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(54) **POLYETHYLENE TEXTILES WITH ENGINEERED FEATURES THAT PROVIDE FOR PASSIVE COOLING AND MANUFACTURE THEREOF**

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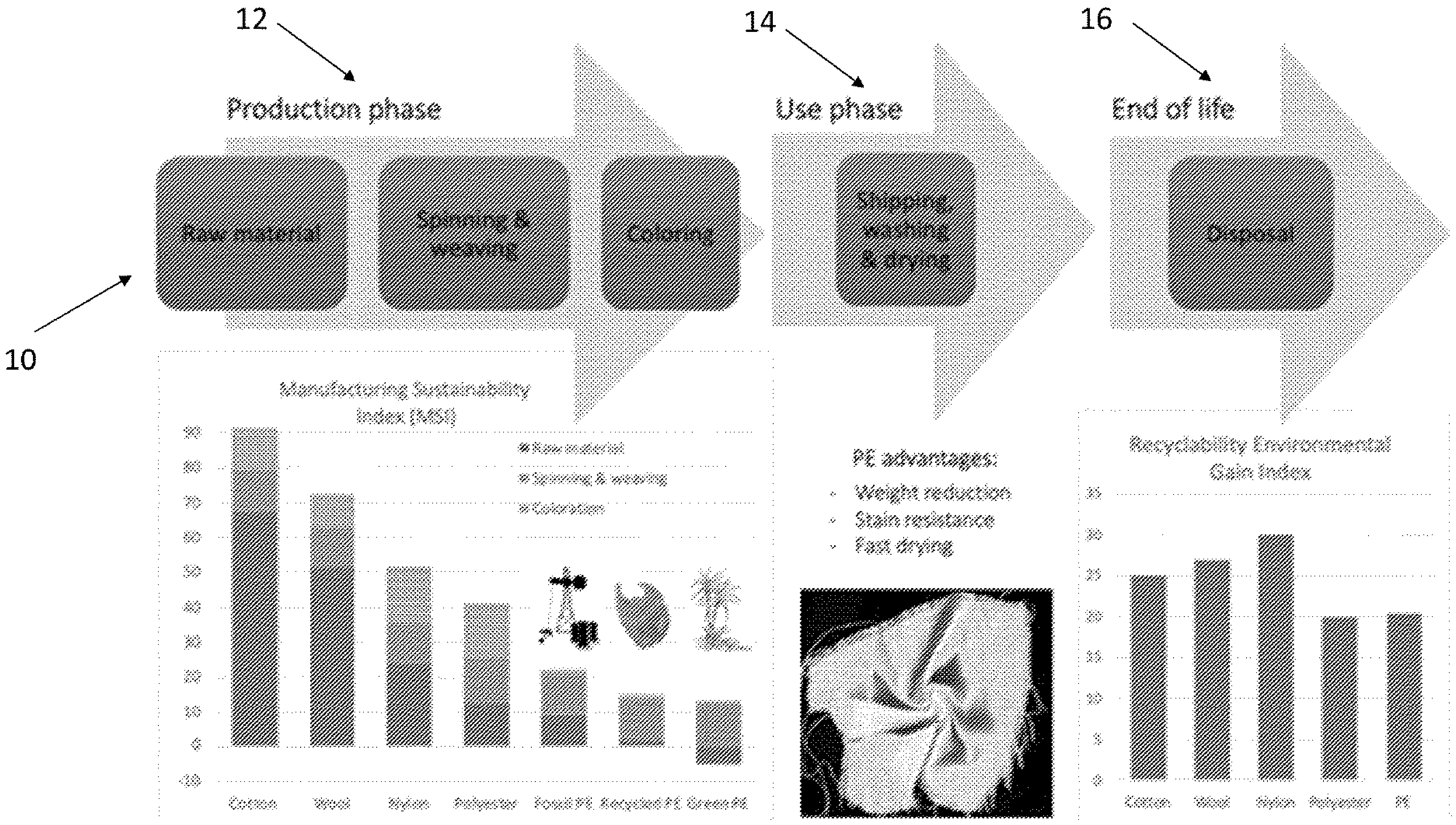
(57) **ABSTRACT**

The present disclosure generally relates to textiles that are optimized to maximize moisture wicking and evaporative performance thereof. In some embodiments, raw polyethylene (PE) powder can be extruded into fibers that can be modified by oxidation along a surface thereof to increase hydrophilicity of the surface. Once sufficiently oxidized, the fibers can be bundled to form multi-filament yarns that can then be spun, weaved, knitted, and/or otherwise associated with one another to form a polyethylene fabric. The PE fibers can be further modified to increase a capillary force of the bundle, thereby further increasing hydrophilicity of the resulting fabric. Engineering of the capillary force can be performed by optimizing one or more of a fiber size, a density, or a cross-section of the fibers and/or the bundles. The resultant fabric can exhibit a strong weight reduction, stain resistance, and drying capabilities, among other capabilities.



