manifold 305. The web shown in FIG. 6A was subjected to impingement from a water jet emanating from the manifold 305.

The tested material is characterized by having layers of fiber webs. Specifically, the employed web comprises a cross-lapped nylon fiber web laid over a polyester cross-lapped fiber web. This combination of webs is passed from the feed roller 308 over the drum 325 to a wind-up roller 309. The tested webs were hit with at least one water jet emanating from an orifice of a nozzle plate illustrated in FIGS. 7A-7C. The experiment was carried out with three different nozzle plates, namely a nozzle plate with a single orifice (FIG. 7A), a nozzle plate with two orifices FIG. 7B), and a nozzle plate with three orifices (FIG. 7C). The nozzle plates were each approximately 38.1 mm (one and-a-half inch) long, approximately 12.7 mm (half-an-inch) wide, and approximately 1 mm thick. These dimensions were such that the nozzle plates can be fixed in the slot of a flange of the manifold. For each of the nozzle plates, an orifice diameter of 130 microns and an orifice-to-orifice spacing of 600 microns were maintained. The jets exiting from the orifices were impinged onto the web mentioned above at a distance of approximately 25.4 mm (one inch) or less. This distance was maintained between the nozzle exit 330 and the web surface with the help of leveling screw 315 on the test-stand.

In conducting the experiments, two different manifold pressures of 100 and 200 bars were utilized in varying experiments to produce the respective jets. Upon the impact of water jets, the webs revealed distinct web structures. However, the common behavior of fibers in all the obtained web structures was bending, twisting, turning, intermingling, and penetrating within the webs. In other words, upon the water jet impact, fibers from the surface are transferred into the bulk of the web and are entangled. The transfer of surface fibers into the bulk is visualized by staining the fibers directly. Since the webs comprise two different polymer fibers, they can be dyed preferentially. Accordingly, the surface fibers were dyed/stained accordingly after water jet impingement. Subsequently, the cross-sections of the web were examined and analyzed by using an optical microscope. The surface penetrating nylon fiber web has a darker color and can be differentiated from the bulk after dyeing the web structures.

FIG. 6B shows an optical cross-sectional view of surface fiber transfer into the bulk of the web when a single jet emanating from a single nozzle was tested. FIGS. 8A-8C illustrate optical cross-sectional views of the hydroentangled webs impinged by (A) a single jet, (B) two jets and (C) three jets.

FIGS. 9 to 11 show the depth of fiber penetration values as a function of input/gauge pressure for the web structures impacted by a single jet, two jets, and three jets. The results indicate that % fiber penetration increases with an increase in pressure from 100 to 200 bars. This trend is similar for web structures impinged with a single jet, two jets and three jets. This is due to the increase in impact force that pushes the surface fibers deeper into the bulk of the web.

On the other hand, when the depth of fiber penetration was compared for web structures impinged with a single jet, two jets and three jets, the trend was different from the effect of pressure on depth of fiber penetration. FIG. 11 illustrates the effect of increasing the number of jets on the depth of fiber penetration. The results exhibited a decrease of % fiber penetration corresponding to an increase in the number of jets. This trend is considered to be a result of the interaction of fibers that are under the influence of neighboring jets when two or more jets are impinged on a nonwoven web.

The above experiment suggests that traditional hydroentangling systems, which use multiple jets positioned in a row across the nonwoven web at a typical spacing of 600 microns, provides for surface bonding, but limits bonding within the depth of the structure. FIGS. 12 and 13 are schematic illustrations of certain findings of the experiments conducted with jet nozzles spaced at 600 microns. In the case of a single jet, surface fibers are penetrating deep inside the web at the jet impact region as the high-speed water jet pushes the surface fibers deep into the bulk of the web. As illustrated in FIG. 12, when impinging a fabric with a single jet, there is better fiber movement along the jet direction and the inter-fiber friction is negligible when compared to the applied impact force. On the other hand, when three jets spaced at 600 microns are utilized, the depth of fiber penetration is found to be lower than the single jet and two jets under the same pressure. The reason for this behavior can be attributed to the fact that, in a three-jet system, jet number 1 and jet number 3 hold and restrain the two ends of a fiber, while the middle jet number 2 pushes the fiber down. However, due to no freedom of movement for the fiber, the fiber movement is restrained and effective fiber penetration is reduced. Since the distance between the jets spacing or orifice-to-orifice distance is 600 microns and the standard fiber length is 2500 microns (25 mm), it is assumed that at least one fiber could be interacting with more than one jet. Consequently, when water jets from a nozzle strip with three orifices impinge the web, adjacent jets would hold the fibers coming under their action and swirl the fibers, entangle them with each other, and restrain them from penetrating deeper.

Therefore, as illustrated in FIG. 13B, for example, a consolidated and integrated structure is obtainable when hydroentangled with three or more jets. This represents the standard practice of the current industry. Such configurations of multiple jets provide for surface bonding. Thus to summarize, the study of the effect of an increasing number of water jets indicates that water jets may interact with the neighboring jets resulting in intermingling of fibers rather than deeper fiber penetration. FIG. 11 also shows that depth of fiber penetration increases with an increase in pressure from 100 to 200 bars, regardless of the number of jets used to impinge the fibrous web.

FIGS. 14-16 illustrate the three-dimensional structures of webs hydroentangled with a single jet, two jets and three jets, each jet strip having the standard 600 micron orifice spacing. The images were obtained using a Digital Volumetric Imaging technique - a three-dimensional image forming procedure. FIG. 14 shows the difference between (A) jet impact and (B) non-jet impact region with fibers penetrating deep inside the bulk of the web hydroentangled with a single jet stream. The darker nylon fibers are clearly shown as having penetrated into the nonwoven web in Fig. 14A, while the figure in FIG. 14B shows less intermingling between the darker nylon fibers and the lighter polyester fibers. FIGS. 15 and 16 illustrate a grouping of surface penetrating fibers and the formation of twisted strands along the jet direction due to the fiber interaction mechanism associated with the additional jets.

Example 2

Examples were produced utilizing the hydroentangling system substantially as illustrated in FIG. 1. In the exemplary embodiment, the system is equipped with five pressure vessels or manifolds, also referred to as banks, of which the first one (manifold 1) is employed to pre-wet the fibrous materials utilizing a standard jet strip having nozzles spaced at approximately 600 microns. Downstream manifolds 2 and 3 were provided with jet strips having orifice spacing S greater than the standard 600 micron spacing. However, the jet strips at manifolds 2 and 3 were of similar spacing in order to provide consistency in the registering of the various jet streams. Furthermore, both jet strips at manifolds 2 and 3 were stationary and non-oscillating in order to further increase consistency of the various jet streams. The non-oscillating aspect is important so multiple jets may register for defining a predetermined "quilting" of the web. For some experiments, only one of manifolds 2 and 3 are used.

As illustrated in FIGS. 17A-17B, for example, the theoretical impact force of fluid streams per meter of fibrous web material decreases as nozzle orifice spacing S increases. However, the percent of fiber penetration increases as nozzle orifice spacing S increases. These results were recorded for a material passed through a single manifold having the listed jet spacing. As shown in FIG. 17B, for example, for a jet spacing of 1800 microns and above, percent fiber penetration was approximately 80% and upwards to 100%. Moreover for a more quantitative comparison purpose, the depth of fiber penetration can be measured by image analysis techniques and used to characterize the structures impinged with varying water jets.

FIGS. 18A-18E illustrate optical cross-sectional images of webs that are hydroentangled using nozzle strips with increasing jet spacing. Each nozzle has a diameter d of 130 microns and the pressure P is 100 bar. FIGS. 19A-19E illustrate optical cross-sectional images of webs that are hydroentangled using nozzle strips with increasing jet spacing. Each nozzle has a diameter d of 130 microns and the pressure P is 200 bar. The cross-sectional images reveal the surface fiber transfer into the bulk of the web. FIGS. 18 and 19 illustrate the "depth" bonding achieved when a water jet drags the fibers peripheral to the jet impact region. The fibers are twisted and grouped together forming a twisted and consolidated strand of fibers along the thickness direction. These strands with twisted fibers penetrate into the bulk of the web by accumulating fibers along its path during the jet impingement. The formation of twisted fiber strands is also accompanied by interlocking of these fibers in the bulk of the web resulting in entanglement regions as the fibers are unrestrained.

As illustrated in FIGS. 18 and 19, utilization of a wider orifice spacing gradually decreases the degree of web compression and compression is only observed at the jet impact region with wider orifice spacing. As illustrated in FIGS. 19D and 19E, for example, "quilted" structures are formed where orifice spacing is 2400 microns and 4800 microns, respectively. For orifice spacing of 2400 and 4800 microns, for example, the energy imparted by the water jets at 200 bar is sufficient to rebound off of the mesh utilized in forming the web and produces a mirror "quilt". By contrast, as illustrated in FIG. 19A for example, a "quilt" construction is not formed for the similar 200 bar water jets spaced at 600 microns. Furthermore, as illustrated in FIGS. 18 and 19, when the amount of jet impact pressure is increased from 100 bar to 200 bar, the impact force transferred by the water jets onto the web is higher. Therefore, bond depth penetration increases as pressure increases.

Example 3

Fiber webs were subjected to water jet impingement by using one or more manifolds in an experimental set-up substantially similar to the system of FIG. 1, containing nozzle strips having orifices placed at an interval higher than 600 microns and operating at pressures between 100 to 200 bars. When entangled only on one surface, upon impingement, water jets re-register jet marks, thereby creating and maintaining a quilt like structure.

In one experiment, a web is pre-entangled by using jet strips having a spacing of 4800 microns in four banks followed by using jet strips having a spacing of 600 microns in the final bank to "finish" the fabric instead of using five banks of 600 microns spacing. This will result in a similar fabric produced with much lower amounts of energy. Note that when the fabric cross-section is examined, it can be seen that fibers penetrate deeper at pre-determined spacing corresponding to the orifice spacing when the wider spaced strips are utilized. FIG. 20 shows water jet marks in the web following two passes through a jet strip with an orifice spacing of 4800 microns. FIGS. 21A and 21B illustrate the difference in fiber penetration when comparing a single pass through a 600 micron spaced jet strip (A) and a single pass through a 4800 micron spaced jet strip followed by a 600 micron spaced jet strip (B).

In a second experiment, nonwoven fibrous webs were subjected to water jet impingement only on the face-side using a nozzle strip having wider orifice spacing or fewer orifices on the aforementioned hydroentangling machine. With this action, fibers are well entangled and form bond points at the jet impact regions. As mentioned earlier, the pre-entangled web is characterized by fibers forming strands which are twisted and grouped. This can be accomplished by passing the webs under nozzle strips having orifices spaced at least 1200 microns apart or greater. The pre-entangled web is further subjected to water jet impingement with manifolds containing nozzle strips with higher orifice density (reduced spacing) than the former strips.

The webs subjected to hydroentanglement are described as follows: nylon fibers of approximately 50.8 mm (2-inch) fiber length and 3.3 denier were cross-lapped into a fibrous web with a basis weight of 40 g/m^2. Polyester fibers of 6 denier and approximately 50.8 mm (2-inch) fiber length were layered to form a cross-lapped nonwoven web of 160 g/m^2 basis weight. These two nonwoven fibrous webs were laid over each other to form a consolidated web with two layers (a composite layered web). The resultant web is configured with nylon web forming the surface and polyester web as a bulk with a total basis weight of 200 g/m^2. The above-mentioned samples were prepared in the pilot facility of the Nonwovens Institute at North Carolina State University in Raleigh, N.C.

The initial manifold for pre-wetting comprised a nozzle strip with orifices of 130 μm diameter spaced at 600 μm, and operated at a pressure of 30 bar. The second manifold was used for entangling at 200 bar using jet strips with varied orifice spacing during subsequent tests. Tests were run for orifice spacing of 600 microns, 1200 microns, 1800 microns, 2400 microns, and 4800 microns.

Table 1 lists the properties of the hydroentangled fabrics. Absorbency, permeability, and thickness are improved significantly as orifice spacing increases. Tear seems to be essentially unaffected. Tensile strength is lowered as spacing increases. Use of the wider-spaced nozzles results in significant reduction in the specific energy needed to create the hydroentangled web. At 4800 micron spacing, the energy is about 12% of that for 600 micron spacing.

Table 1

Jet spacing (μm)	Thickness (mm)	Specific energy (J/kg)	Mass flow rate (kg/s)	Absorbency (g/g)	Air permeability (cfm)	Grab tensile (N)		Tongue tear (N)	
						MD	CD	MD	CD
600	1.55	27,468	2.87	3.00	119.08	447.16	443.69	93.80	81.63
1200	1.76	13,734	1.43	3.96	147.57	421.32	387.69	88.39	79.00
1800	1.97	9,173	0.96	4.31	152.45	394.00	397.41	91.21	75.50
2400	1.84	6,892	0.72	4.08	151.69	335.19	288.26	91.60	75.20
4800	2.43	3,471	0.36	5.69	171.65	273.16	234.83	84.02	65.80

Example 4

The data shown in Table 2 below was generated using a system similar to the hydroentangling system as described with respect to Example 3 above except that two manifolds were employed for entangling instead of one. These are the second and third manifolds shown in FIG. 1. The spacing of the respective nozzles was the same for the respective manifolds enabling a consistent registration of the respective jet streams to be recorded. The pre-wet manifold at 30 bar was fitted with 600 micron spaced strips while manifolds 2 and 3 were fitted with jet strips originally spaced at 600 microns for a control sample and then provided with jet strips having wider spaced nozzles and pressurized at 200 bar. Note that all fabric properties are improved and the tear increases with increasing orifice spacing. Furthermore, the difference in tensile is smaller when multiple hydroentangling manifolds are utilized.