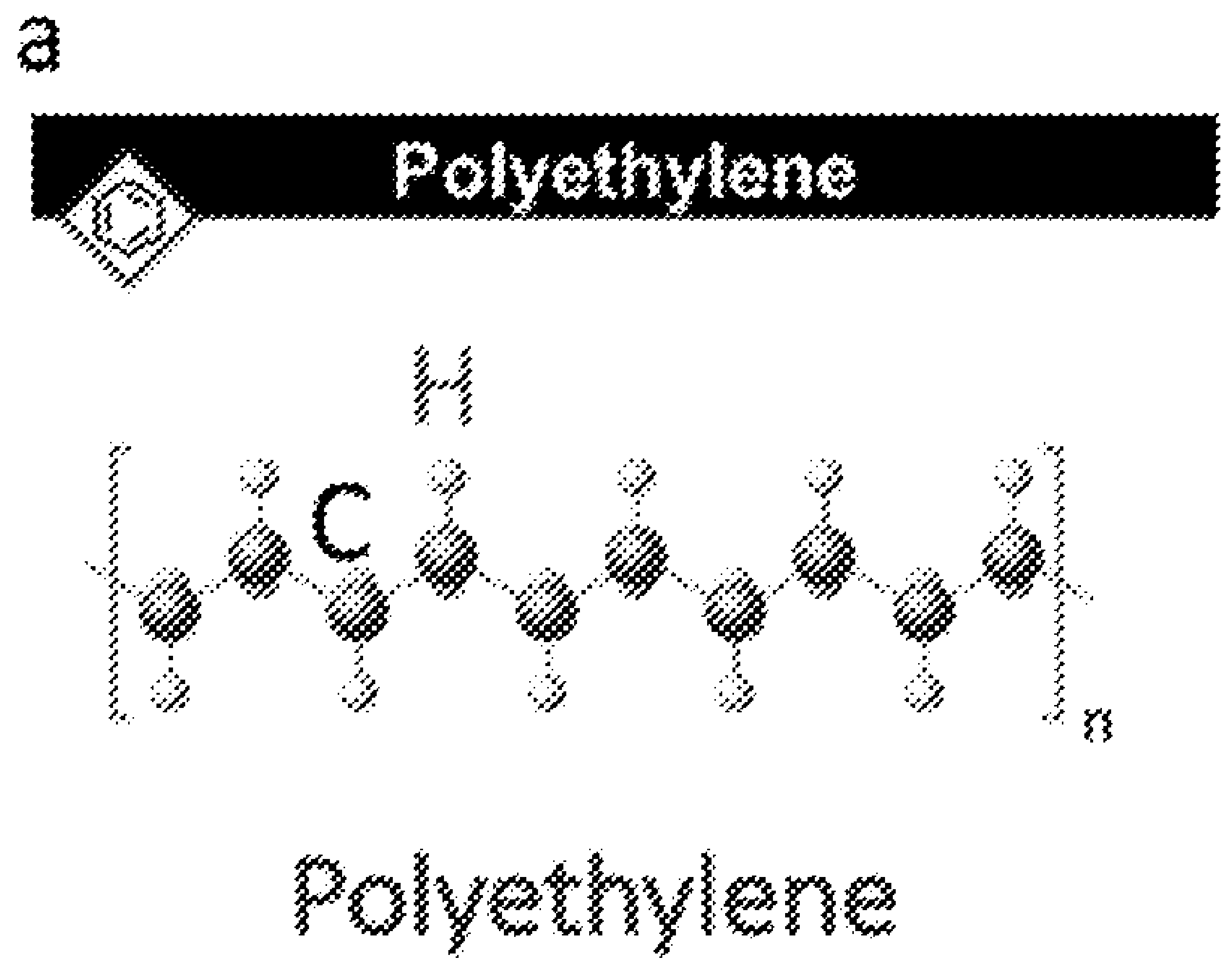


FIG. 1A

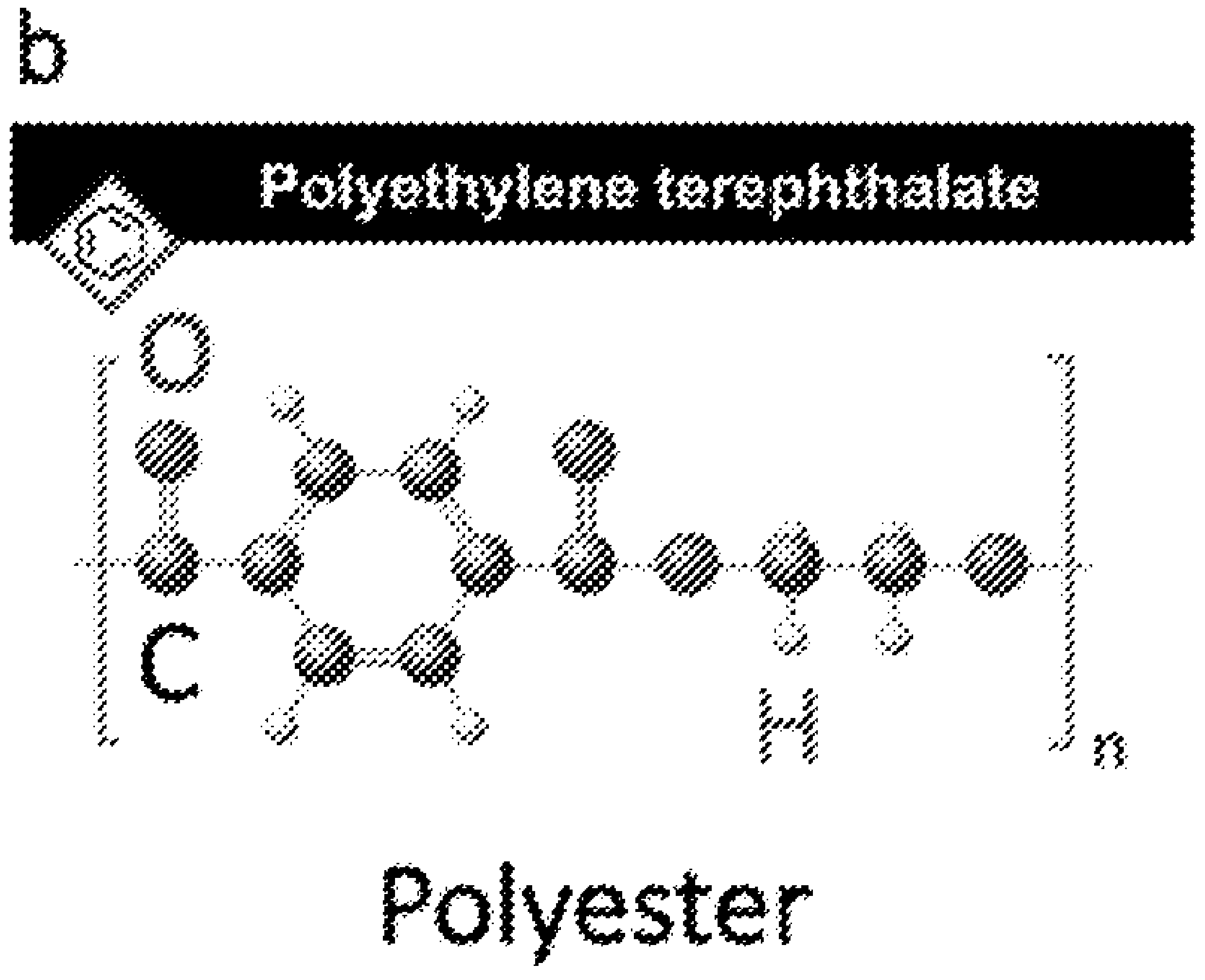


FIG. 1B

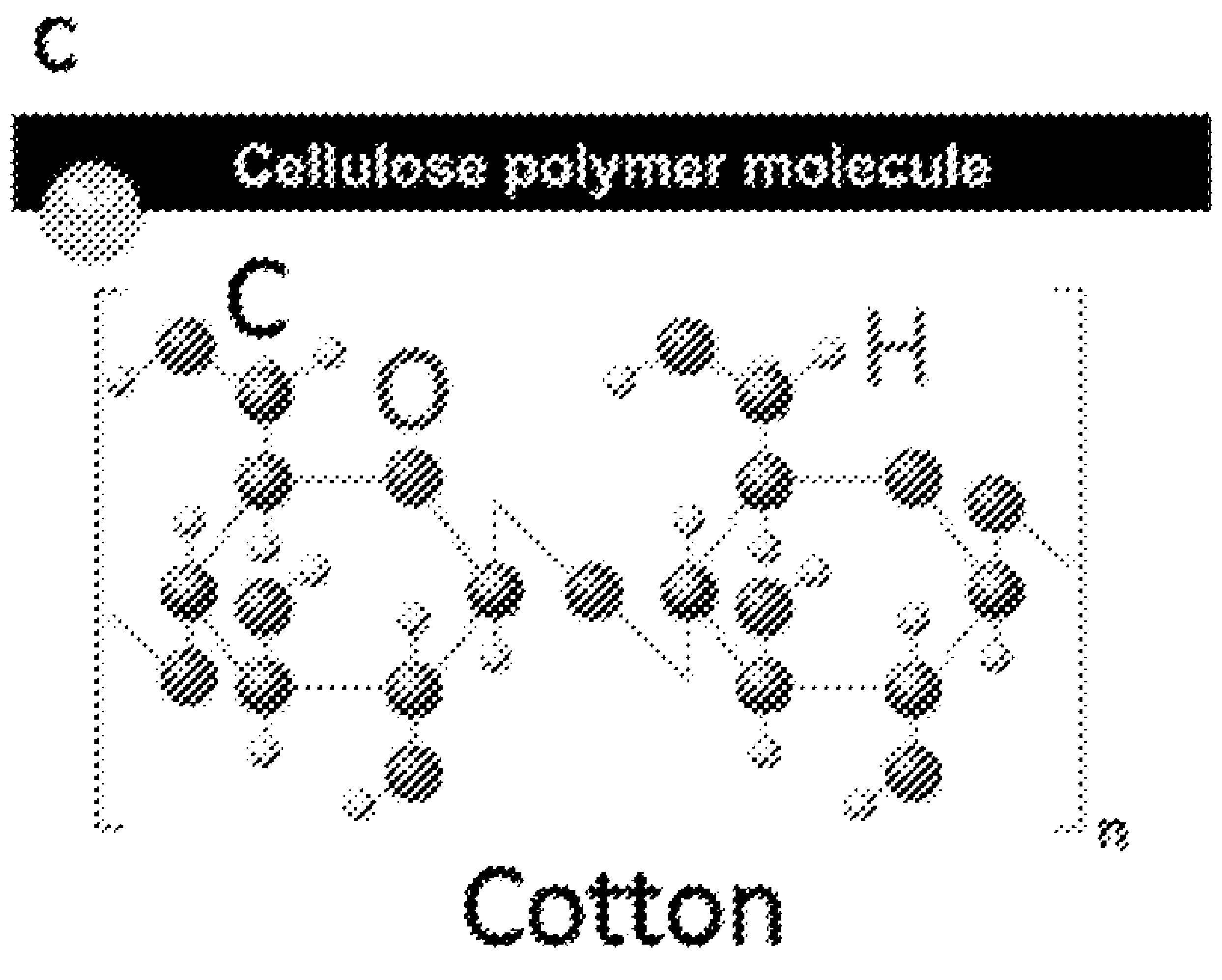


FIG. 1C

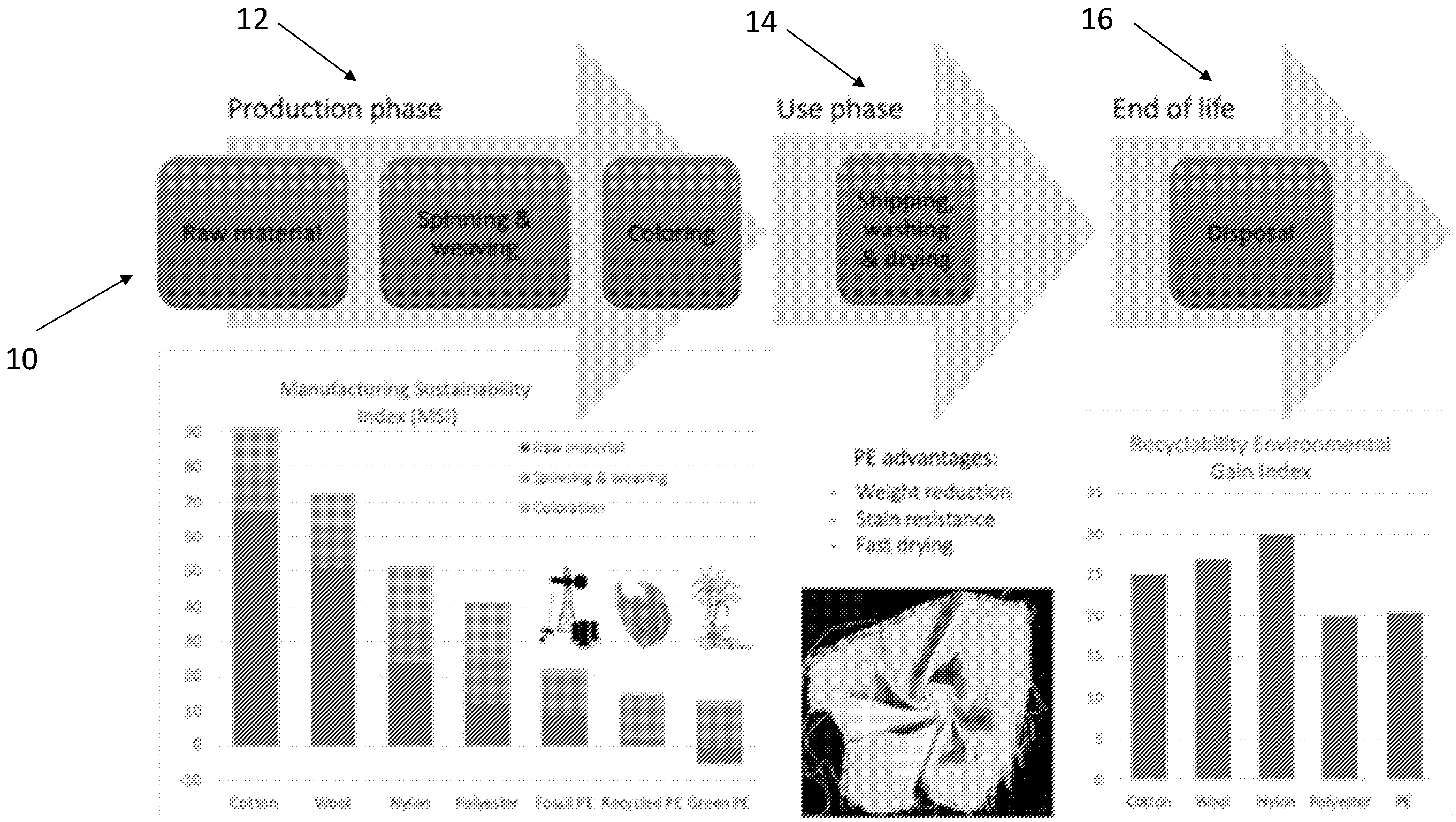

12
14
16
10
Production phase
Use phase
End of life
Raw material
Spinning & weaving
Coloring
Shipping, washing & drying
Disposal
Manufacturing Sustainability Index (MSI)
Raw material
Spinning & weaving
Coloration
90
80
70
60
50
40
30
20
10
0
-10
Cotton
Wool
Nylon
Polyester
Fossil PE
Recycled PE
Green PE
PE advantages:
Weight reduction
Stain resistance
Fast drying
Recyclability Environmental Gain Index
35
30
25
20
15
10
5
0
Cotton
Wool
Nylon
Polyester
PE