Table 2

Jet spacing (μm)	Thickness (mm)	Specific energy (J/kg)	Mass flow rate (kg/s)	Absorb-ency (g/g)	Air permea-bility (cfm)	Grab tensile (N)		Tongue tear (N)	
						MD	CD	MD	CD
600	1.866	54,937	5.75	4.79	160.00	356.93	414.25	77.83	70.56
1200	2.090	27,468	2.88	5.12	176.78	434.23	513.49	83.52	69.39
1800	2.084	18,346	1.92	6.37	177.80	392.66	382.67	93.23	81.40
2400	2.632	13,784	1.44	4.24	199.39	358.78	458.65	89.79	82.20
4800	2.828	6,943	0.73	5.93	200.10	252.63	326.41	80.97	81.01

Example 5

The data shown in Table 3 below is derived from the same hydroentangling system as utilized with respect to Example 3, except that two manifolds were employed for entangling instead of one and different fibers were used than the fibers utilized in Example 3. The fibers used in this example were nylon 6 and pulp. The web was produced by carding and crosslapping and the pulp was introduced during hydroentangling by feeding a sheet of pulp. Cellulose fibers comprising 50 g/m^2 of pulp (jet side) and 50 g/m^2 of nylon (PA6) (belt side) are hydroentangled.

The pre-wet manifold at 30 bar was fitted with 600 micron spaced strips while manifolds 2 and 3 were fitted with jet strips having nozzles originally at 600 microns for a control sample and then with wider spaced nozzles emitting fluid at 200 bar. The spacing of the respective nozzles was the same for Manifolds 2 and 3 for maintaining consistency of registering the fluid streams. Note that the absorbency of the standard 600 micron spacing is attained by expending less energy. Furthermore, a smaller difference in tensile and tear strength is maintained.

Table 3

Jet spacing (μm)	Thickness (mm)	Specific energy (J/kg)	Basis weight (gsm)	Absorbency (g/g)	Grab tensile (N)		Tongue tear (N)	
					MD	CD	MD	CD
600	0.91	54,937	127	6.71	361.23	392.84	64.6	45.77
1200	0.97	27,468	120	5.23	289.86	356.45	80.76	48.34
2400	1.05	13,784	137	6.83	243.89	326.85	55.58	46.87
4800	1.00	6,493	134	6.55	171.91	310.98	49.12	51.36

Example 6

The data shown in Table 4 below is derived from a hydroentangling system as defined for Example 3, except that two manifolds were employed for entangling instead of one and a spunbonded web is used. The spunbond web is described in U.S. Patent No. 7,981,336, the entire disclosure of which is herein incorporated by reference. The web was fed to the hydroentangling unit together with a sheet of pulp. Cellulose fibers comprising 50 g/m^2 of pulp (jet side) and 50 g/m^2 of mixed media (belt side) are hydroentangled.

The pre-wet manifold at 30 bar was fitted with 600 microns spaced strips while Manifolds 2 and 3 were fitted with similar jet strips with varying spacing at 200 bar. Note that mechanical properties have improved and a smaller difference in absorbency is maintained over the standard 600 microns spacing while expending lesser energy.

Table 4

Jet spacing (μm)	Thickness (mm)	Specific energy (J/kg)	Basis weight (gsm)	Absorbency (g/g)	Grab tensile (N)		Tongue tear (N)	
					MD	CD	MD	CD
600	0.93	54,937	116	6.03	290.31	178.51	10.31	16.98
1200	0.82	27,468	121	5.04	296.14	170.25	8.56	18.52
2400	0.81	13,784	107	5.02	308.83	161.99	9.39	19.14
4800	0.93	6,493	110	5.10	307.45	177.9	11.09	17.88

Example 7

This example describes another set of results obtained in order to minimize the required hydroentangling energy. Webs were hydroentangled using a jet strip with 4800 micron jet spacing followed by a jet strip having 600 micron spacing (labeled as 4800+600). The fabric is compared with the results obtained when using only 600 micron spacing for the two jet strips (labeled as 600+600). The series were hydroentangled at 100 bar pressure. The results are summarized in Table 5 below. The mechanical properties are comparable and this suggests that by altering the sequence of jet strips and jet spacing, one can attain comparable mechanical properties accompanied by reduction in the amount of energy required.

Table 5

Jet spacing (μm)	Specific energy (J/kg)	Mass flow rate (kg/s)	Absorbency (g/g)	Grab tensile (N)		Tongue tear (N)	
				MD	CD	MD	CD
600+600	19,420	4.06	4.06	356.7	313.2	78.8	62.4
4800+600	10,937	2.30	5.04	308.8	356.7	78.3	68.1

Example 8

The advantages of utilizing wider spaced jet nozzles were also tested utilizing splittable bicomponent fibers. The samples used are spunbonded bicomponent nonwoven webs composed of polymers polyester (PET) and nylon (PA) forming a 16 segmented-pie configuration. The obtained spunbonded webs comprised PET/PA in the ratio of 80:20 with a basis weight of 100 g/m^2. These examples were subjected to water impingement on the face and back by a total of five manifolds as shown in FIG. 1 with Manifolds 2 and 3 subjecting the web on a first surface and Manifolds 4 and 5 subjecting the web to hydroentangling forces while on a drum on an opposite surface. The jet spacing for Manifolds 2-5 were varied as indicated in Table 7 below. For example, reference to " 1800 + 600" means that manifolds 2 and 4 were operated at an orifice spacing of 1800 microns and manifolds 3 and 5 were operated at an orifice spacing of 600 microns. In the configuration used, each manifold comprises one jet strip with the indicated orifice spacing.

In these examples, the first or initial manifold for each pass was kept constant for pre-wetting the sample. It consisted of a jet strip with 600 microns jet spacing and an orifice diameter of 130 microns. After the web was pre-wetted, the web was subjected to the four manifolds described above. The pressures used for the manifolds are shown in Table 6 below. For all of these samples, the webs were subjected to two passes through the hydroentangling machine, such that a total of 8 manifolds (other than pre-wetting) were used for entangling. Table 7 below compares the energy consumption and mechanical properties after two passes. Note that at lower energies, the hydroentangled fabric performance is improved for all initial orifice spacing larger than 600 microns.

Table 6

Manifold(s)	Pressure (Bar)
1	25
2	150
3	220
4	220
5	220

Table 7

Jet spacing (µm)	Specific energy (J/kg)	Air permeability (cfm)	Grab tensile (N)		Tongue tear (N)	
			MD	CD	MD	CD
600+600	45,614	8.17	423.9	260.1	30.3	17.1
1800+600	30,414	7.36	431.8	277.3	31.7	17.8
2400+600	28,498	8.63	437.7	288.2	34.2	20.7
4800+600	25,652	8.12	508.9	282.3	33.9	19.8

Example 9

The same fabrics used in Example 8 are subjected to three passes through the hydroentangling unit indicating a total of 12 manifolds (other than pre-wetting) are used for hydroentangling. 600 + 600 + 600 means the fabric was passed through the hydro unit three times and uses 600 micron spacing for all 4 manifolds in all three passes. 1800 + 600 + 600 means the fabric was subjected to 1800 micron spacing for all 4 manifolds on a first pass, followed by two passes where all 4 manifolds had 600 micron spacing. In all cases, the pre-wet manifold used 600 micron spacing.

Table 8 below compares the energy consumption and mechanical properties after three passes. Here again, the fabric is superior to those produced with standard 600 micron spacing. Even increasing the jet spacing from 600 to 4800 microns resulted in a sample with improved mechanical properties without compromising other fabric properties. Note that the air permeability is essentially the same in these fabrics, thus indicating the same level of consolidation/splitting of the fibers. These results demonstrate that one can achieve strong fabrics by reducing the amount of energy required for hydroentangling when we utilize at least one widely-spaced jet strip.

Table 8

Jet spacing (µm)	Specific energy (J/kg)	Air permeability (cfm)	Grab tensile (N)		Tongue tear (N)	
			MD	CD	MD	CD
600+600+600	68,421	5.13	365.3	227.9	24.7	16.1
1800+600+600	53,221	5.08	418.4	252.0	25.6	14.4
2400+600+600	51,305	5.68	419.4	221.2	27.0	13.1
4800+600+600	48,459	5.23	408.9	242.5	27.0	14.9

Example 10

In another example, a fabric is constructed of polyester staple fibers and the resulting web was produced by carding and crosslapping. This fabric was subsequently hydro entangled. The results are described below.

An advantage of the wider spaced nozzles is evidenced by the increase in bulk exhibited by nonwovens subjected to the subsequent wider spaced water jets. FIGS. 22, 23 and 24 illustrate the results that were achieved. As shown in FIG 22, a nonwoven substrate subjected to a single manifold of water jets spaced apart 4800 microns exhibited a thickness almost twice as great as a nonwoven substrate subjected to a single manifold of water jets spaced apart the standard 600 microns. This results in a much bulkier substrate.

Additionally, as shown in FIG. 23, the surface area of nonwovens subjected to wider spaced nozzles have a more uniform consistency due to the removal of the frequency of the water streaks and subsequent surface bonds. The contrast shown on the Y axis relates to the strength of the texture clarity and the distance shown on the X axis is the spacing along the width of the fabric. The period is indicative of the spacing of the texture. Details of the technique used to measure texture is described in J. Sobus, B. Pourdeyhimi, J. Gerde and Y. Ulcay, Assessing Changes in Texture Periodicity Due to Appearance Loss in Carpets: Gray Level Co-occurrence Analysis, Textile Research Journal, 61, (10), 557-567, (1991), and O. Berkap, B. Pourdeyhimi and A. Seyam, Texture Evolution in Hydroentangled Nonwovens, International Nonwovens Journal, Spring, 1-0, Spring (2003), the entire disclosures of each are herein incorporated by reference. Furthermore, the widening of the water nozzles produces wider bands of bonded fibers as shown in FIG. 24. This produces a more consistent surface area for wipes and the like.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. A method for hydroentangling a fabric material moving in a processing direction to form a nonwoven fabric, the method comprising:

advancing the fabric material in the processing direction;

subjecting the fabric material to fluid jet streams from one or more hydroentangling jet strips, each hydroentangling jet strip comprising a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction, wherein the one or more hydroentangling jet strips comprise one or both of (i) at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1200 microns; and (ii) a series of hydroentangling jet strips comprising a first hydroentangling jet strip and a second hydroentangling jet strip spaced apart in the processing direction, wherein the first hydroentangling jet strip is upstream of the second hydroentangling jet strip in the processing direction and comprises a plurality of nozzle orifices having a first spacing between nozzle orifices that is greater than a second spacing between nozzle orifices of the second hydroentangling jet strip, the first spacing being at least about 1200 microns.

2. The method of claim 1, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1500 microns.

3. The method of claim 1, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1800 microns.

4. The method of claim 1, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 2000 microns.

5. The method of claim 1, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 3000 microns.

6. The method of claim 1, wherein the first spacing is at least about 1500 microns.

7. The method of claim 1, wherein the first spacing is at least about 1800 microns.

8. The method of claim 1, wherein the first spacing is at least about 2000 microns.

9. The method of claim 1, wherein the first spacing is at least about 3000 microns.

10. The method of claim 1, wherein the first spacing is at least about 4000 microns.

11. The method of claim 1, wherein the first spacing is at least about 1800 microns and the second spacing is less than about 1500 microns.

12. The method of claim 1, wherein the first spacing is at least about 2000 microns and the second spacing is less than about 1500 microns.

13. The method of claim 1, wherein the first spacing is at least about 2000 microns and the second spacing is about 600 microns.

14. The method of claim 1, further comprising a pre-wetting jet strip positioned to wet the fabric material with a fluid stream and positioned upstream of the one or more hydroentangling jet strips.

15. The method of claim 14, wherein the pre-wetting jet strip operates at a fluid pressure of less than about 80 bar.

16. The method of claim 1, wherein the one or more hydroentangling jet strips operate at a fluid pressure of about 100 bar or greater.

17. The method of claim 1, comprising:

subjecting the fabric material to fluid jet streams at a first fluid pressure from a pre-wetting jet strip in order to pre-wet the fabric material;

subjecting the fabric material to fluid jet streams from a series of hydroentangling jet strips spaced apart in the processing direction and downstream from the pre-wetting jet strip, each hydroentangling jet strip operating at a second fluid pressure greater than the first fluid pressure and comprising a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction, wherein the series of hydroentangling jet strips comprises a first hydroentangling jet strip comprising a plurality of nozzle orifices having a spacing between nozzle orifices greater than about 1200 microns and a second downstream hydroentangling jet strip having a spacing between nozzle orifices of about 600 microns.

18. The method of claim 17, wherein the pre-wetting jet strip operates at a fluid pressure of less than about 80 bar.

19. The method of claim 17, wherein the hydroentangling jet strips operate at a fluid pressure of about 100 bar or greater.

20. The method of claim 17, wherein the first hydroentangling jet strip comprises a plurality of nozzle orifices having a spacing between nozzle orifices greater than about 2000 microns.

21. A system for hydroentangling a fabric material moving in a processing direction to form a nonwoven fabric, the system comprising one or more hydroentangling jet strips, each hydroentangling jet strip comprising a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction, wherein the one or more hydroentangling jet strips comprise one or both of (i) at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1200 microns; and (ii) a series of hydroentangling jet strips comprising a first hydroentangling jet strip and a second hydroentangling jet strip spaced apart in the processing direction, wherein the first hydroentangling jet strip is upstream of the second hydroentangling jet strip in the processing direction and comprises a plurality of nozzle orifices having a first spacing between nozzle orifices that is greater than a second spacing between nozzle orifices of the second hydroentangling jet strip, the first spacing being at least about 1200 microns.

22. The system of claim 21, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1500 microns.

23. The system of claim 21, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 1800 microns.

24. The system of claim 21, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 2000 microns.

25. The system of claim 21, wherein the one or more hydroentangling jet strips comprise at least one hydroentangling jet strip having a spacing between nozzle orifices of at least about 3000 microns.

26. The system of claim 21, wherein the first spacing is at least about 1500 microns.

27. The system of claim 21, wherein the first spacing is at least about 1800 microns.

28. The system of claim 21, wherein the first spacing is at least about 2000 microns.

29. The system of claim 21, wherein the first spacing is at least about 3000 microns.

30. The system of claim 21, wherein the first spacing is at least about 4000 microns.

31. The system of claim 21, wherein the first spacing is at least about 1800 microns and the second spacing is less than about 1500 microns.

32. The system of claim 21, wherein the first spacing is at least about 2000 microns and the second spacing is less than about 1500 microns.

33. The system of claim 21, wherein the first spacing is at least about 2000 microns and the second spacing is about 600 microns.

34. The system of claim 21, further comprising a pre-wetting jet strip positioned to wet the fabric material with a fluid stream and positioned upstream of the one or more hydroentangling jet strips.

35. The system of claim 34, wherein the pre-wetting jet strip operates at a fluid pressure of less than about 80 bar.

36. The system of claim 21, wherein the one or more hydroentangling jet strips operate at a fluid pressure of about 100 bar or greater.

37. The system of claim 21, comprising:

a pre-wetting jet strip configured to subject the fabric material to fluid jet streams at a first fluid pressure in order to pre-wet the fabric material;

a series of hydroentangling jet strips spaced apart in the processing direction and downstream from the pre-wetting jet strip, each hydroentangling jet strip operating at a second fluid pressure greater than the first fluid pressure and comprising a plurality of nozzle orifices spaced across a width of the fabric material substantially perpendicular to the processing direction, wherein the series of hydroentangling jet strips comprises a first hydroentangling jet strip comprising a plurality of nozzle orifices having a spacing between nozzle orifices greater than about 1500 microns and a second downstream hydroentangling jet strip having a spacing between nozzle orifices of about 600 microns.

38. The system of claim 37, wherein the pre-wetting jet strip operates at a fluid pressure of less than about 80 bar.

39. The system of claim 37, wherein the hydroentangling jet strips operate at a fluid pressure of about 100 bar or greater.

40. The system of claim 37, wherein the first hydroentangling jet strip comprises a plurality of nozzle orifices having a spacing between nozzle orifices greater than about 2000 microns.

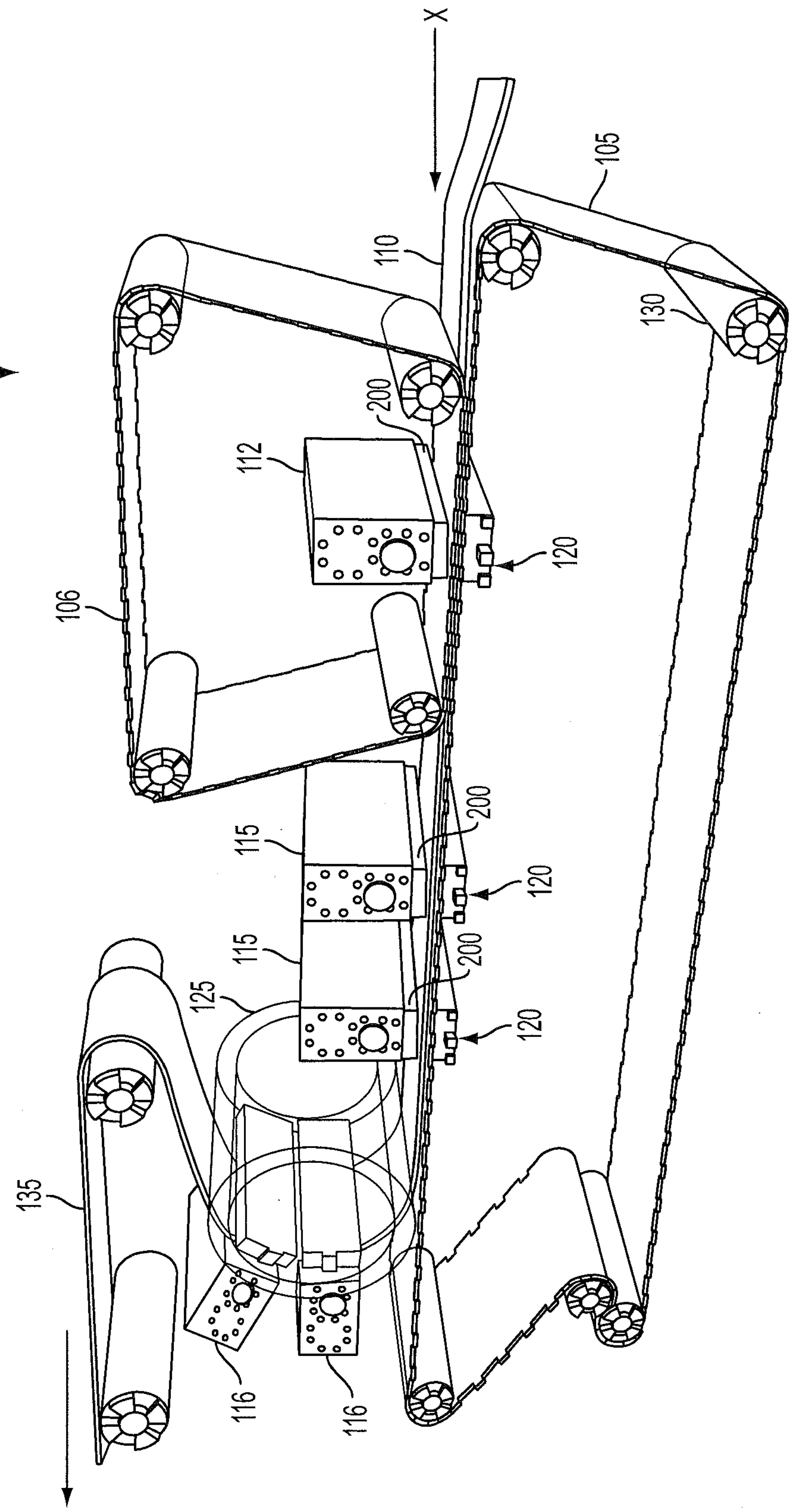
X
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FIG. 1