FIG. 2

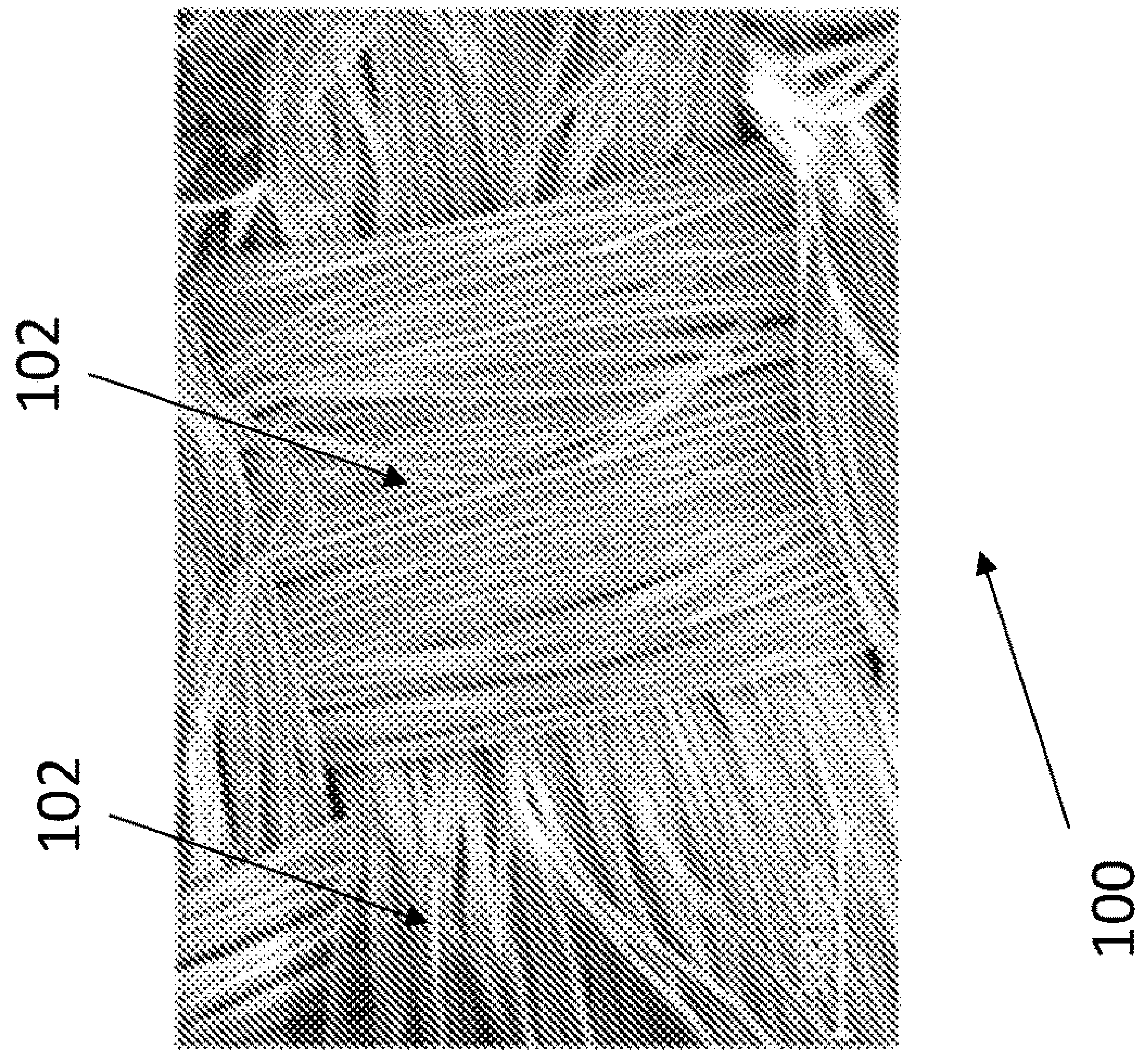


FIG. 3A

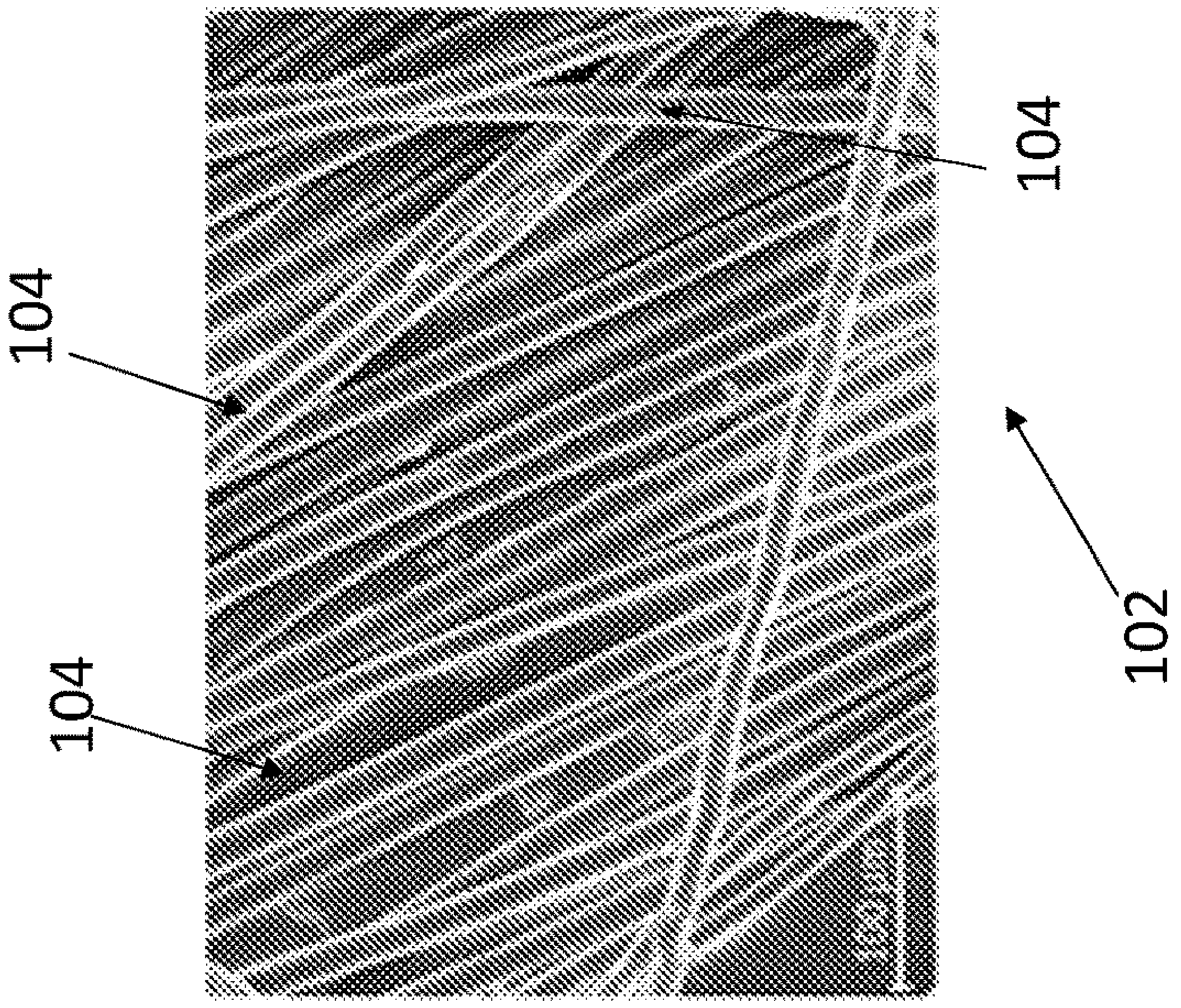


FIG. 3B

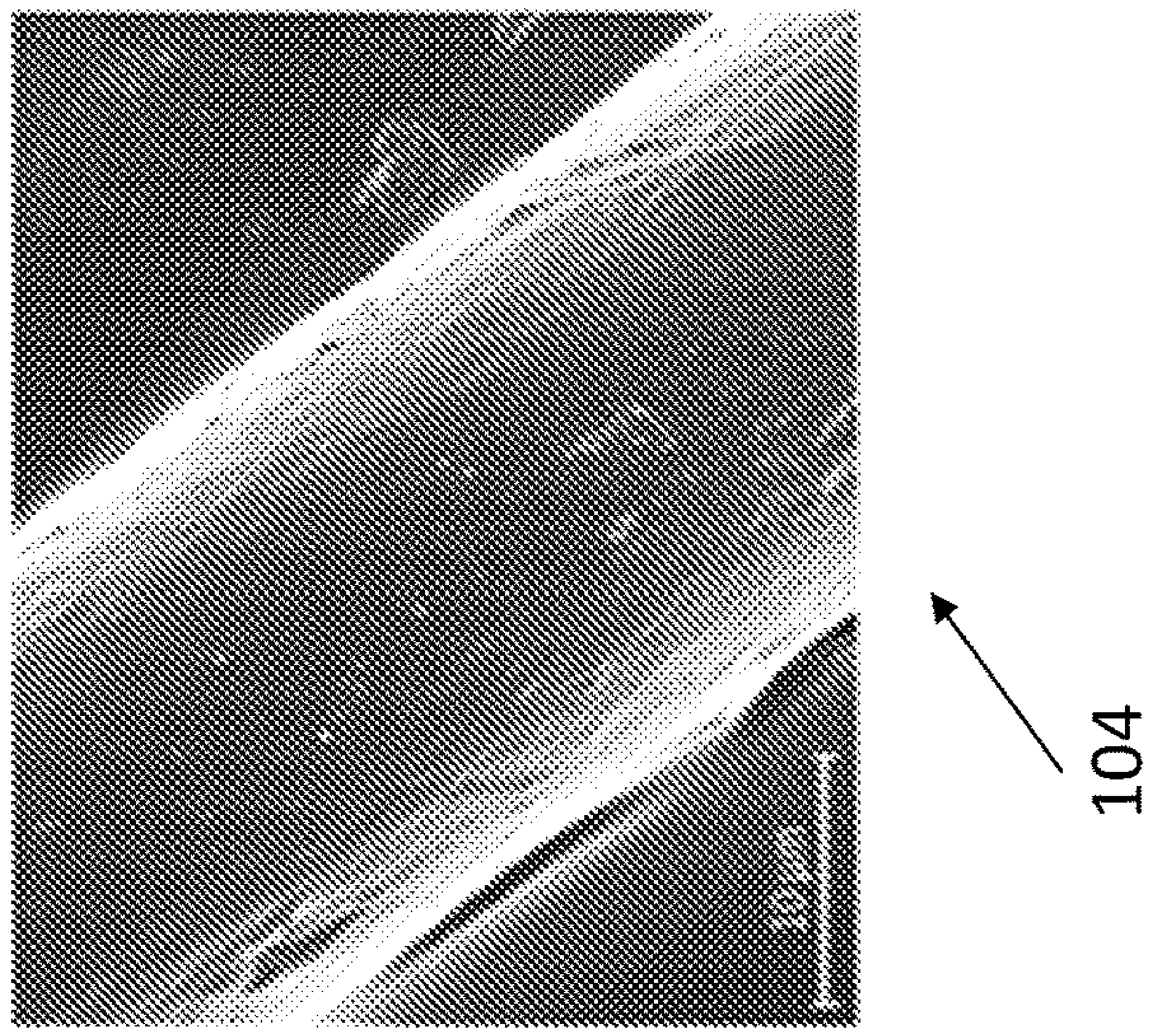
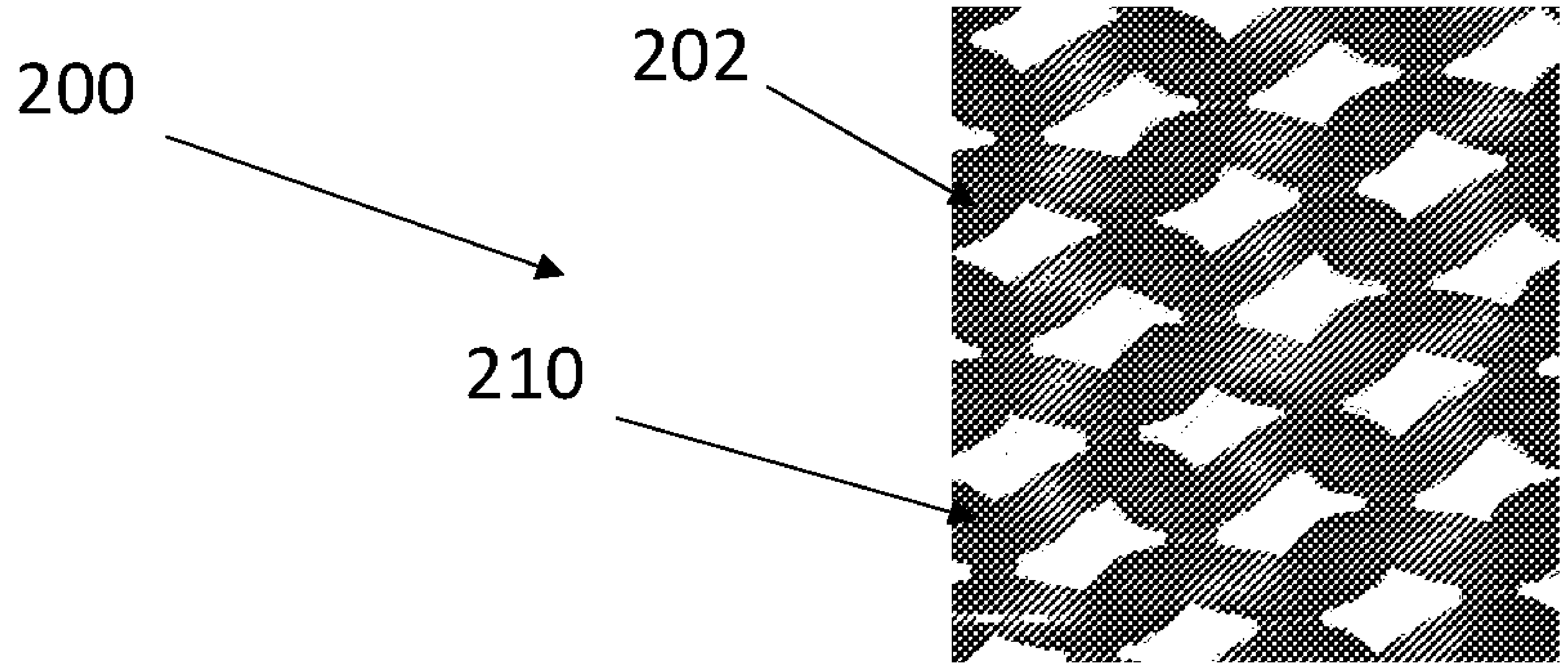