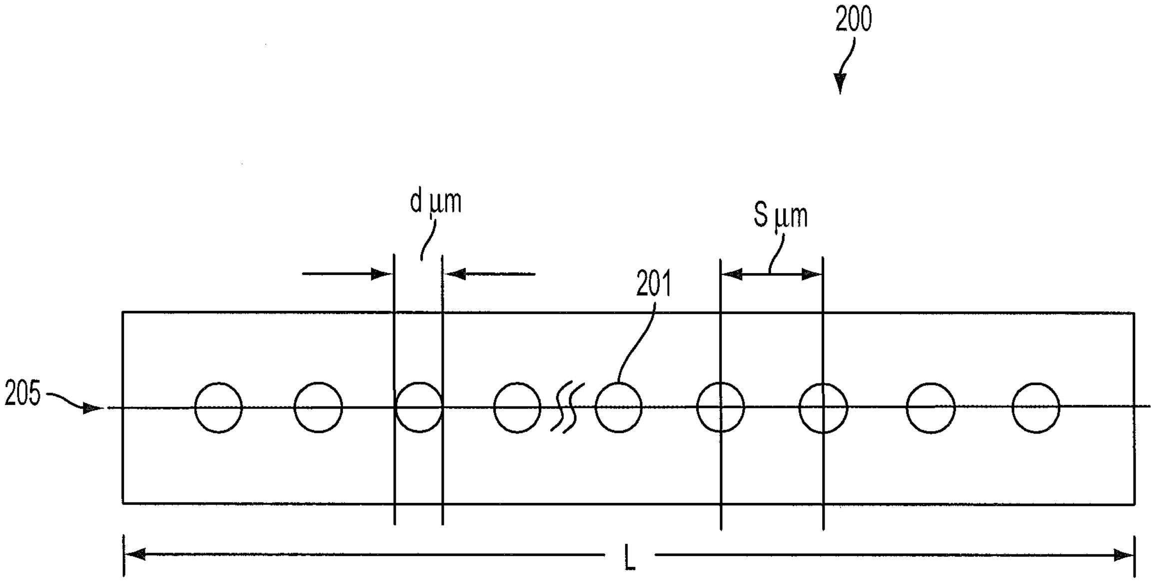


FIG. 2

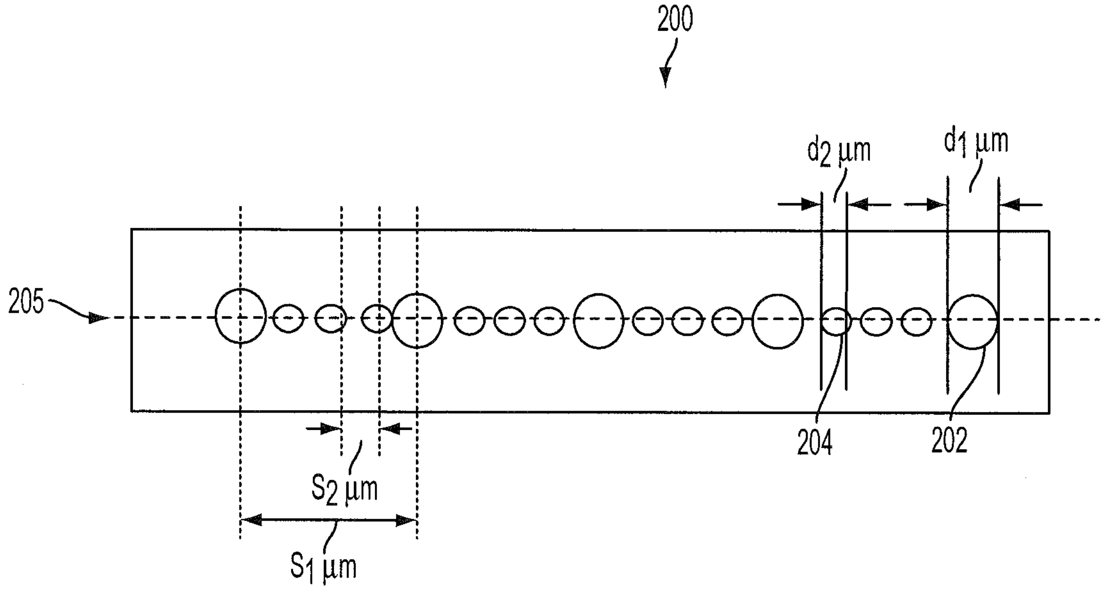


FIG. 3A

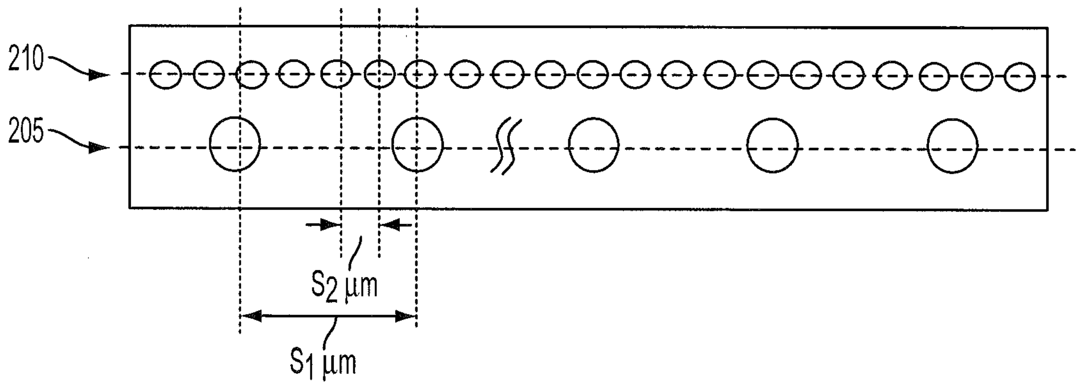


FIG. 3B

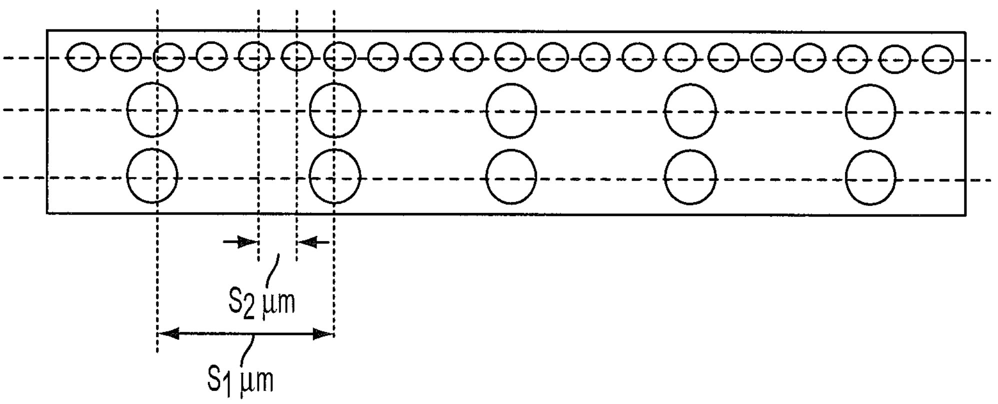


FIG. 3C

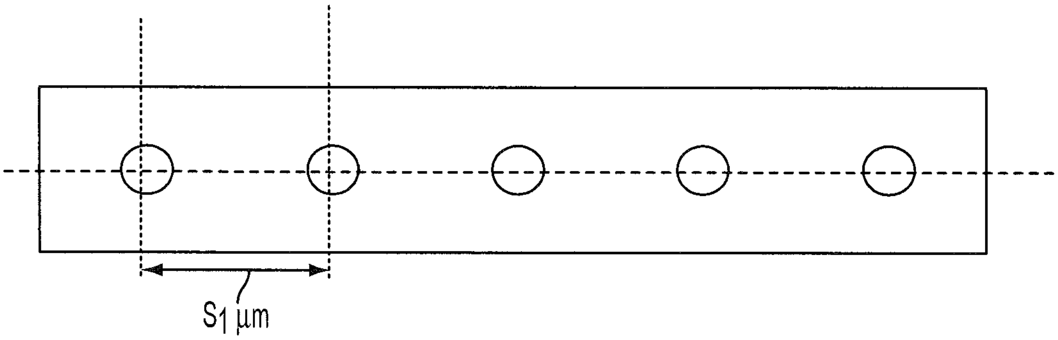


FIG. 3D

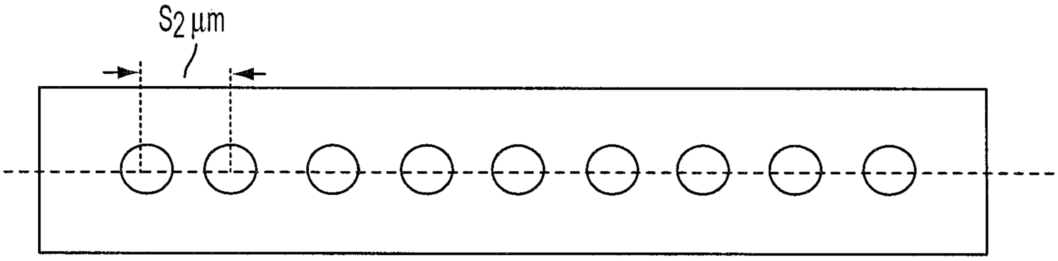


FIG. 3E

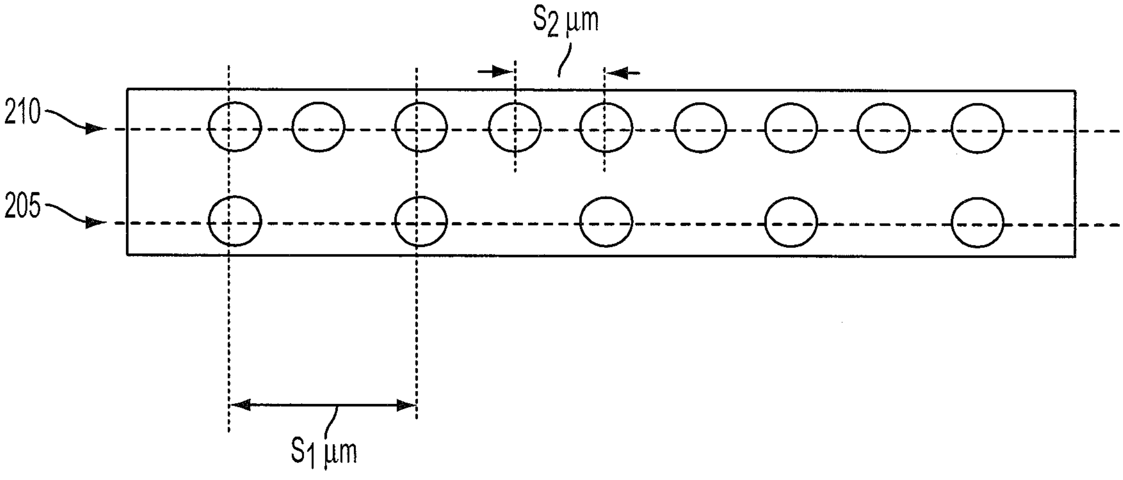


FIG. 3F

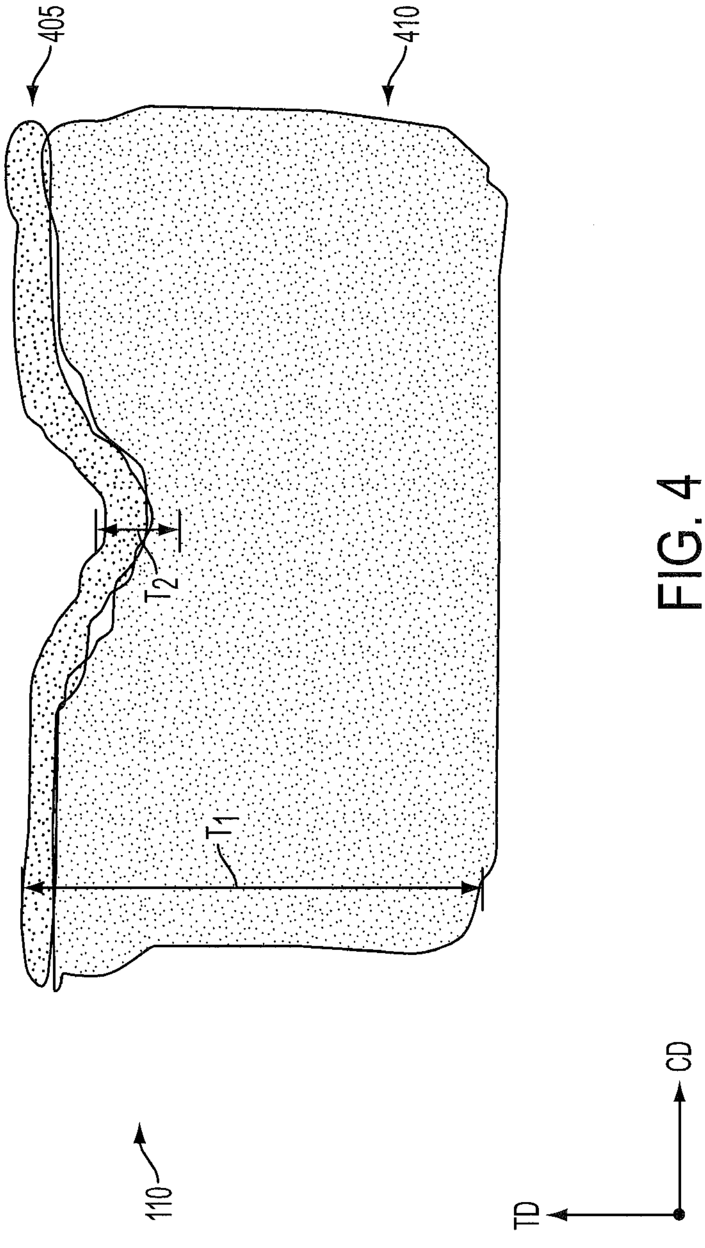


FIG. 4

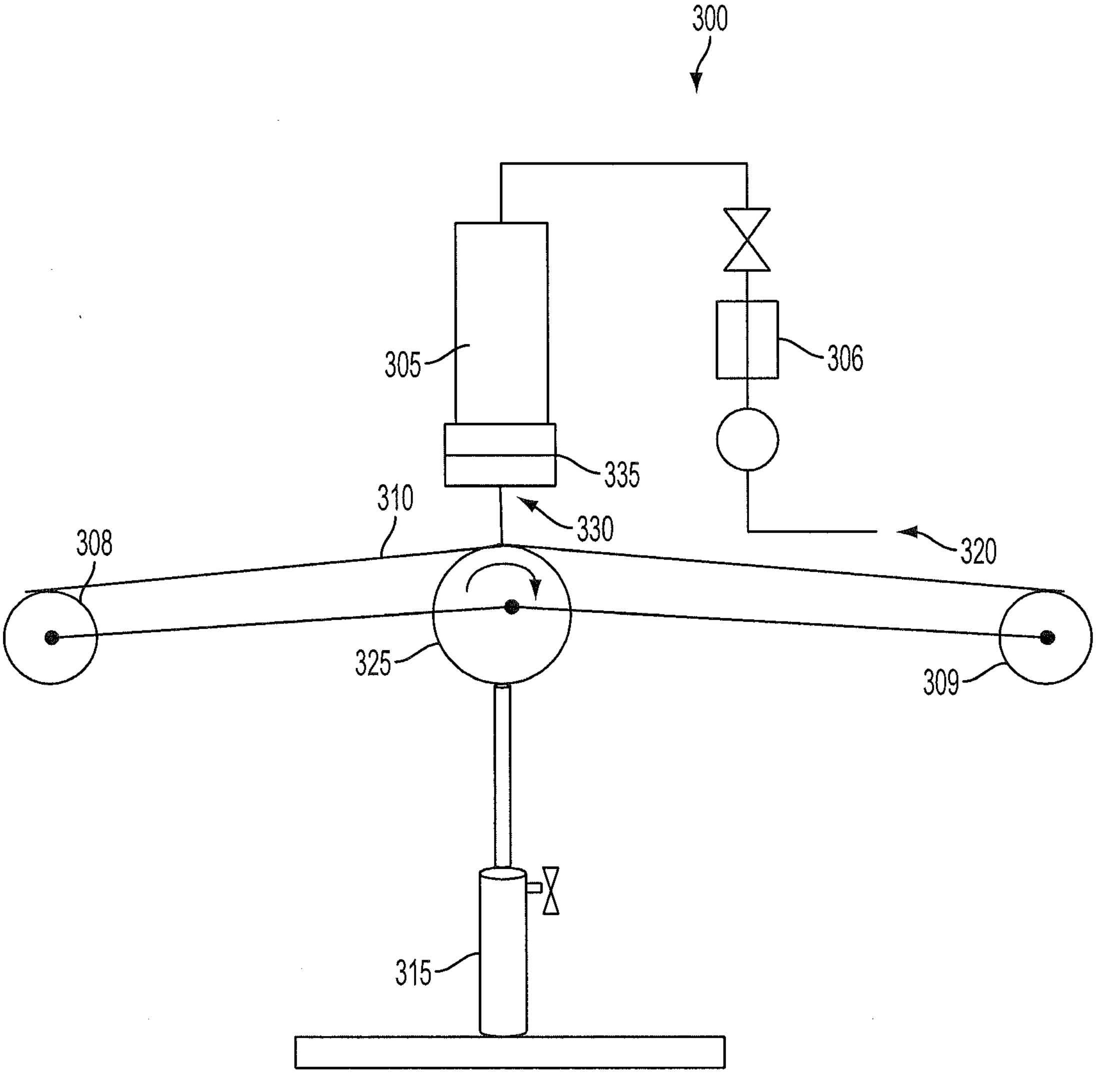
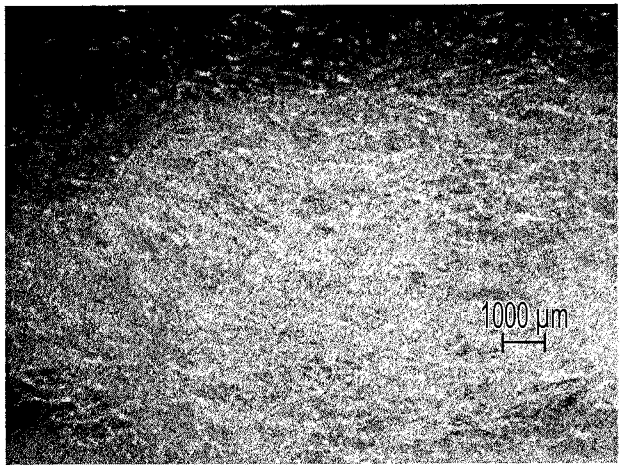
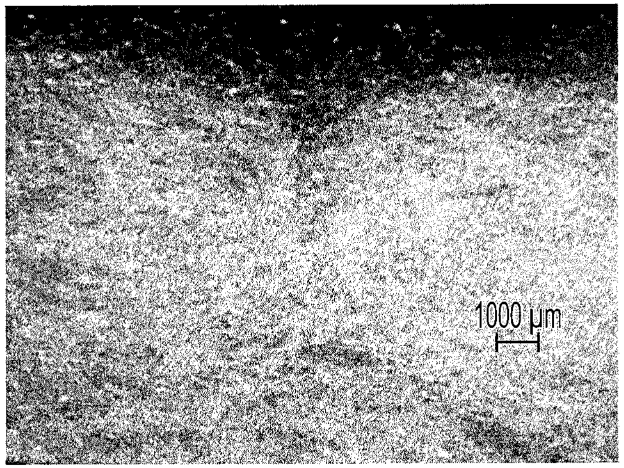