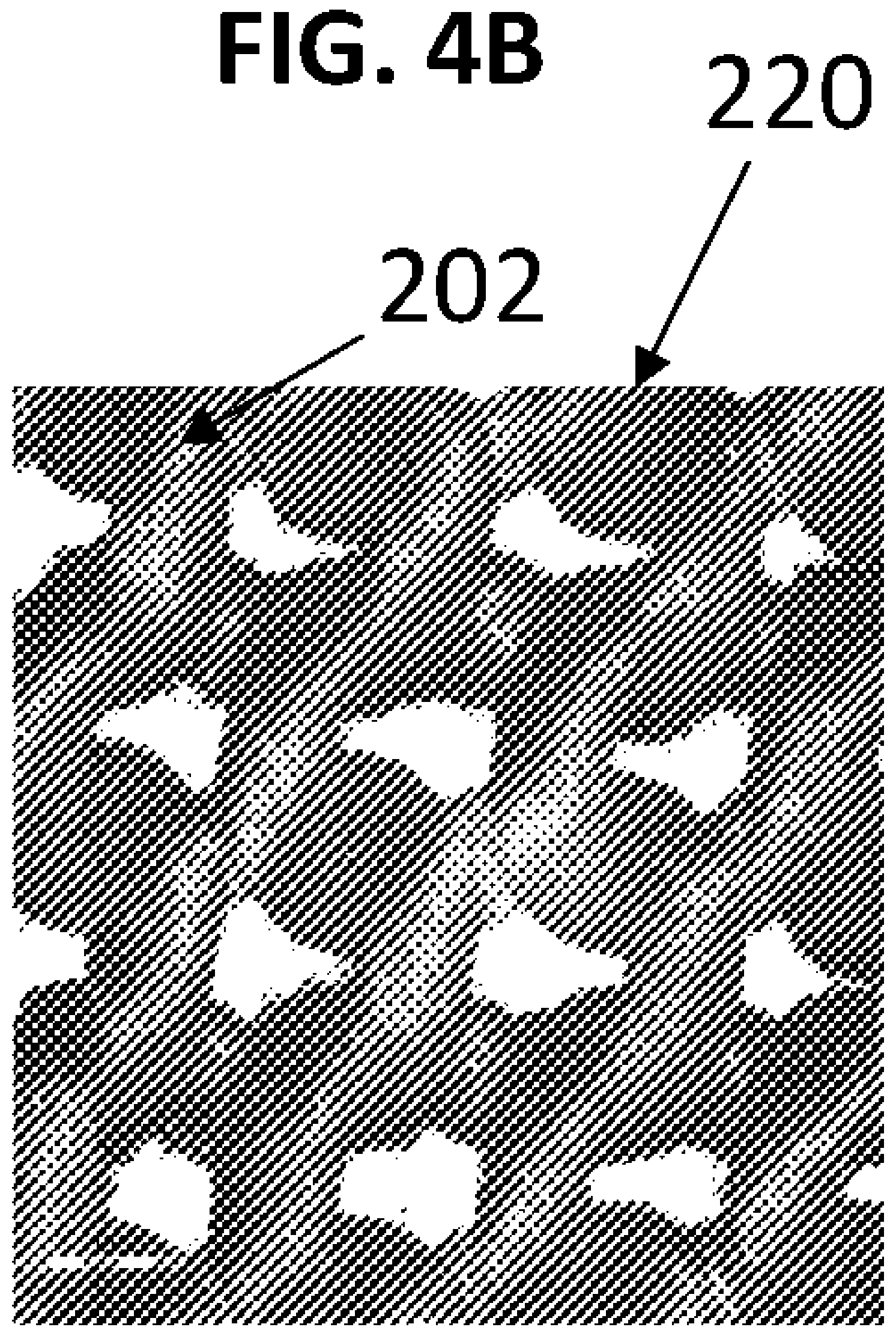
FIG. 3C

FIG. 4A



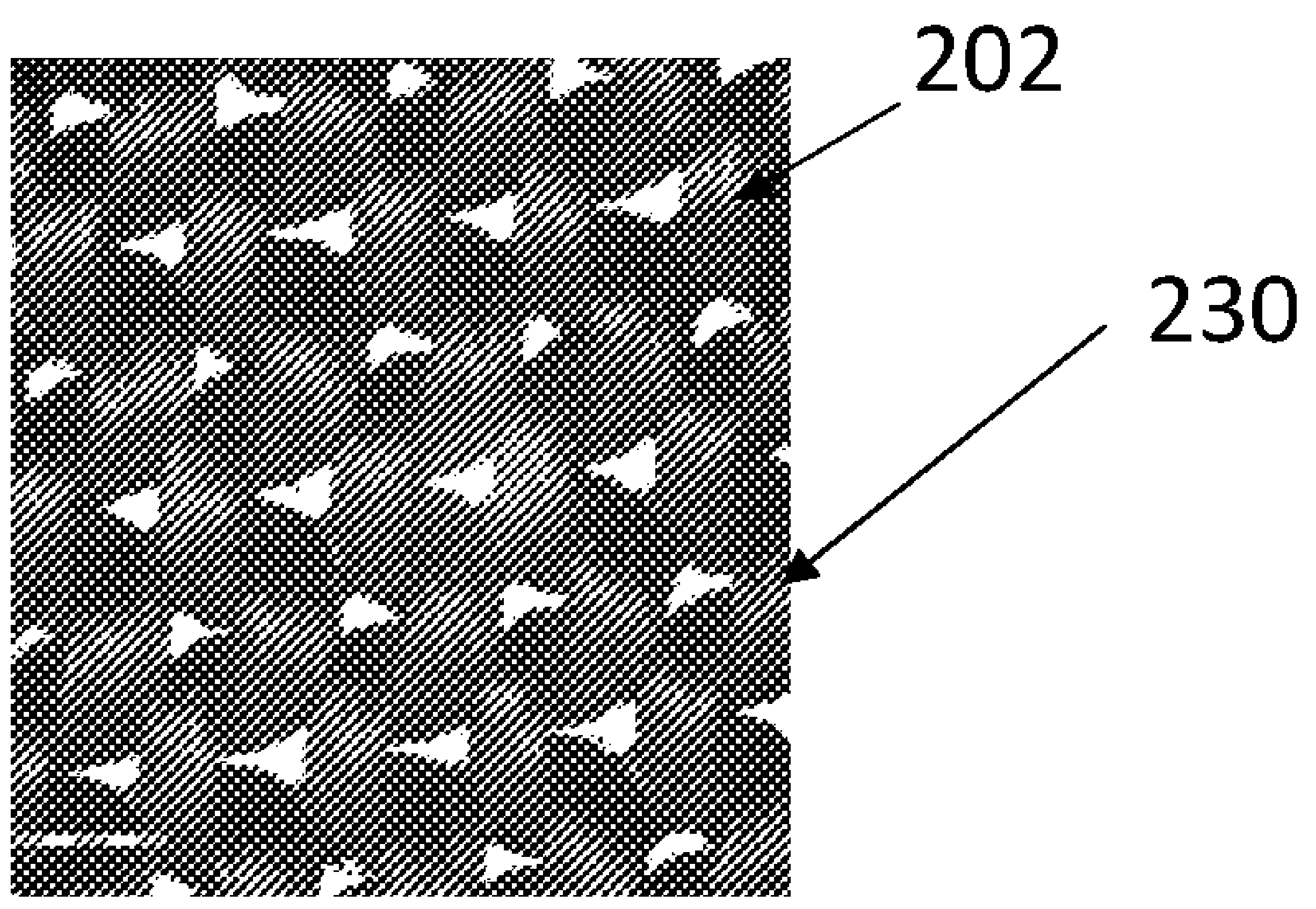
LLDPE1 knit structure
Stitches per inch = 19
wales x 20 courses: .26g

FIG. 4B

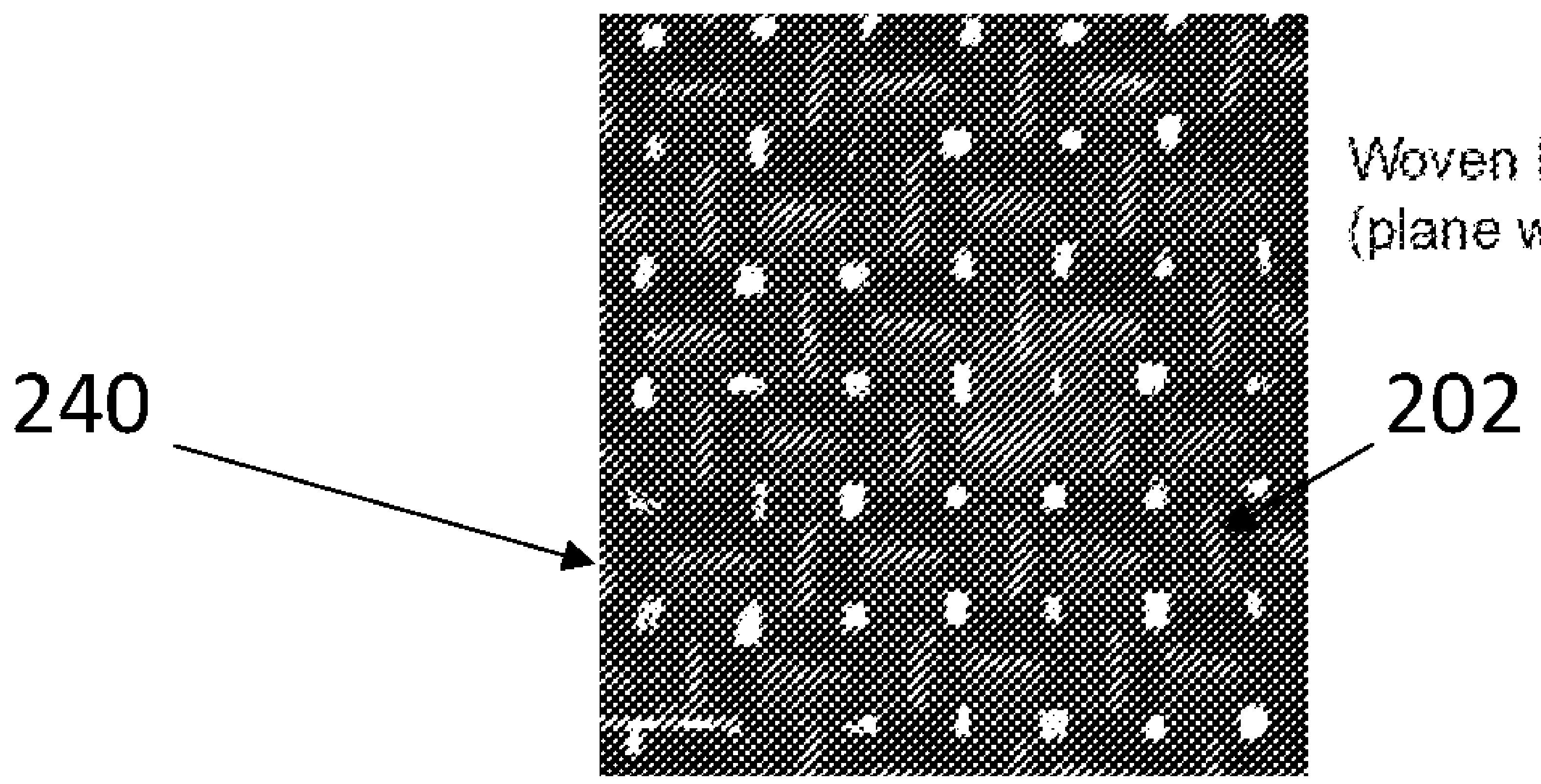


LLDPE2 knit structure
Stitches per inch = 17
wales x 17 courses: .30g

FIG. 4C

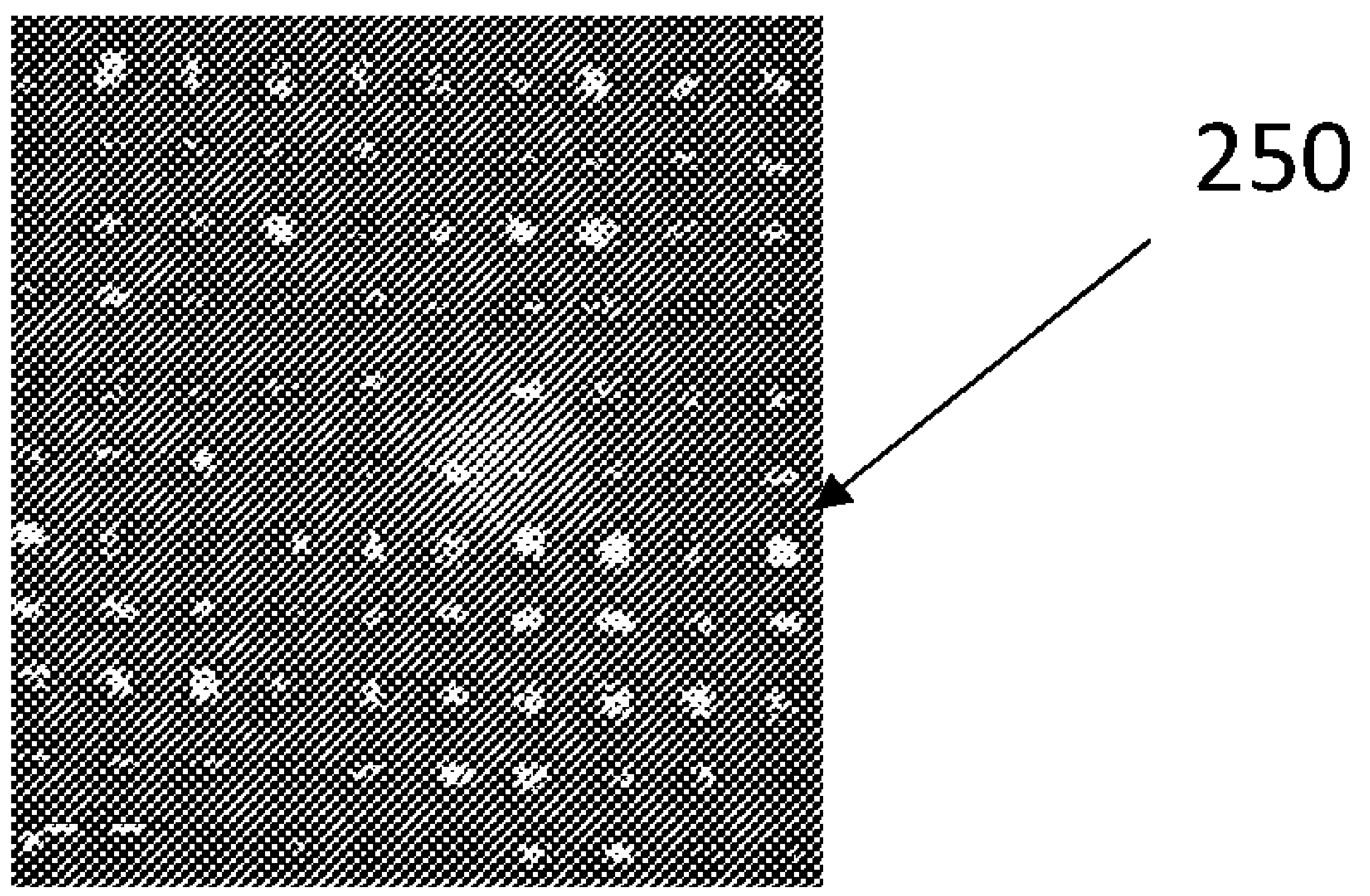


LLDPE3 knit structure
Stitches per inch = 16
wales x 22 courses: .46g



Woven LLDPE fabric
(plane weave)

FIG. 4D



Woven cotton fabric
(plane weave)