FIG. 5



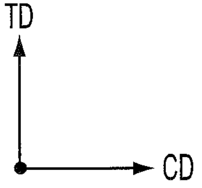
BEFORE JET IMPACT

FIG. 6A



SINGLE JET, AFTER JET IMPACT

FIG. 6B



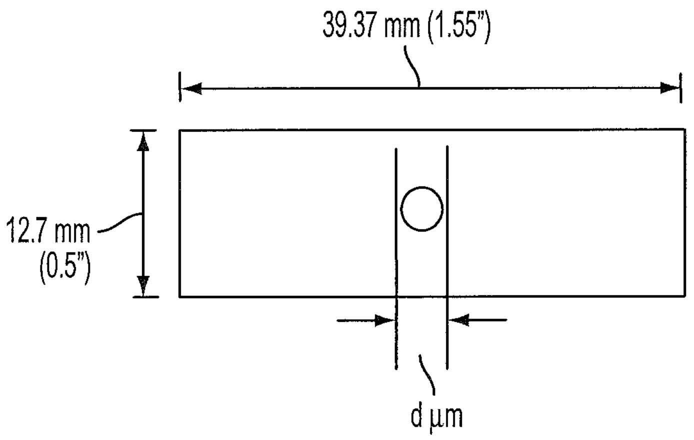


FIG. 7A

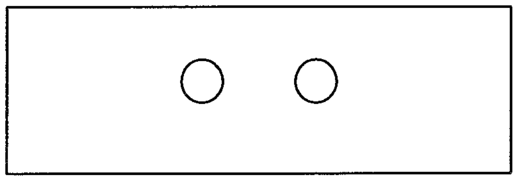


FIG. 7B

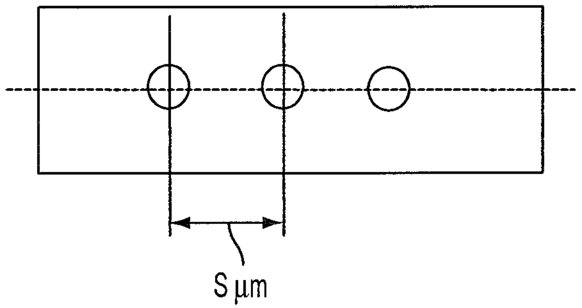
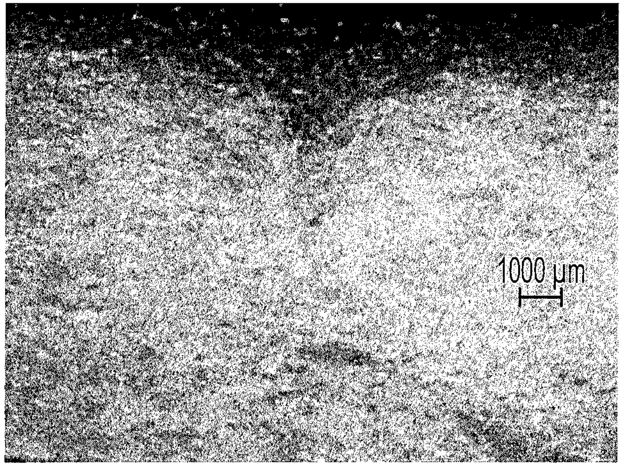
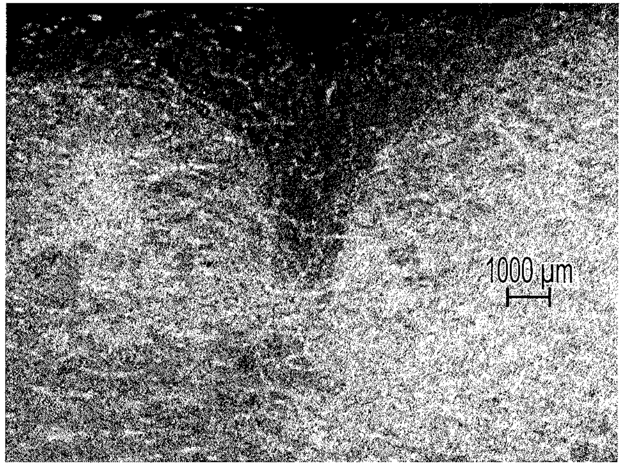


FIG. 7C



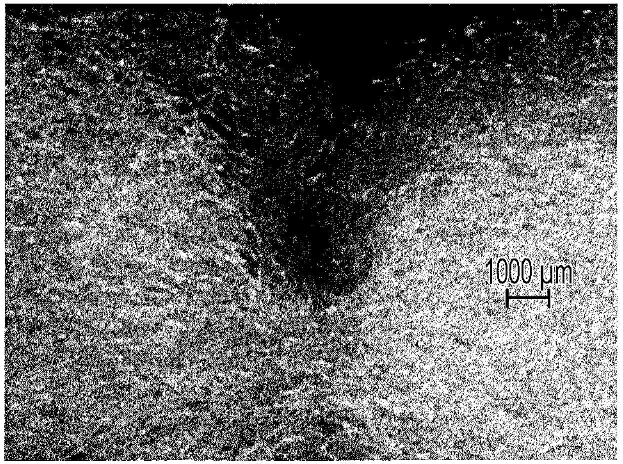
SINGLE JET

FIG. 8A



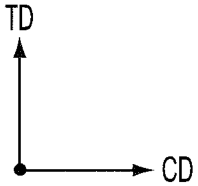
TWO JETS

FIG. 8B



THREE JETS

FIG. 8C



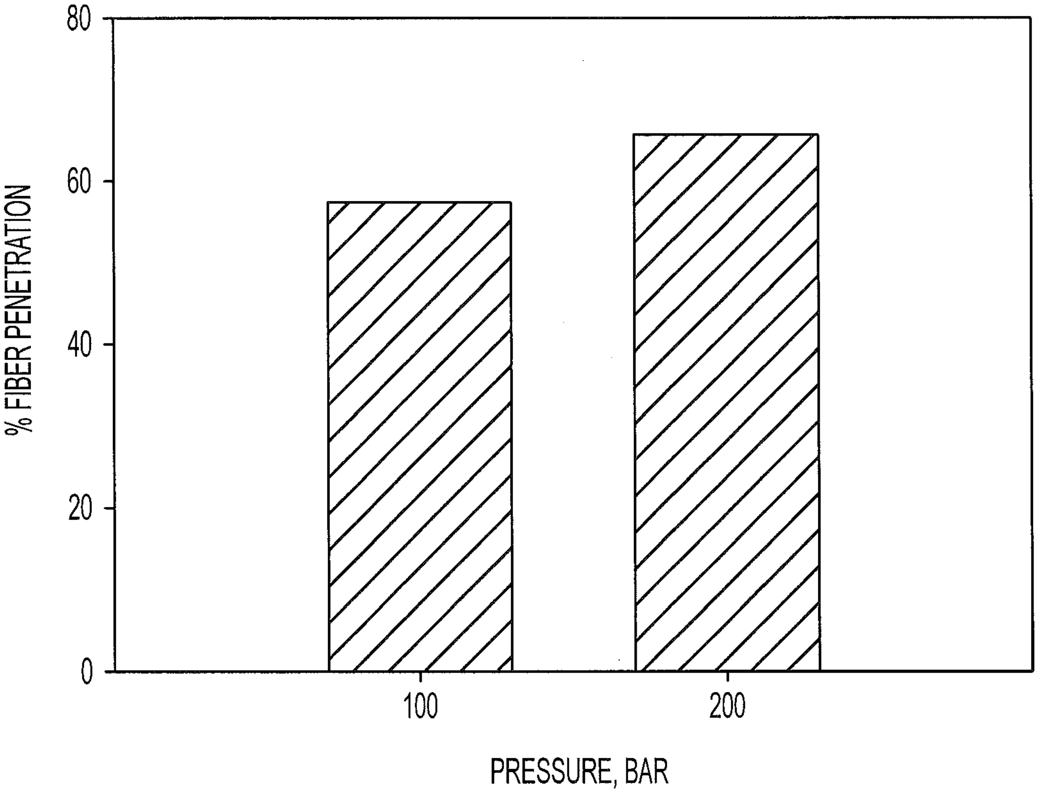


FIG. 9

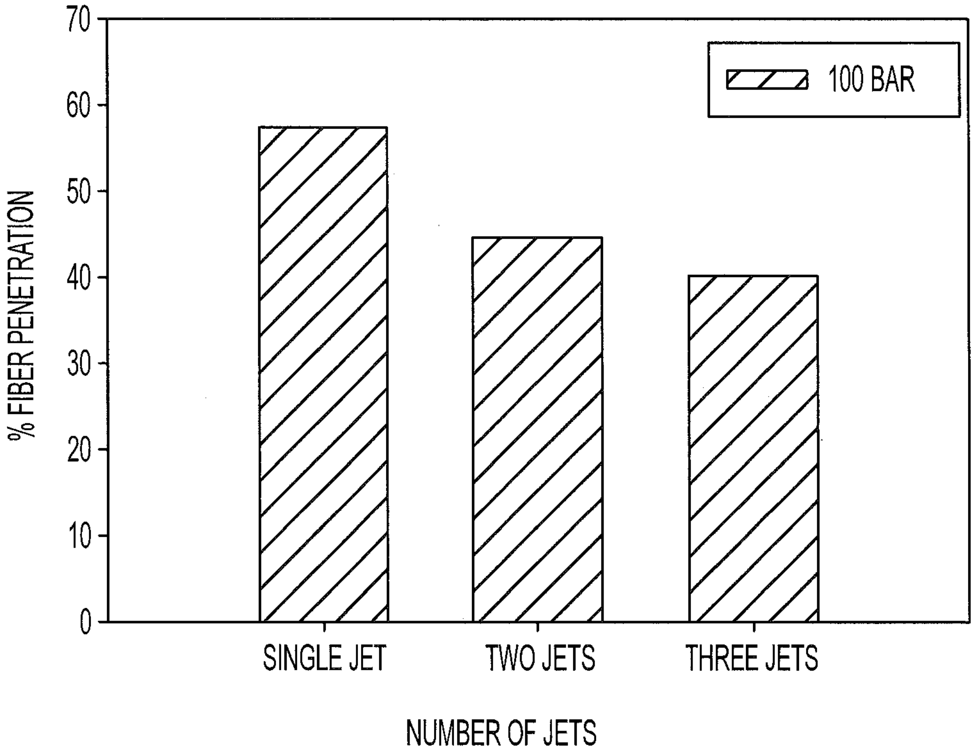

70
60
50
40
30
20
10
0
% FIBER PENETRATION
100 BAR
SINGLE JET
TWO JETS
THREE JETS
NUMBER OF JETS

FIG. 10

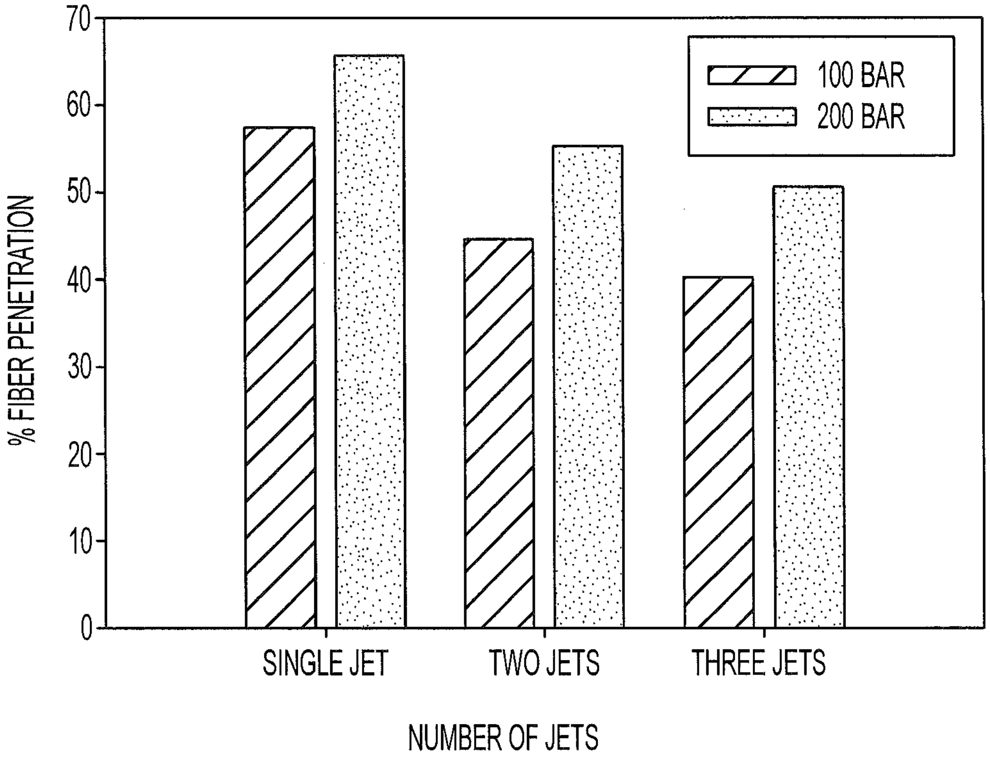
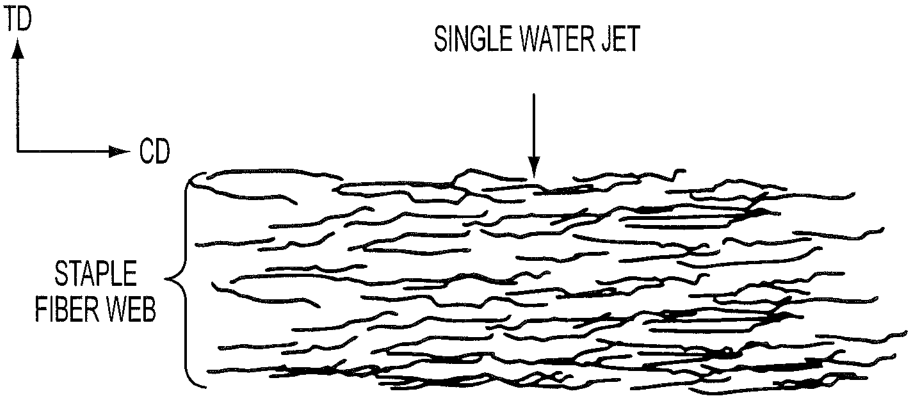
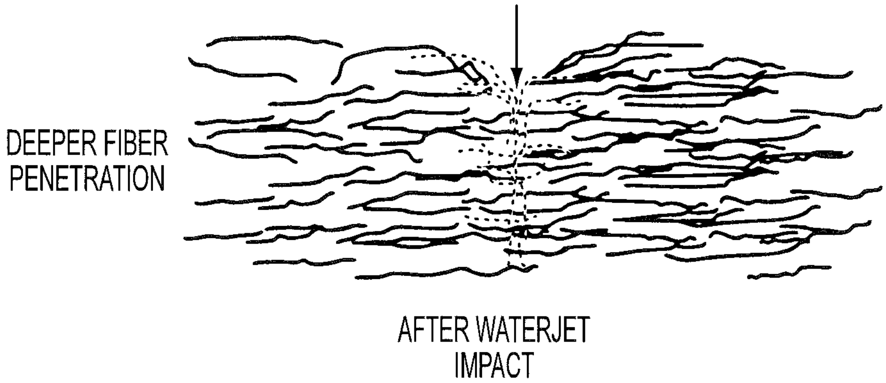