FIG. 4E

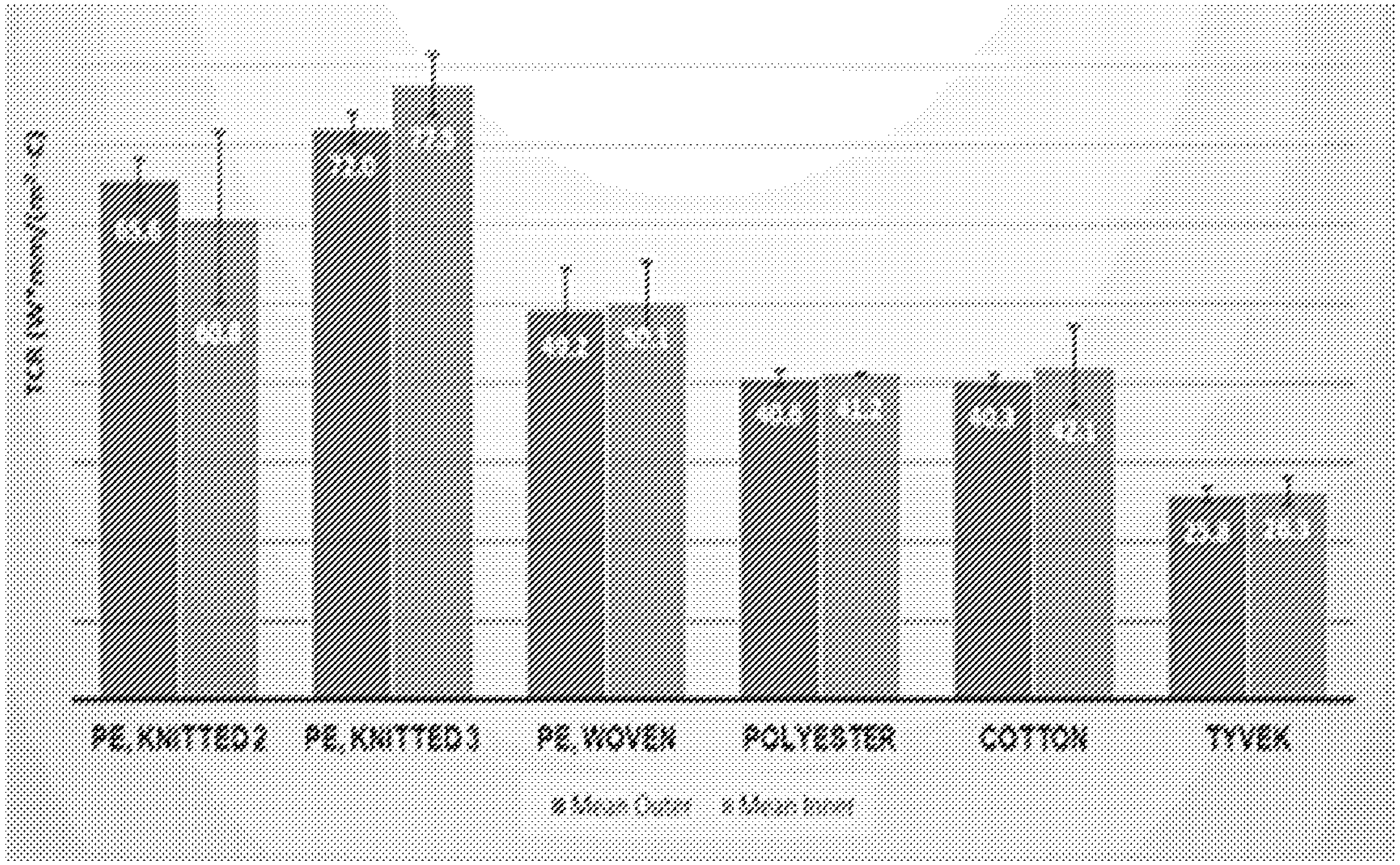

TCR (W*mm/(m²·C))
63.8
60.4
72.0
77.5
49.2
50.1
40.4
41.2
40.3
42.1
25.4
26.3
PE, KNITTED 2
PE, KNITTED 3
PE, WOVEN
POLYESTER
COTTON
TYVEK
Mean Outer
Mean Inner

FIG. 5

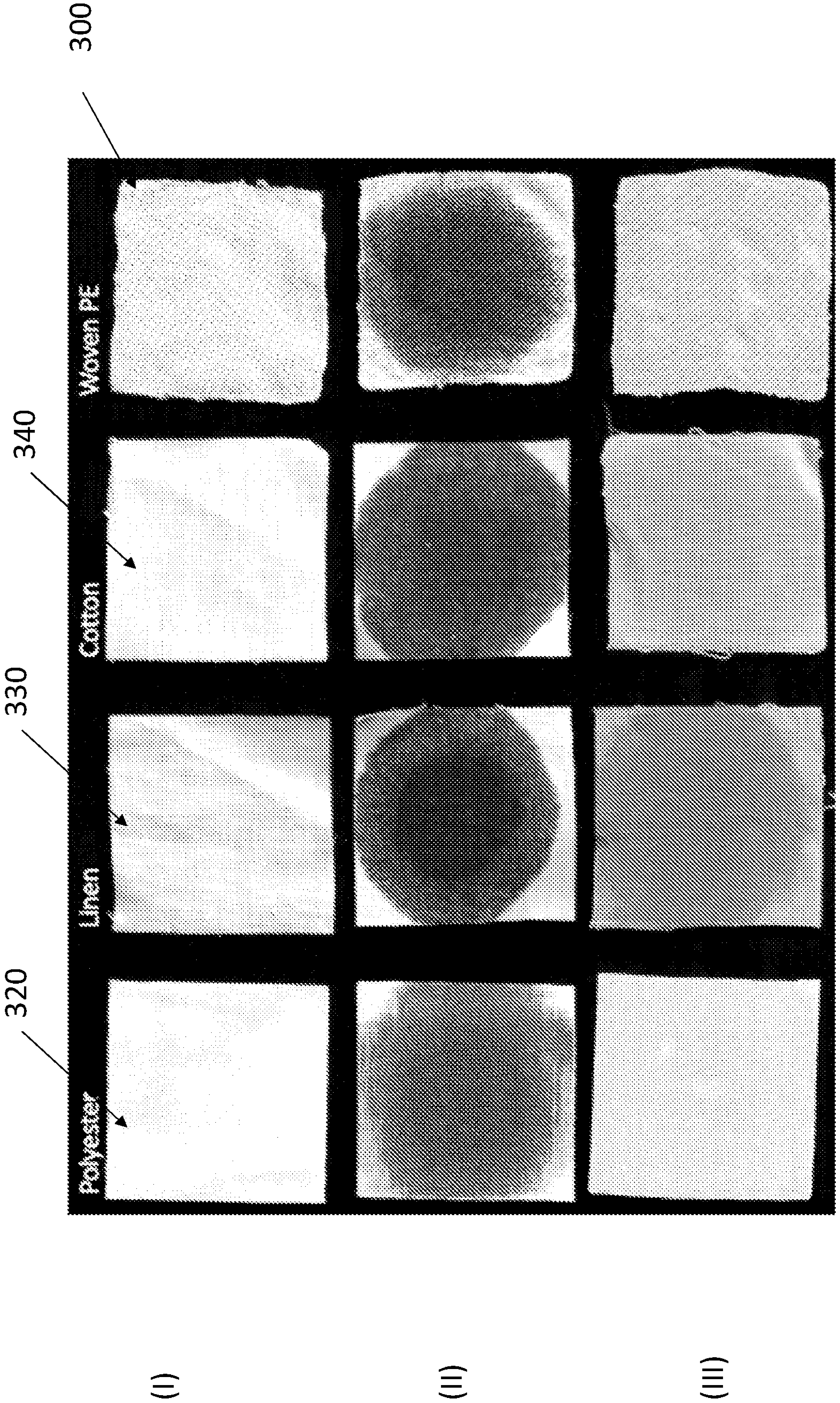


FIG. 6

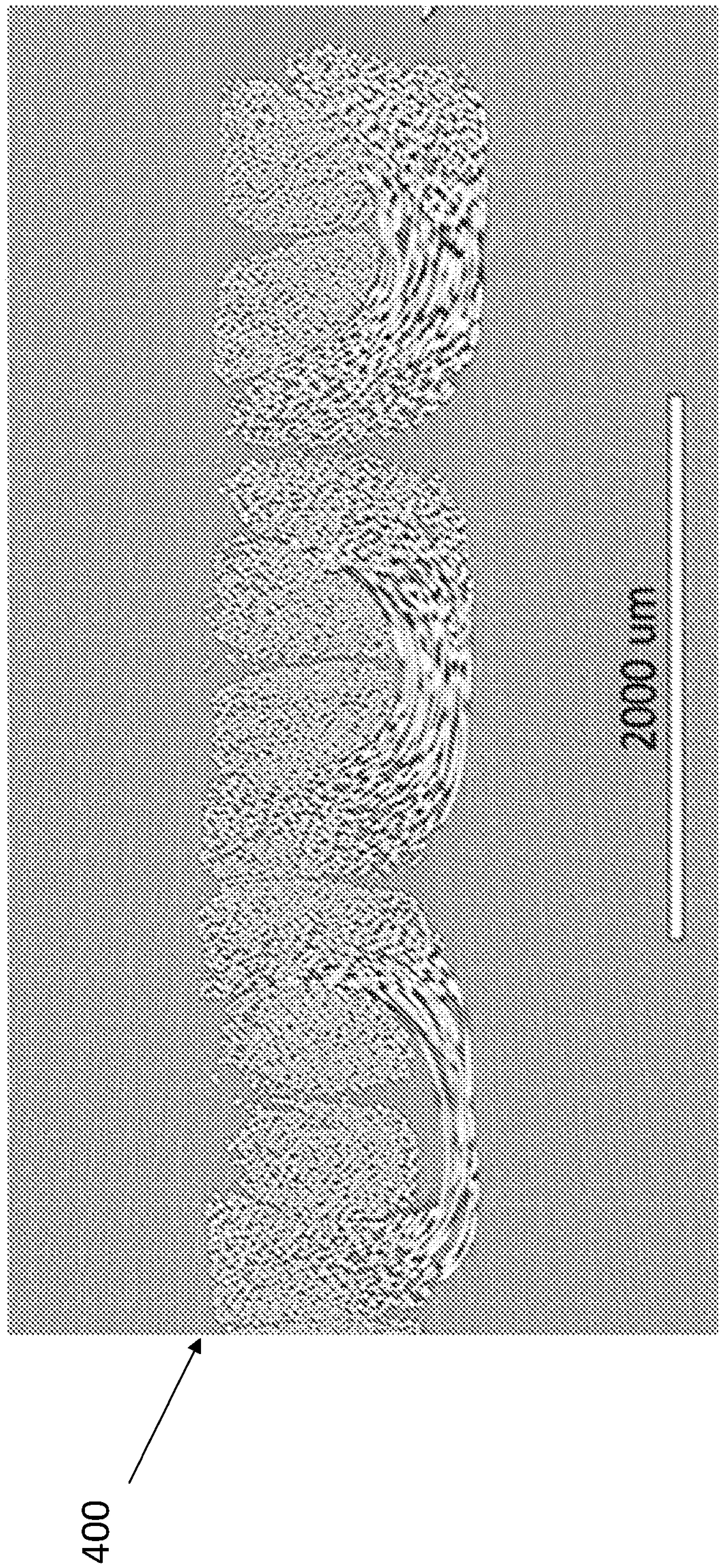


FIG. 7

POLYETHYLENE TEXTILES WITH ENGINEERED FEATURES THAT PROVIDE FOR PASSIVE COOLING AND MANUFACTURE THEREOF

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present disclosure claims priority to and the benefit of U.S. Provisional Application No. 63/161,424, entitled “Polyethylene Fabrics and Textiles Manufactured to Provide Passive Cooling by way of Thermal Conduction,” filed on Mar. 15, 2021, and U.S. Provisional Application No. 63/139,760, entitled “Polyethylene Textiles with Engineered Moisture Transport for Passive Cooling,” filed on Jan. 20, 2021, both of which are incorporated by reference herein in their entireties.

GOVERNMENT RIGHTS

[0002] This invention was made with Government support under Grant No. W15QKN-16-3-0001 awarded by the Department of Defense, and under Grant No. W911NF-13-D-0001 awarded by the Army Research Office. The Government has certain rights in the invention.

FIELD

[0003] The present disclosure relates to polyethylene textiles, and more particularly relates to engineering polyethylene textiles to utilize various techniques for moisture transport that results in passive cooling.

BACKGROUND

[0004] The textile industry is a global commercial enterprise, producing about 62 million tons of fabrics each year. It is also one of the most polluting industries on earth, second only to oil and gas, consuming massive amounts of water, and generating millions of tons of textile waste. The textile industry is responsible for approximately in the range of about five (5) percent to about ten (10) percent of global greenhouse gas emissions annually. Textile maintenance while being used often consumes even more energy and water than when it is produced and presents unique challenges in off-grid locations and/or in situations in which frequent washing, drying, and/or re-using of fabrics are needed. Moreover, colored or blended textiles complicate waste-sorting with near-infrared scanners, and most textiles end up in landfills and/or burned.

[0005] The textile industry has long made use of natural fibers such as wool, cotton, silk, and linen, until the last century has witnessed rapid adoption of synthetic materials, including polyester, acrylic, and nylon. Despite being cheap, corrosion-resistant, easy to make, and easy to recycle and convert to a new fuel source at the end of its lifespan, polyethylene (PE), which is a common plastic, has not been used in the textile industry. PE has been largely overlooked as a high-performance material for wearable textile production. The recent emergence of PE as a promising polymer for wearable textiles can be attributed to its high infrared transparency and tuneable visible opacity, which allows the human body to cool via thermal radiation, potentially saving energy on building refrigeration. Non-woven polyethylene materials are used for lab wear and protective apparel, but they do not provide functionalities expected from everyday clothes or bedding textiles. Ultrahigh molecular weight (UHMWPE) fibers are very strong yet prohibitively expensive for everyday textile applications, finding use in bulletproof vests, ropes, and fishing nets.

[0006] Conventional textile production has a few shortcomings that has led to PE being ignored in production thereof. Although PE is one of the most-produced materials in the world, and is fully recyclable, either mechanically via a melt-extrusion process or chemically via solvent dissolution and pyrolysis, most of PE waste is incinerated. This is at least because it is not usually economically viable to recycle it in the form of low-cost plastic bags and films. Moreover, fabrics and textiles are manufactured and used for their environmental protection, but have the unpleasant characteristic of forming a microenvironment that accumulates dirt and serves as a breeding ground for a variety of harmful microorganisms. In addition to the health risks caused by microorganism and bacterial growth, other undesirable effects include unpleasant odor, as well as degradation in the fabrics appearance and eventually in their mechanical strength. These effects are exacerbated in high-risk environments such as hospitals and in geographical locations and situations where access to hot water, electrical power, and/or cleaning supplies is either limited or temporarily unavailable.

[0007] A typical approach to addressing these issues relies on fabrics modification via addition of antimicrobial agents in the fibers or via their grafting onto the textile/fiber surface. The commonly used antimicrobial agents include quaternary ammonium compounds, triclosan, metal salts, and polybiguanides. However, the presence of similar antimicrobial agents in many products available increases the risk of negative effects associated with microorganisms developing resistance to these agents. For example, the rise of multi-drug-resistant bacteria species is increasing at an alarming rate, with over-use of triclosan in non-healthcare environments considered as one of the major causes of this process.

[0008] Accordingly, there is a need for fabrics with superior moisture wicking and evaporative performance characteristics that are wearable, comfortable, non-toxic to both the consumer and to the environment, and/or preferably have high recycling capability.

SUMMARY

[0009] The present application is directed to production of polyethylene textiles that are optimized to increase moisture wicking and overall performance thereof. Optimization of the textiles is a result of modifications (i.e., engineering) made to the polyethylene materials from which the textiles are manufactured to increase a hydrophilicity thereof. During the production phase, the surface of the polyethylene fibers are slightly modified to induce oxidation of the surface. In some embodiments, oxidation can be performed by oxygen plasma treatment, or the like, which can increase affinity of the fibers to moisture. Once the surfaces are sufficiently oxidized, the fibers can be bundled to form yarns that are woven, knit, spun, and/or otherwise associated to form fabrics. During bundling of the fibers, further modifications to the fibers can increase a capillary force of the bundle, thereby further increasing hydrophilicity and moisture wicking of the resulting fabric. Capillary force modifications can be performed by optimizing one or more of a fiber size, a density, and/or a cross-section of the bundle, among other features. In some embodiments, fibers can be arranged in parallel during weaving of the fabric to promote hydrophilicity and moisture transport therethrough.

[0010] One exemplary embodiment of a hydrophilic fabric includes at least one of multi-filament yarns that comprise polyethylene or continuous fibers that comprise polyethylene. The at least one of multi-filament yarns that comprise polyethylene or continuous fibers that comprise polyethylene are at least one of spun, woven, or knitted together to form the fabric. Further, the at least one of the multi-filament yarns that comprise polyethylene or the continuous fibers that comprise polyethylene have a modified surface that causes the respective yarns and/or fibers to be at least partially-hydrophilic, with the continuous fibers being aligned substantially in parallel with respect to each other. The fabric is devoid of non-polyethylene yarns and non-polyethylene fibers that mechanically reinforce the fabric.

[0011] The modified surface can include at least one of a changed fiber size, a changed fiber density, or a changed cross-section of the at least one of multi-filament yarns that comprise polyethylene or continuous fibers that comprise polyethylene. The at least one of multi-filament yarns that comprise polyethylene or continuous fibers that comprise polyethylene can include a pattern arrangement of such yarns and/or fibers, the arrangement having a regular triangular arrangement and/or a square arrangement. In some embodiments, an exposed surface of the fabric is hydrophilic and a portion of the fabric below the exposed surface is hydrophobic.

[0012] The fabric can be devoid of a coating disposed on the multi-filament yarns that comprise polyethylene and/or the continuous fibers that comprise polyethylene to make the polyethylene more hydrophilic. In some embodiments, the fabric can have a thickness approximately in the range of about 300 microns to about 1000 microns, and a thermal conductivity of the continuous fibers that comprise the fabric can be approximately in the range of about 0.1 Watts per meter Kelvin to about 60 Watts per meter Kelvin. The polyethylene can include at least one of low-density polyethylene, linear low-density polyethylene, medium-density polyethylene, high-density polyethylene, low molecular weight polyethylene, and/or ultra-high molecular weight polyethylene. A fiber crystallinity of the fabric can be approximately in the range of about 50% to about 100%. In some embodiments, the fabric can have a thickness approximately in the range of about 300 microns to about 1000 microns.

[0013] A density of the multi-filament yarns that comprise polyethylene and/or the continuous fibers that comprise polyethylene can be optimized. At least one of a yarn of the multi-filament yarns or a fiber of the continuous fibers can have a diameter approximately in the range of about 1 micron to about 150 microns. The fibers can include at least one of a single type of polyethylene or a blend of more than one type of polyethylene. A water-fiber contact angle of the hydrophilic fabric can be approximately in the range of about 50 degrees to about 80 degrees.

[0014] One exemplary method of manufacturing a fabric includes extruding one or more continuous fibers comprising polyethylene, modifying a surface energy of the one or more continuous fibers comprising polyethylene to change a hydrophilicity of the fibers, and bundling the one or more continuous fibers to form a plurality of yarns. Further, the method includes one or more of spinning, weaving, or knitting one or more yarns of the plurality of yarns with another yarn of the plurality of yarns to form the fabric.

[0015] In some embodiments, modifying a surface energy of the one or more continuous fibers can increase the hydrophilicity of the fibers without either applying a coating to the fibers or reinforcing the fabric with at least one of non-polyethylene yarns or non-polyethylene fibers. Alternatively, or in addition, modifying a surface energy of the one or more continuous fibers comprising polyethylene can further include at least partially oxidizing a surface of the one or more continuous fibers comprising polyethylene.

[0016] In some embodiments, bundling the one or more continuous fibers can include arranging the one or more continuous fibers substantially in parallel to optimize capillary action through the plurality of yarns. Modifying a surface energy of the one or more continuous fibers can include adjusting at least one of one or more of a fiber size, a density, and/or a cross-section of the one or more continuous fibers or one or more of a size, a density, or a cross section of the bundled one or more continuous fibers. The one or more continuous fibers can include at least one of low-density polyethylene, linear low-density polyethylene, high-density polyethylene, and/or ultra-high molecular weight polyethylene.

[0017] The method can further include adjusting at least one of a weight fraction, a size, and/or a drawing ratio of at least one of the one or more continuous fibers comprising polyethylene. In some embodiments, the method can further include optimizing a chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene. Optimizing the chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene can include post-treating the one or more initially extruded continuous fibers comprising polyethylene.

[0018] The method can further include coloring the one or more continuous fibers by at least one of dry-coloring or spin-dying the one or more continuous fibers with one or more of an organic colorant or an inorganic colorant. In some embodiments, the method can further include restoring hydrophilicity to the fabric by exposing the surface of the one or more continuous fibers to one or more of an oxygen plasma treatment, ultraviolet radiation, and/or friction.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] This disclosure will be more fully understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

[0020] FIG. **1**A is a structure of a polyethylene molecule that can be used in the textile industry for the manufacture of clothing and other wearable items;

[0021] FIG. **1**B is a structure of a polyester molecule that can be used in the textile industry for the manufacture of clothing and other wearable items;

[0022] FIG. **1**C is a structure of a cotton molecule that can be used in the textile industry for the manufacture of clothing and other wearable items;

[0023] FIG. **2** is a schematic of a lifecycle of fabrics illustrating comparative environmental burdens of each step;

[0024] FIG. **3**A is a scanning electron microscopy (SEM) image of an exemplary embodiment of a woven PE fabric of the present embodiments;

[0025] FIG. **3**B is an SEM image of an exemplary embodiment of a multi-filament PE yarn used in the fabric of FIG. **3**A;

[0026] FIG. **3**C is an SEM image of an exemplary embodiment of an individual PE fiber filament used in the yarn of FIG. **3**B;

[0027] FIG. **4**A is an image of a knitted PE fabric showing the fabric structure;

[0028] FIG. **4**B is an image of another knitted PE fabric showing the fabric structure;

[0029] FIG. **4**C is an image of another knitted PE fabric showing the fabric structure;

[0030] FIG. **4**D is an image of a woven fabric showing the fabric structure;

[0031] FIG. **4**E is an image of a cotton sample as a standard reference material to the structures of FIGS. **4**A-**4**D;

[0032] FIG. **5** is a series of bar graphs illustrating through-fabric thermal conductivity of PE textiles compared to those of a non-woven commercial PE textile (Tyvek, DuPont) and woven textiles made of conventional natural (cotton) and synthetic (polyester) fibers;

[0033] FIG. **6** is a photograph showing samples of polyester, linen, cotton, and woven PE stained by a commercial food colorant and subsequently rinsed under running cold tap water without the use of soap or any chemicals; and

[0034] FIG. **7** is a cross-section of exemplary fabric having a thickness of approximately 820 micron, a weight (mass per unit area) of about 0.05 g/cm^2, total yarn denier of 994 (double-plied 497 denier yarn), a fiber crystallinity of about 52% and orientation factor of about 0.26, and 16 wales and 22 courses per square inch (352 stitches per square inch).

DETAILED DESCRIPTION

[0035] Certain exemplary embodiments will now be described to provide an overall understanding of the principles of the structure, function, manufacture, and use of the systems, devices, and methods disclosed herein. One or more examples of these embodiments are illustrated in the accompanying drawings. Those skilled in the art will understand that the systems, compositions, and methods specifically described herein and illustrated in the accompanying drawings are non-limiting exemplary embodiments and that the scope of the present disclosure is defined solely by the claims. The features illustrated or described in connection with one exemplary embodiment may be combined with the features of other embodiments. Such modifications and variations are intended to be included within the scope of the present disclosure. Like-numbered components across embodiments generally have similar features unless otherwise stated or a person skilled in the art would appreciate differences based on the present disclosure and/or his/her knowledge. Accordingly, aspects and features of every embodiment may not be described with respect to each embodiment, but those aspects and features are applicable to the various embodiments unless statements or understandings are to the contrary.

[0036] To the extent that the instant disclosure includes various terms for components and/or processes of the disclosed devices, systems, methods, and the like, one skilled in the art, in view of the claims, present disclosure, and knowledge of the skilled person, will understand such terms are merely examples of such components and/or processes, and other components, designs, processes, and/or actions are possible. To the extent that the fabrics of the present embodiments are discussed as being "modified" or "engineered," a person skilled in the art will recognize that the terms are being interchangeably applied to one or more of a series of actions performed on the fabric to change the existing structure of the body and/or a surface thereof. Any one action can be considered a modification or an engineering action, as can any combination of those actions.

[0037] The present disclosure generally relates to textiles that are optimized to maximize moisture wicking and evaporative performance thereof. For example, engineering modifications to the structure of polyethylene (PE), which is a cheap, abundant, and lightweight material, can produce a fabric that is superior to conventional materials such as nylon, polyester, and so forth. The modification of the structure of the PE can provide a fabric having a high level of personal comfort, is fully recyclable, offers stain and dirt resistance, and/or has high potential for anti-microbial protection without use of toxic nano-agents. The textile(s) can include a plurality of yarns that are spun, weaved, and/or are otherwise associated to form a fabric. Each yarn can be made of a plurality of fibers that can be bundled together to form the overall structure of the yarn. A surface of the fibers can be modified, for example by oxidation, to increase hydrophilicity of the surface of the fibers. Once the surfaces are sufficiently oxidized, in some embodiments, the fiber can be bundled and/or further engineered to increase a capillary force of the bundle, thereby further increasing hydrophilicity of the resulting fabric. Engineering of the capillary force can be performed by optimizing one or more of a fiber size, a density, and/or a cross-section of the bundle, among other features. In some embodiments, coloring can be added to the fabric to modify the color of the fabric. The resultant fabric can exhibit a strong weight reduction, stain resistance, and/or drying capabilities.

[0038] The fabrics of the present embodiments can be manufactured via standard industrial processes known to persons skilled in the art, with adjustments to such processes being able to be made by the skilled person based on the disclosures provided for herein. Some non-limiting examples of such standard industrial processes include spinning, twisting, plying, knitting, weaving, extruding, spin-dyeing, and/or employing techniques such as thermal treatment based on heating-cooling processes, plasma treatment, and/or ultraviolet (UV) light irradiation, and so forth.