70
60
50
40
30
20
10
0
% FIBER PENETRATION
100 BAR
200 BAR
SINGLE JET
TWO JETS
THREE JETS
NUMBER OF JETS

FIG. 11



BEFORE WATERJET IMPACT

FIG. 12A



AFTER WATERJET IMPACT

FIG. 12B

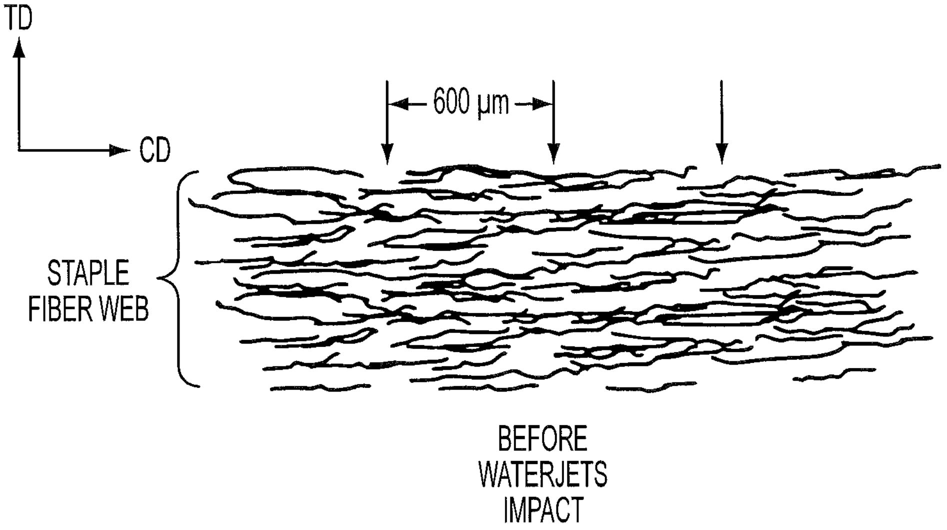


FIG. 13A

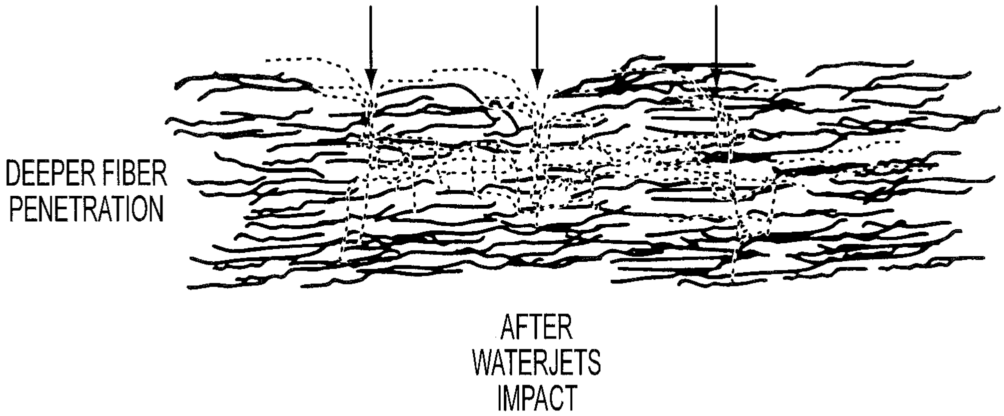


FIG. 13B

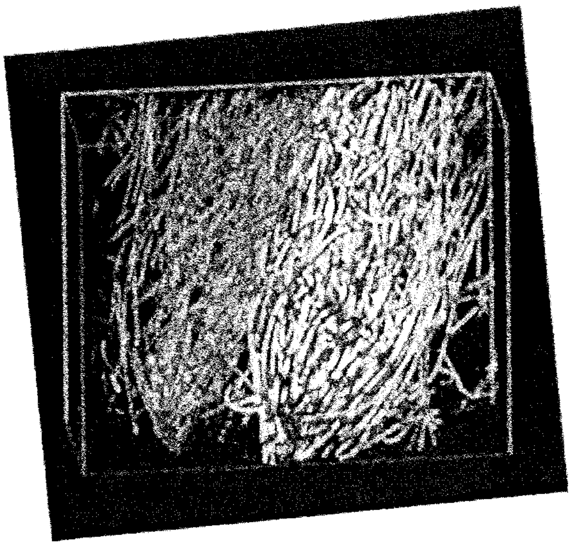


FIG. 14B

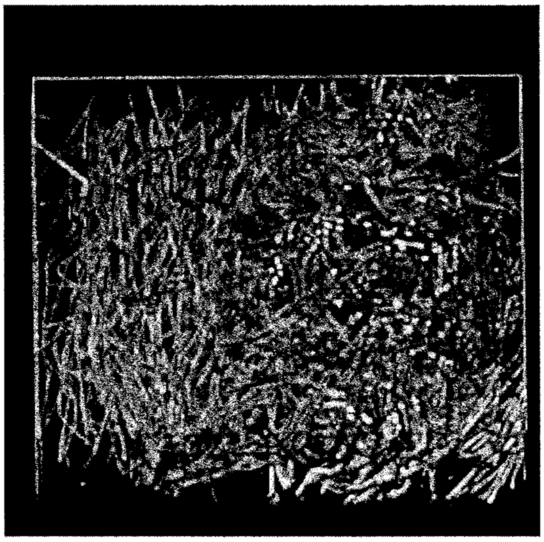


FIG. 14A

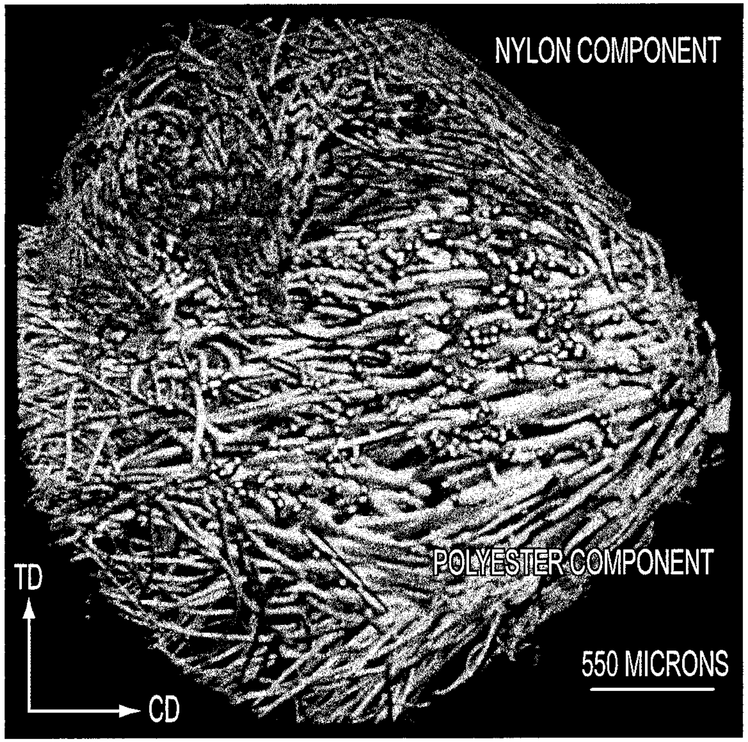


FIG. 15A

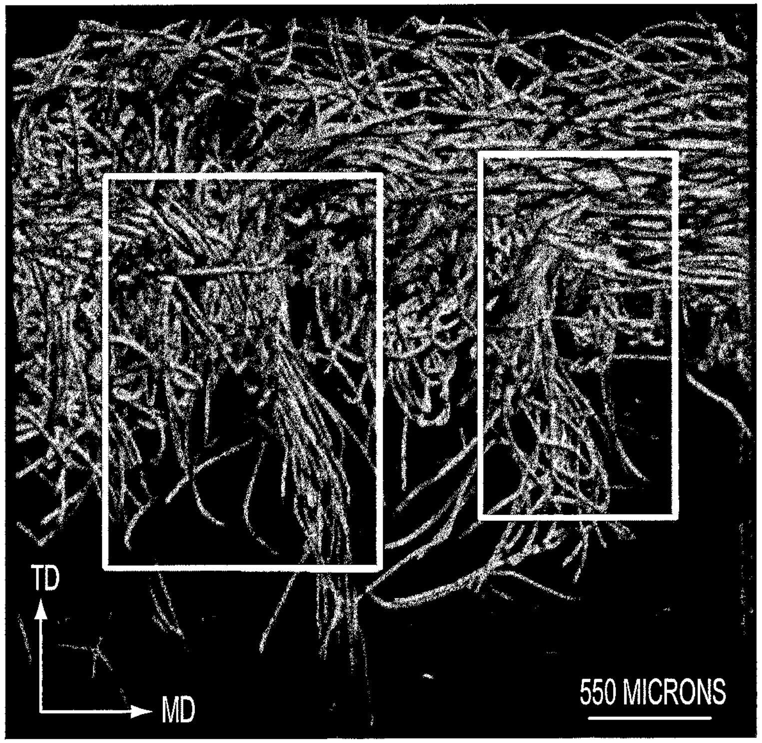


FIG. 15B

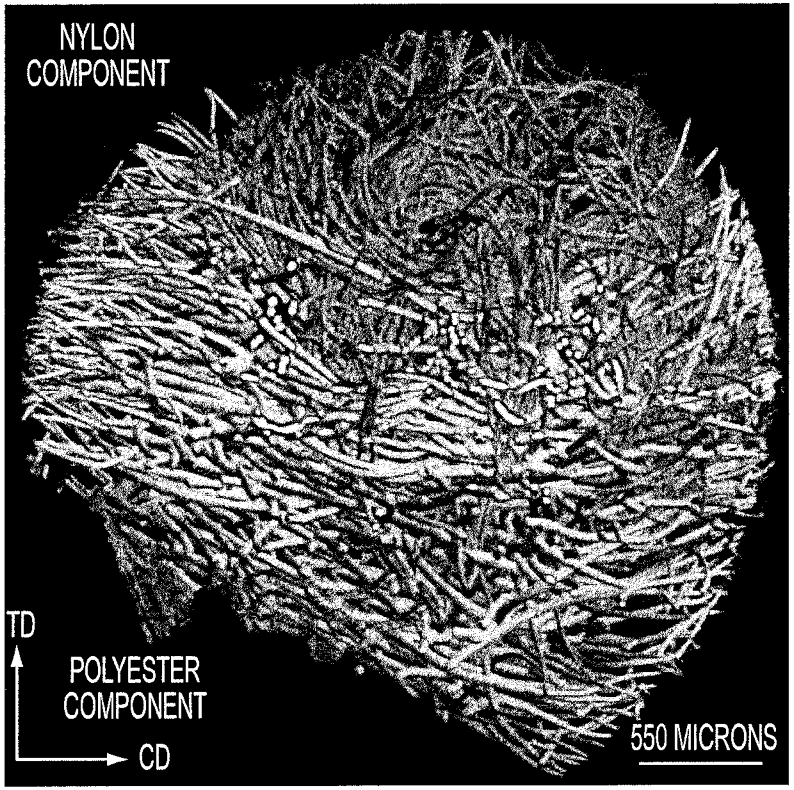


FIG. 16A

FIG. 16B

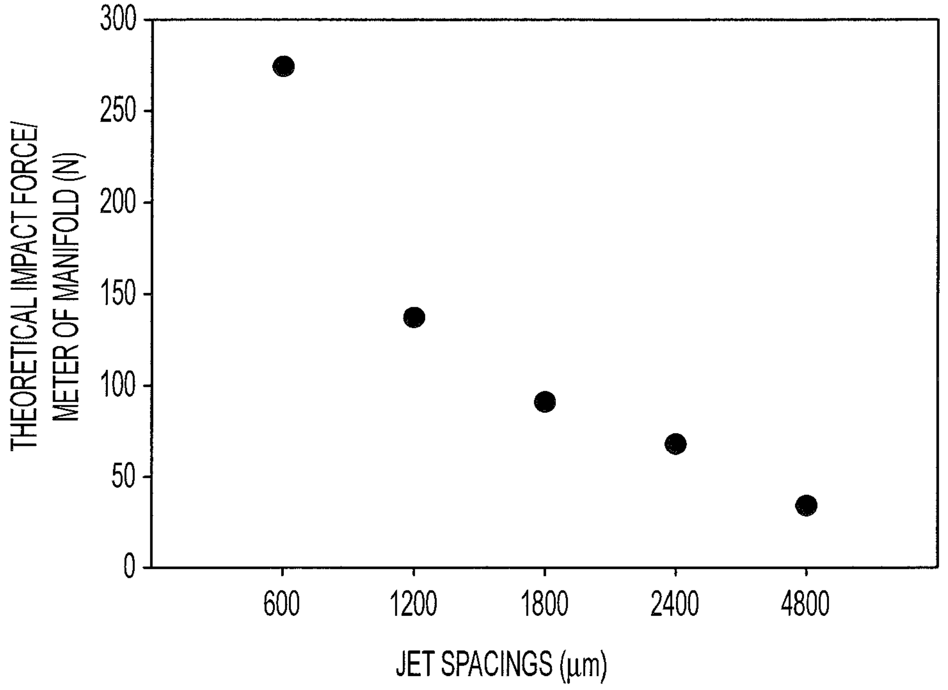


FIG. 17A

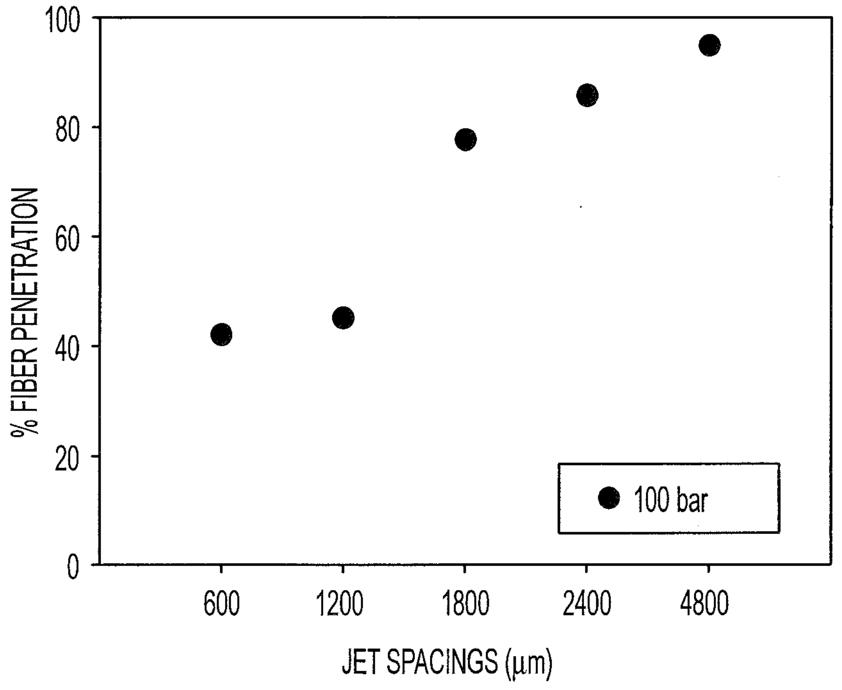
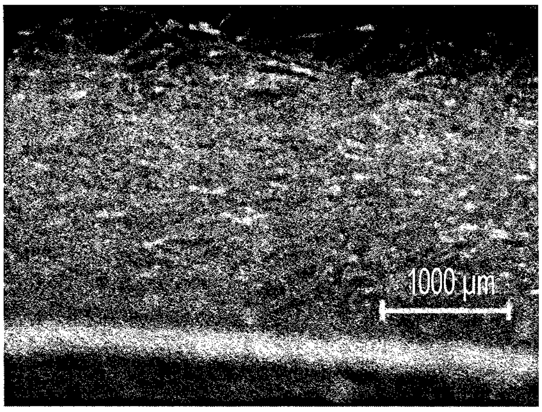
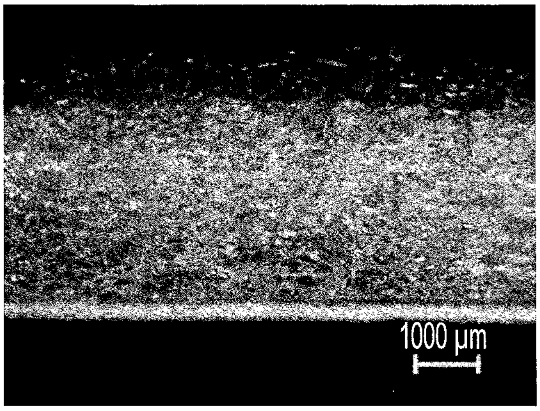