[0039] PE fabrics can utilize the human body's innate ability to thermally radiate heat as a cooling mechanism during the summer season when environmental temperatures are high. However, thermal radiation transport from some areas of the human body not directly exposed to the environment (such as, for example, armpits or shoe-clad feet) is severely hindered. The presently disclosed fabrics can allow heat to pass through the fabric rather than trap the heat therein. That is, the fabrics of the present embodiments can provide for cooling the human body and re-distributing the heat more uniformly between areas that are exposed to the environment and those that are hidden from the environment. In general, the fabrics of the present disclosure optimize a number of cooling factors, including but not limited to conduction, convection, evaporation, and/or radiation. The present disclosure allows for the optimization of these factors to help manage performance, as opposed to previous disclosures in the art, which typically optimized primarily for strength. More particularly, the techniques disclosed herein including using heat conduction in conjunction with heat convection for cooling and heat redistribution. The total amount of heat transferred from the skin into and through the fabric material as it touches the skin quantifies the efficiency of the passive fabric cooling by conduction, and also defines the sensory thermal feeling of a fabric as it touches the human skin—i.e., warm-cool touch feeling of the fabric.

[0040] As a result, the fabrics and textiles of the present embodiments can be thicker than would be expected, which can be beneficial at least because the heat can travel through the material via thermal conduction to be subsequently removed from the large surface area of the porous textile by convection. These thick materials can also provide cooling features due, at least in part, to the way the fibers and/or yarns are formed. More particularly, the fibers, yarns, and/or textiles can include PE that is spun, knitted, and/or weaved in a manner that allows the fibers and/or yarns to wick away moisture. The result is silky, lightweight fabrics and textiles that absorb and evaporate fluids (e.g., water) more quickly than common fabrics textiles such as cotton, nylon, or polyester. Further, the resultant fabrics and textiles can have a smaller ecological footprint than counterpart fabrics formed from cotton and/or nylon fabrics and textiles. Because of the sustainability that results from the present disclosures, plastic bags often used at grocery stores and the like, as well as other polyethylene products, can be turned into wearable textiles, adding to the sustainability of the material. Further, as described in greater detail below, the resulting textiles can also show enhanced abilities for stain removal as compared to typical, comparable textiles that do not utilize the presently disclosed manufacturing techniques.

[0041] FIGS. **1A**-**1C** illustrate exemplary structures of polyethylene as compared to common fabric textiles used in the textile industry for the manufacture of clothing and other wearable items. As shown, the PE molecule is simple as compared to other organic polymer molecules commonly used for fabrics production. Conventionally, the cooling capabilities of PE were known by those skilled in the art, but due to its perceived inability to absorb water and sweat due to its hydrophobicity, its use in the manufacture of textiles was rejected. The hydrophobicity of unmodified polyethylene stems, at least in part, from the lack of ionic bonds or polar molecular groups for water molecules to attach.

[0042] For example, as shown in FIG. **1**A, a molecule of PE has a backbone of carbon atoms, each having two hydrogen atoms covalently attached thereto. The carbon-hydrogen bond is repeated throughout the structure of the molecule to form a Teflon-like architecture that resists water and other molecules. The lack of ionic bonds or polar groups in the PE structure prevents other molecules from permanently attaching to the surfaces of PE fibers and textiles. Polyethylene internal properties can be varied by engineering, for example, the polymer chain length and branching, as well as by the optimization and/or control of material crystallinity and molecular chain orientation. Through a combination of mechanical, X-ray, and thermal characterization of the PE fibers and fabrics, control over the fiber tensile strength, melting temperature, and/or abrasion resistance via internal polymer properties and fabric structure can be achieved. Prevention of attachment of other molecules to the surfaces of the PE allows for inhibition of dirt and microorganisms to accumulate on the surface thereof. By way of comparison, polymer molecules of polyethylene terephthalate (polyester) and cellulose (cotton), which are more conventionally used in textile manufacturing, are more complex than those of PE. This is clearly illustrated by the molecular structure shown in FIGS. **1**B and **1**C. For example, as shown, these compounds offer multiple sites for the strong attachment of dyes, dirt, and/or contaminants such as microorganisms.

[0043] FIG. **2** illustrates a schematic of the lifecycle of fabrics **10**, and the corresponding estimate of the environmental burden of each step. As shown, fabric lifecycles can undergo three phases: a production phase **12**, a use phase **14**, and an end of life phase **16**. PE fabrics exhibit ultralight weight, low material cost, low processing temperatures, as well as recyclability, thereby predicting low environmental footprint of PE fabrics in the production phase. In the production phase **12** of the fabric lifecycle **10**, the fabric can be manufactured by integration of a raw material stage with spinning and/or weaving said raw material, and adding coloring, for instance via a spin-dyeing (also known as solution-dyeing or spin-doping) process, as desired. As shown in the manufacturing sustainability index (MSI), the environmental footprint for manufacturing each of the PE materials at each of the stages of the production phase is superior to that of conventional materials such as cotton, wool, nylon, and polyester. Specifically, while the spinning and weaving portion of the production phase is largely the same across all of the synthetic materials (e.g., nylon and polyester), PE provides for much better sustainability, and thus less environmental impact, as a result of the raw materials used and a more sustainable coloration process. The environmental footprint reduction is achieved through lower manufacturing temperatures and fewer chemicals used in production. Comparatively, as illustrated in FIG. **2**, PE produces a smaller environmental impact in the raw material stage, thereby contributing to its superiority for textile manufacturing. Further, by using bio-derived PE resins, environmental impact can be further reduced, while, in some embodiments, achieving a negative carbon footprint of the PE resins, such as the footprint produced from sugar cane biomass. Comparatively, PE produces little to no environmental impact in the raw material stage, thereby contributing to its superiority for textile manufacturing. A person skilled in the art will recognize that while the MSI presented in FIG. **2** represents the environmental footprint of one kilogram of polyethylene woven fabric as compared to the same amounts of conventional woven textiles, a person skilled in the art will recognize that these comparisons increase and/or decrease proportionately with weight of fabrics being compared.

[0044] Upon completion of production, the fabric can enter the use phase **14**. In the use phase, the fabric is shipped, washed, dried, worn, and put under additional stresses commonly known to fabrics. In the use phase **14**, PE demonstrates superior weight reduction, stain resistance, and drying capability when compared to conventional materials, as discussed in greater detail below. After sufficient use, the fabric can enter the end of life phase **16** at which point it is disposed. While standard PE is shown as being comparable to polyester and exceeding each of cotton, wool, and nylon according to the Recyclability Environmental Gain Index (REGI), modifications made to the fabric during the production phase **12**, e.g., spinning, weaving, and so forth, can further enhance the recyclability of the PE fabric to be superior to that of the conventional textile materials having comparable modifications, as also discussed in greater detail below.

[0045] FIGS. **3**A-**3**C illustrate the structure of PE fabrics in more detail. For example, PE can be cast into fiber form and formed into a textile or fabric **100**. The fabrics can be formed by using conventional textile industry procedures and equipment. The fabric **100** can be made from a plurality of strands of yarn **102** that are engaged or otherwise associated with one another. In some embodiments, the yarn **102** can be spun, knit, and/or weaved to form the fabric **100**. Weaving of the fabric can be performed on an industrial loom or otherwise manufactured by a technique known to one skilled in the art. In some embodiments, the yarns can be a woven or knitted continuous multi-filament yarn that is formed into the fabric in a crisscross or a plain-woven pattern.

[0046] The yarn **102** can be made up of one or more fibers **104**. For example, in some embodiments, the multi-filament yarns can be made from 50 to 300 individual fiber monofilaments **104** with circular cross sections. The fibers **104** can be made from polyethylene or continuous fibers that include polyethylene. Some non-limiting examples of materials that make up the fibers can include low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), medium-density polyethylene (MDPE), low molecular weight polyethylene, ultra-high molecular weight polyethylene (UHMWPE), and/or blends of several PE materials. The PE used in the embodiments herein can include oil-based virgin fossil-derived PE, bio-derived PE, and/or recycled PE. These forms of PE can reduce the environmental footprint of the textile industry, with recycled and bio-derived material offering further reduction in both energy usage and environmental damage. While all of the fibers can be of a similar construction, in some embodiments one or more of the fibers of a fabric can differ in size (e.g., length, thickness, diameter), weight, shape, and/or material used to formulate the fiber and/or the fabric.

[0047] FIG. **3**C illustrates a fiber filament **104** that makes up the multi-filament yarn **102**. As mentioned above, a common reservation to the use of polyethylene for wearable textiles stems from the inherent PE hydrophobicity, which is expected to prevent perspiration wicking. Engineering modifications to the PE molecule can increase hydrophilicity of the PE, which would increase moisture wicking and evaporative performance of the resulting textile. Engineering PE molecules in this manner, however, at least prior to the present disclosures, was counter-intuitive to the knowledge of the skilled person, at least because of the inherent hydrophobicity of PE. For example, earlier demonstrations of porous non-woven PE textiles achieved water-wicking performance by chemically modifying the PE surface with a hydrophilic agent, such as polydopamine (PDA), to be hydrophilic (see P.-C. Hsu et al. "Radiative human body cooling by nanoporous polyethylene textile." Science, Volume 353, pp. 1019-1023, 2016).

[0048] Increasing hydrophilicity within the scope of the present disclosure refers to the ability of a material to absorb water and/or to allow water to travel along, through, and/or across a material. Hydrophilicity of a material can be represented as partial hydrophilicity, such that a surface of the material is hydrophilic while a core of the material is not hydrophilic, or even hydrophobic, or vice versa. A person skilled in the art will recognize that in conjunction with the present disclosures any change in the ability of the material to absorb water as a result of engineering and/or a modification can be referred to as an increase in hydrophilicity. For example, with respect to PE, any increase in the affinity for water exhibited by the material that results in the fiber surface exhibiting a static contact angle with water of less than 90 degrees can represent a modification that has made a material change to the hydrophilicity thereof.

[0049] In some embodiments, one or more of fiber size, fiber arrangement, and/or surface properties can be modified to improve hydrophilicity of the fabric, which can improve the wicking performance of the textile overall. The fiber size and the dense plain-woven pattern of the PE textile can be chosen to optimize the moisture transport and fast-drying performance of the material, and/or to promote comfort feeling and efficient passive cooling via evaporative process. By way of non-limiting example, with respect to fiber size, an efficient diffusion of sweat through the textile results in a larger effective area of evaporation than that of bare skin and, thus, in a higher drying rate. In some embodiments, a radius of the fibers in the fabric can depend on a target hydrophilicity and/or a target porosity of the fabric being manufactured.

[0050] As mentioned above, the fibers used in the fabric of the present embodiments can be circular. For circular shapes, in some embodiments a diameter of a fiber of multi-filament yarn, woven, or knitted, can be approximately in the range of about 1 microns to about 150 microns. Alternatively, in some embodiments, the fiber cross-sectional shape can be textured featuring grooves along the fiber length. In some embodiments, the multi-filament yarns **102** can be composed of fiber monofilaments **104**, as shown in FIGS. **3**B and **3**C, with radii that are approximately in the range between about 5 μm to about 20 μm. Moreover, besides circular cross-sections, some non-limiting examples of cross-sections of the fiber can be scalloped oval, tetraskelion, trilobal, multilobal, and/or corrugated circular shapes.

[0051] A fabric mass unit area of fabric provided for herein can be approximately in the range of about 100 grams per square meter to about 1500 grams per square meter, while in some instances the area can be approximately 350 grams per square meter or larger. A distance between the monofilament fibers **104** comprising each yarn can yield average yarn porosity approximately in the range of about 45% to about 65%. Lower values, e.g., closer to about 45%, may result in a stiff fabric, while higher values, e.g., closer to about 65%, can produce a fragile and/or transparent textile. A person skilled in the art will recognize that different applications, such as hospital bedding or safety clothing, may require a different or extended range of yarn porosity than the non-limiting values suggested.

[0052] In some embodiments, an engineering modification to increase hydrophilicity of the fibers can occur via oxidation during the production phase **12**. For example, during the spinning and weaving stage of the production phase **12**, the PE fabric of the present embodiments can be modified by running a melt-spin fabrication process in air, which can cause polymer thermoforming in the surfaces of the fiber monofilaments **104**. Polymer thermoforming can partially oxidize the surface of the material, which can cause the surfaces of the fibers **12** to acquire partially-hydrophilic properties. The increased fiber surface hydrophilicity due to the oxidation can remain stable over multiple wetting cycles of the fiber **104**.

[0053] In some embodiments, polymer thermoforming can form initiation sites for future oxidation in the presence of oxygen even at ambient temperatures. For example, in some instances future oxidation can persists for days, though in some embodiments, it can persist for months and/or years. Future oxidation can further increase hydrophilicity of the fibers **104**. PE fiber oxidation may be reduced in the process of wetting and air drying, while hydrophilicity can be restored by oxygen plasma treatment, ultraviolet radiation, and/or by friction, e.g., a simple fabric hand-rubbing process. For example, during the fabrication process, conventional treatments, such as, corona discharge, plasma treatment, and/or UV-ozone, among others, can be used to increase the number of polar groups on the surface of the fibers, such as —OH and C═O. The time of exposure can be tuned to obtain an average water-fiber contact angle in a desired range for optimally-engineered yarn and fabric structure. Optimum moisture wicking can be observed in at least some instances for water-fiber contact angles approximately in the range from about 50° to about 80°, though in some embodiments, they can be approximately in the range from about 50° to about 70°. Lower values can reduce the stain-resistant properties of the fabric, while higher values can result in poor wicking performances and hindering the efficient spread and evaporation of sweat.