FIG. 17B



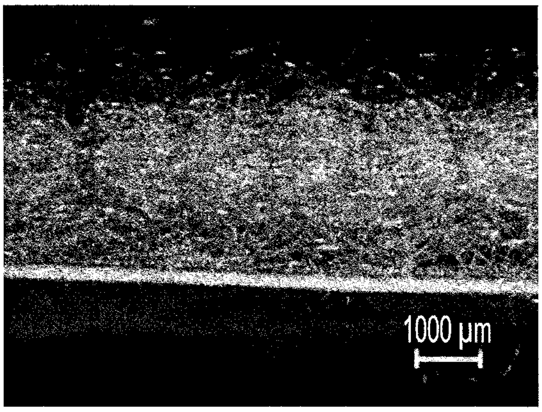
S = 600 μm, 100 BAR

FIG. 18A



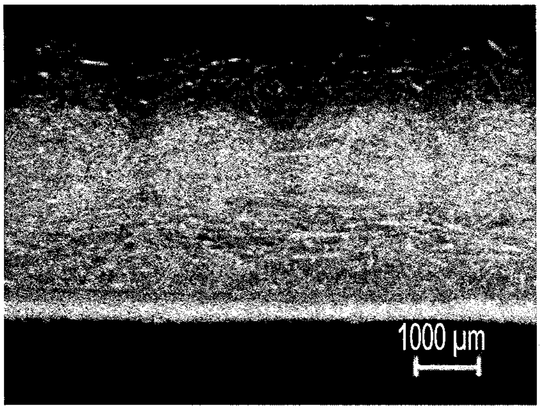
S = 1200 μm, 100 BAR

FIG. 18B



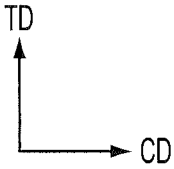
S = 1800 μm, 100 BAR

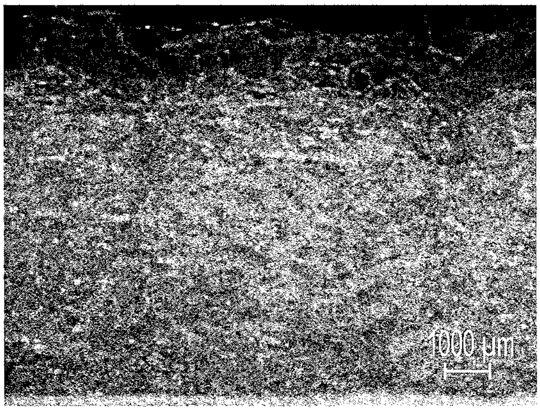
FIG. 18C



S = 2400 μm, 100 BAR

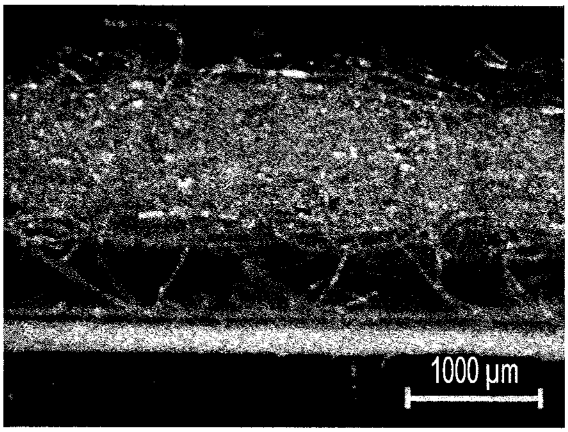
FIG. 18D





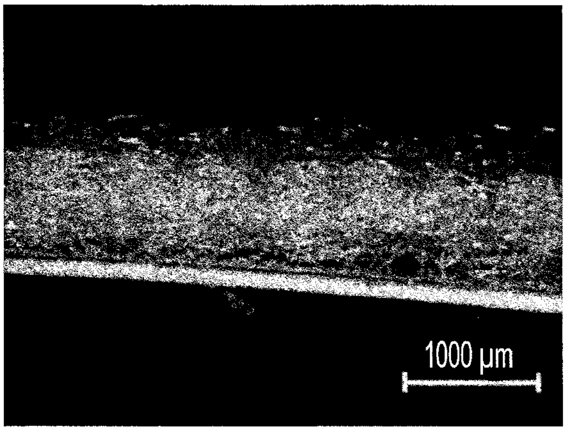
S = 4800 μm, 100 BAR

FIG. 18E



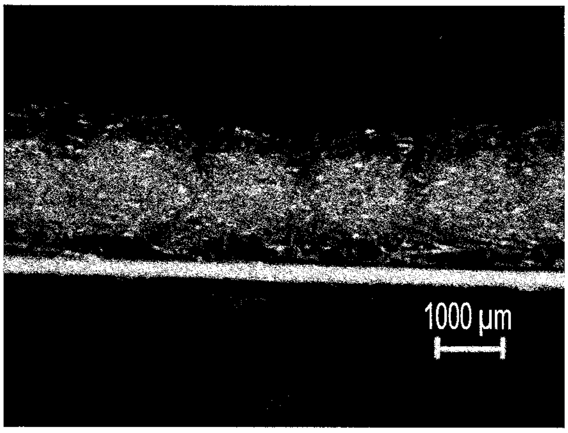
S = 600 µm, 200 BAR

FIG. 19A



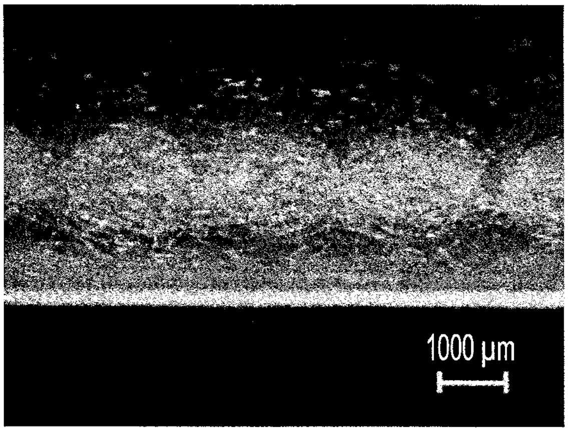
S = 1200 µm, 200 BAR

FIG. 19B



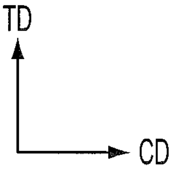
S = 1800 µm, 200 BAR

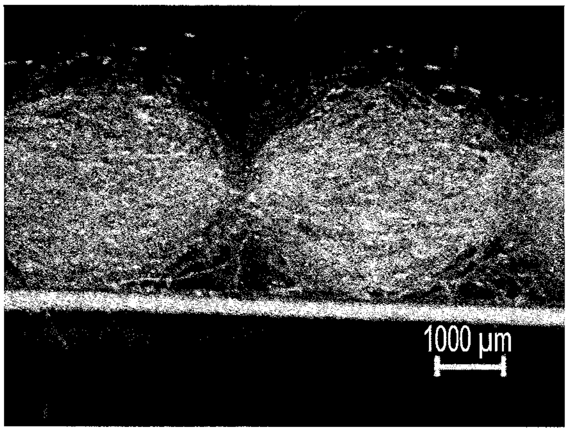
FIG. 19C



S = 2400 µm, 200 BAR

FIG. 19D





S = 4800 µm, 200 BAR

FIG. 19E

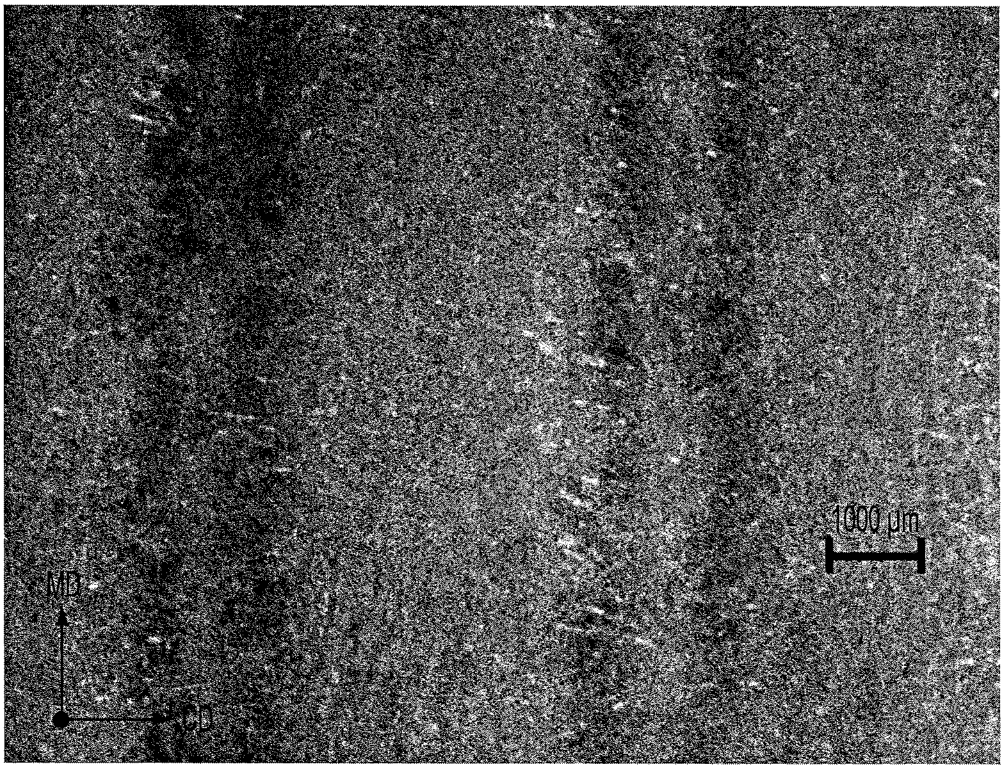
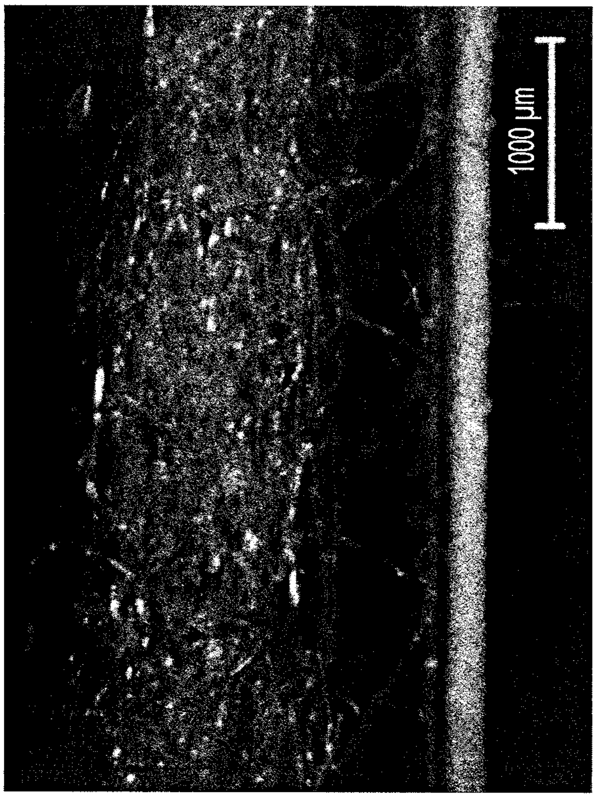
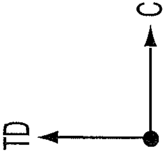


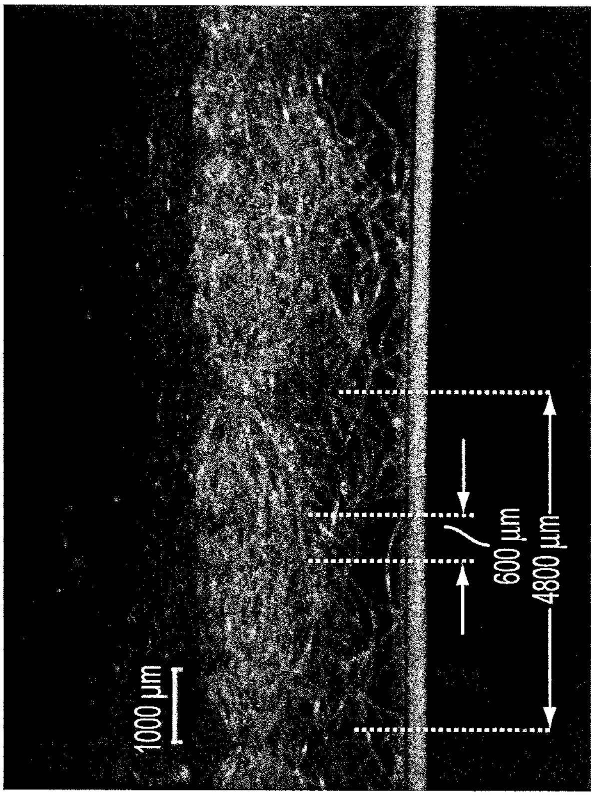
FIG. 20



S = 600 µm

FIG. 21A





S = 4800 + 600 µm

FIG. 21B

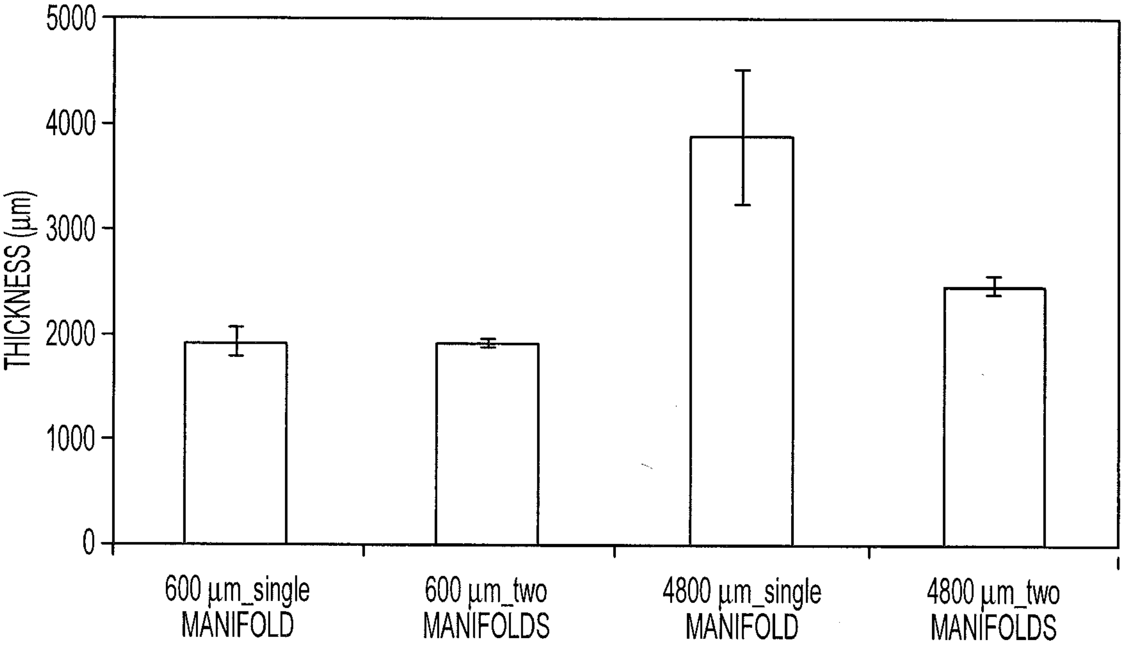

5000
4000
3000
2000
1000
0
THICKNESS (µm)
600 µm_single MANIFOLD
600 µm_two MANIFOLDS
4800 µm_single MANIFOLD
4800 µm_two MANIFOLDS

FIG. 22

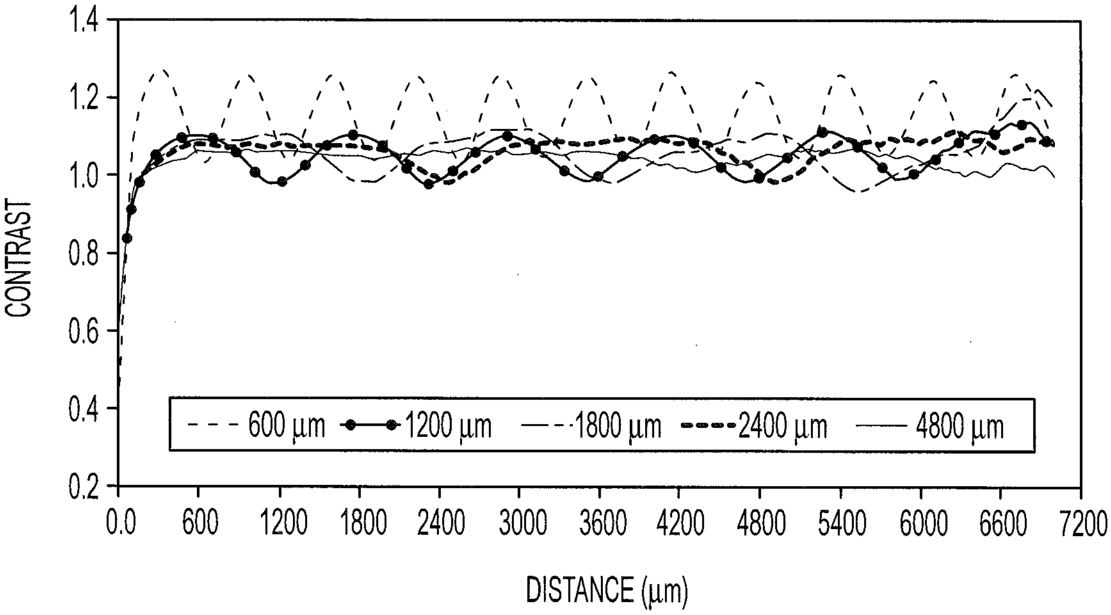

1.4
1.2
1.0
0.8
0.6
0.4
0.2
CONTRAST
0.0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000
6600
7200
DISTANCE (μm)
600 μm
1200 μm
1800 μm
2400 μm
4800 μm

FIG. 23

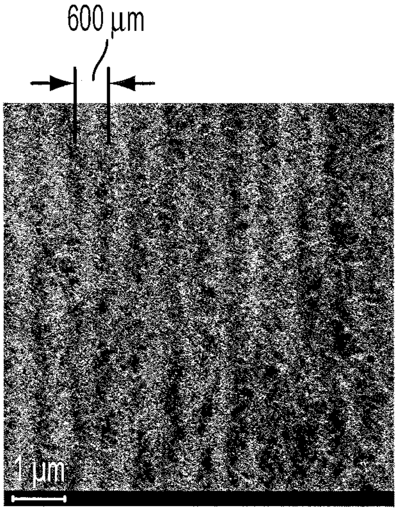


FIG. 24A

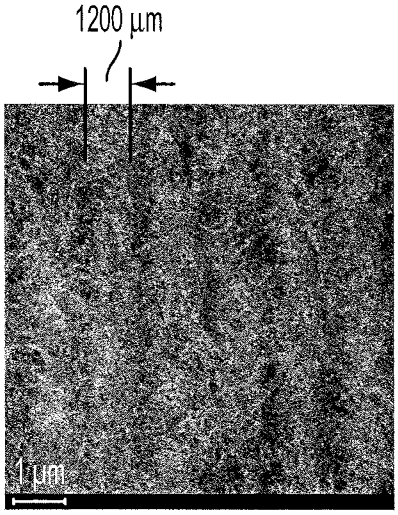


FIG. 24B

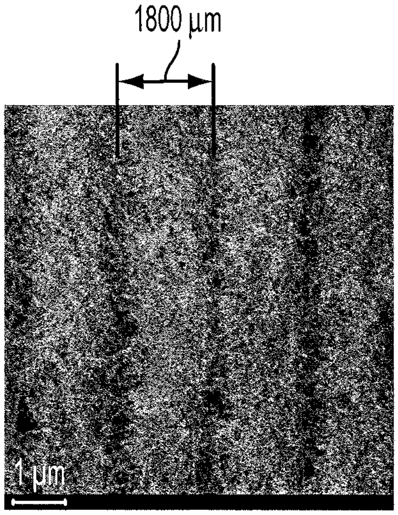


FIG. 24C

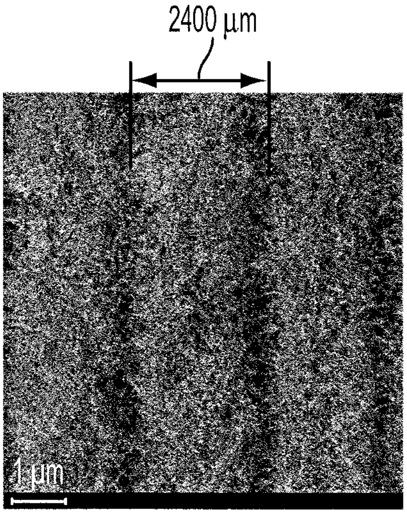


FIG. 24D

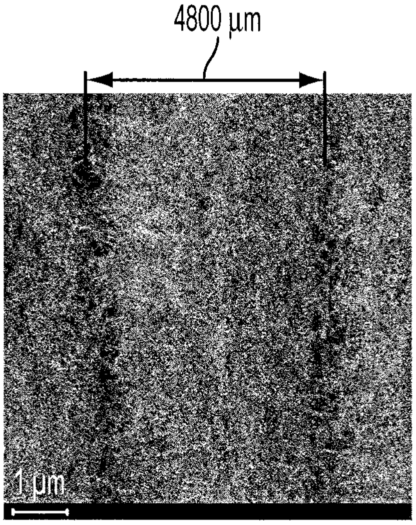


FIG. 24E

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/020319

A. CLASSIFICATION OF SUBJECT MATTER
INV. D94H18/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
D04H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal , WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2008 060327 Al (FLEISSNER GMBH [DE]) 10 June 2010 [2010-06-10] paragraphs [0030], [0032]; figure 1 -----	1-40
X	US 2007/226970 Al (P0URDEYHIMI BEHNAM [US] ET AL) 4 October 2007 (2007-10-04) paragraphs [0010], [0011], [0059]; figure la -----	1,14-21, 34-40
A	FR 2 856 414 Al (GEORGIA PACIFIC FRANCE [FR]) 24 December 2004 (2004-12-24) page 6, paragraph 3; figures 4,7 -----	1-40
A	US 3 943 639 A (VITS HILMAR) 16 March 1976 (1976-03-16) column 1, line 46 - column 2, line 47; figure 3 -----	1-40

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"&" document member of the same patent family

Date of the actual completion of the international search
11 March 2013

Date of mailing of the international search report
18/03/2013

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Authorized officer
Mangin, Sophie

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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