[0054] In exemplary embodiments, the water-fiber contact angle θ can be calculated by measuring a ratio between the maximum length and the thickness of droplets deposited on a PE fiber and the fiber radius. To test the water-fiber contact angle θ, fibers can be extracted from yarns randomly picked from woven PE fabric samples, and fixed with tape between two glass slides. Water can then be sprayed on the fiber **104** to allow the deposition of droplets on its surface. A confocal microscope coupled to a Raman spectrometer (e.g., Horiba, LabRAM HR Evolution) can be used to photograph the droplets deposited on the fiber, at which point length and thickness measurements can be taken. For example, water-fiber contact angles of PE fibers after oxygen plasma treatment for about 1 minute, about 3 minutes, and about 10 minutes showed a reduction of θ by about 14%, about 23%, and about 27%, respectively.

[0055] In some embodiments, the hydrophilicity of the surface of the fibers can be tuned by inclusion of charged or photoactive micro- and nano-particles during the fabrication process. The desired concentration of particles at or close to the surface can be tuned, for example, by optimizing their weight fraction, size, and/or the drawing ratio of the fibers. In particular, multivalent salts ions, such as $Ca2^+$, $Al3^+$, and/or $Fe2^+$, and/or charged metal oxides, such as ZnO, ZrO_2, Ta_2O_5, NiO, VO_2, and/or TiO_2, can be added to the PE during the fabrication process in a weight fraction varying approximately in the range from about 0.1% to about 5%.

[0056] In some exemplary embodiments, a woven fabric with an average porosity varying approximately in the range from about 45% to about 60% and an average contact angle of about 70° can be composed of fibers with an average radius varying approximately in the range of about 6 μm to about 16 μm, while, considering the same porosity range but a contact angle of about 50°, the optimal radius range can vary approximately in the range of about 8 μm to about 20 μm. In some embodiments, the average diameter of the PE fibers is approximately (18.5±6.2) μm, and they are arranged in a closely packed yarn with an average porosity of approximately (53.0±4.8)%.

[0057] Increasing the hydrophilicity of the surface of the fiber **104** while the core remains hydrophobic allows the PE fabric to wick moisture efficiently. The presence of a hydrophobic core can avoid sweat absorption and consequent swelling as moisture is absorbed, which can hinder the transport of fluid. As a result, water fails to penetrate inside the PE fibers **104**, which allows the water to evaporate efficiently from the fiber surface. In contrast, wicking in natural fibers such as cotton and linen can be hindered by the water absorbed and trapped within the fiber volume, which can reduce the fabric drying rate.

[0058] In some embodiments, hydrophilicity of the fabric **100** can be increased further after oxidation is induced on the surface of the fibers **104**. For example, after the fibers **104** are optimized for moisture wicking and evaporative performance, fiber size and density can be engineered to increase a capillary force through the fabric **100**. Capillary pressure through the fabric can allow for efficient moisture transport therethrough, for example by allowing the moisture to travel through the material. Capillary pressure can be modified, for example, by optimizing the bundling of individual fibers into an orientation of a yarn that permits moisture to be transported readily therethrough. The capillary pressure p_c is a function of the yarn porosity, the fiber shape and size, and the water-fiber contact angle. In some embodiments, capillary pressure can increase when the yarn comprises small, hydrophilic and densely packed fibers, yielding larger values of p_c. In some embodiments, capillary pressure can increase when the yarn comprises small, hydrophilic and densely packed fibers, yielding larger values of h_{max}. Further, in some embodiments, for example, moisture wicking properties of the material can depend, at least in part, on the mutual (e.g., parallel) orientation of the fibers within the fabric **100**. Fiber surface corrugation in the direction along the fiber length can further increase the wicking performance of PE yarns.

[0059] In view of the modifications to the fabrics through oxidation and increases in capillary force, hydrophilicity of the fabric **100** of the present embodiments can be increased and/or optimized without adding a hydrophilic coating to the fabric. Unlike previously demonstrated nano-porous polyethylene films and fabrics, the modifications to the fabric of the present embodiments is such that the fabric is neither mechanically reinforced by blending with other fibers nor is it chemically treated to add a hydrophilic coating. Moreover, fabrics of the present disclosure that are devoid of a hydrophilic coating to increase a hydrophilicity thereof can be understood to have been modified via one or more of the modifications disclosed herein to change a property of the material, e.g., polyethylene, itself, rather than adding a foreign substance, layer, or film thereto. These modifications or other engineering of the fabric **100**, and the components thereof (e.g., the yarn **102**, fibers **104**), is distinct from the use of coating to provide any similar hydrophilicity capabilities.

[0060] As noted above, the fibers that make up the presently disclosed fabrics **100** can be produced by extrusion as a result of standard melt-spinning or other similar processes in open air or in oxygen-rich atmosphere. For example, PE in raw powder or pellet form can be used in conjunction with standard textile manufacturing equipment to melt and extrude the polyethylene into thin fibers. The extrusion process can slightly oxidize the material, changing the surface energy of the fiber to make the PE weakly hydrophilic, and able to attract water molecules to its surface. Further modification of the PE fibers can be performed, for example, by controlling the diameter, draw ratio, and/or cooling temperature of the resulting fibers and the environmental conditions in the extrusion chamber (e.g., atmosphere, illumination conditions, etc.).

[0061] Moreover, in some embodiments, a multi-filament extruder can be used to bunch or bundle multiple PE fibers together to make a weavable yarn **102**. Two or more multi-filament yarns can be further plied together by using a yarn twister, increasing the filament count in the yarn and allowing for additional control over the yarn density. That is, when dipped in water, water can wedge within the capillaries and travel up the fiber **104** through capillary action until it is wicked through the fabric and evaporated. It will be appreciated that the surface energy of the bundles can be modified by adjusting one or more of a size, a density, or a cross section of the bundles, as discussed above with respect to individual fibers.

[0062] Strong capillary action has a direct relationship with moisture wicking. For example, materials with strong capillary action can cause strong moisture wicking properties. In some embodiments, further optimization can occur by post-treating the extruded continuous fibers that include polyethylene. For example, in some embodiments, to optimize wicking, fibers of a certain diameter can be aligned in specific directions through the yarn, which can improve the collective wicking ability of the fibers. For example, during weaving, the monofilament fibers **104** of the yarns **102** can be arranged substantially in parallel during the weaving process, e.g., without yarn twisting, while being organized in a regular hexagonal or square arrangement to produce superior moisture wicking performance compared to alternate orientations.

[0063] FIGS. **4**A-**4**E illustrate exemplary embodiments of knit structures **200** of the textiles of the present embodiments in the above-described orientations. The four non-limiting types of fabrics shown in FIGS. **4**A-**4**D, were fabricated from LLDPE multi-filament yarns, including three knitted samples **210**, **220**, **230** with different yarn and knitting densities, and one woven sample **240**. Woven and knitted fabrics comprising multi-filament PE yarns **202** fabricated via a melt-spin process or the like of the present disclosure can reduce skin temperature by several degrees relative to conventional fabric **250** (e.g., made of cotton or polyester). This benefit is achieved by way of heat spreading using thermal conduction along fibers that make up the yarns that form the fabric. The cooling performance of the fabrics **210**, **220**, **230**, **240** can be tuned by engineering aspects of the fiber, including but not limited to the fiber size, linear or branched structure of the polymer molecules in the raw material (e.g., such as typical for LLDPE, MDPE, and HDPE resins), molecular orientation (i.e., alignment of the polymer chains within each fiber) and/or crystallinity (both of which can be controlled, for example, by a fiber drawing process), material composition (e.g., LLDPE-HDPE, where HDPE is high density polyethylene, MDPE-HDPE, or HDPE-UHMWPE, where UHMWPE is ultra-high-molecular-weight polyethylene, blending, use of plasticizers, and/or doping with nanomaterials), and/or fabric knitted/woven pattern.

[0064] In some embodiments, the fabric of the present embodiments can provide passive thermoregulation via control of heat conduction through the fabric from human skin, followed by heat removal from the outer surface of the fabric via a combination of infrared radiative heat emission and/or air convection. These performance features can all be provided in conjunction with high levels of comfort, breathability, and excellent perspiration wicking functionalities. A Fabric Touch Tester (FTT) can evaluate the cool touch feeling of the PE fabrics **200**, via measurements of the maximum thermal flux passing through the textile, as well as the textile thickness made on the same device. The FTT can allow measurements of the thermal conductivity through the fabric both during the fabric maximum mechanical compression between a cold and a hot plate, and during recovery upon removal of the compressing mechanical force. The measured thermal conductivity of the woven PE textile can be compared to the corresponding values of conventional woven textiles and of a commercial non-woven PE material (e.g., Tyvek), measured on the same FTT tester, as shown in FIG. **5**. Woven, and especially knitted PE fabrics, that were measured exhibited higher thermal conductivity values during their compression and recovery as compared to woven cotton and polyester fabrics, and nonwoven PE textile, with experimental uncertainty values larger for the backside measurements due, at least in part, to the higher roughness of the fabrics reverse sides. All the tests were carried out under standard laboratory environmental conditions (approximately 20° C. and approximately 65% relative humidity), standard pressure of 0.41 N/cm^2=0.59 psi during recovery from lateral compression, and both sides of the fabrics were tested (outer and inner). The fibers comprising both knitted and woven PE textiles in FIG. **5** exhibit thermal conductivity values (on a per-fiber basis, in the direction along the fiber length) of approximately 0.62 Watts per meter Kelvin (W/mK), as measured separately via a steady-state thermal conductivity measurement technique. In some embodiments, the thermal conductivity of the fibers comprising PE textiles can be approximately in the range of about 0.5 Watts per meter Kelvin to about 60 Watts per meter Kelvin. These values of thermal conductivity significantly exceed those typical for cotton (approximately in the range of about 0.026 W/mK to about 0.065 W/mK), polyester (approximately 0.16 W/mK), nylon (approximately 0.17 W/mK), and silk (approximately 0.12 W/mK), and can be enhanced, by way of non-limiting example, by increasing the alignment of the PE polymer chains with carbon backbones inside the fiber. This can be achieved, by way of non-limiting examples, by the choice of raw PE materials with linear molecular chains featuring few branches (e.g., as typical for LLDPE, MDPE, HDPE, and UHMWPE resins and their blends) and/or controlling the parameters of the fiber melt-spinning and drawing processes to promote chain alignment.

[0065] The data in FIG. **5** reveals that all yarn-based PE fabric samples **210**, **220**, **230**, **240** exhibited higher through-fabric thermal conductivities—more than doubling that of the non-woven PE textile—and exceeding the thermal conductivities of both natural and synthetic conventional woven fabrics. The cool touch feeling of PE fabrics is also perceivable via touching it with bare hands, allowing for their use as conduction-cooling textiles for bedding, car seats and furniture upholstery, cooling towels, and socks production, among other uses. The high thermal conductivity of PE fibers can be due to the molecular orientation and/or higher crystallinity of polyethylene than that of other textile polymers. The crystallinity of the raw PE powder is typically increased as a result of the fiber melt-drawing process, which at the same time can generate certain preferential orientation of the polymer molecules (or chains) in the drawing direction. The molecular orientation can be further enhanced as the fiber drawing is increased, which can be determined, for example, by the draw ratio (final length/initial length). The degree of the chain alignment can be conventionally characterized by the Hermann orientation function, which can vary approximately in the range between about 0.1 to about 1 (the latter corresponding to the complete alignment of the chains in the fiber direction, which produces the highest thermal conductivity of the fiber). The degree of crystallinity of the PE fiber can be approximately in the range from about 10% to about 100%. It was observed in conjunction with the present disclosures that the drawing capability of polyethylene can be increased at least twofold when using a plasticizer such as polybutene (PB), reaching draw ratios up to about 200 in polyethylene films and at least over about 100 in PE fibers without breaking or tearing.

[0066] The fiber material crystallinity can be further enhanced through a treatment using liquid nitrogen after the fiber has been drawn. For example, the crystallinity of drawn PE can be increased after being treated with liquid nitrogen for a few minutes (e.g., approximately three minutes), reaching crystallinity values of approximately 90% or higher, starting from draw ratios of about 60. The treatment with liquid nitrogen can correspond to a cooling treatment that promotes the crystallization of the previously disentangled and oriented polymer chains due, at least in part, to the drawing process.

[0067] The thermal conductivity mentioned above can be mainly associated with the conductivity in one direction, which can be the direction in which the chains are partially oriented due to the drawing process. The conductivity can be enhanced in at least one more direction if the polymer chains create a 3D ordered structure, for example through intermolecular covalent bonds. This can be achieved, for example, through a crosslinking process that in PE can be carried out using high energy radiation, such as gamma rays. Alternatively, species with double bonds in their structure, such as polybutadiene (PBdE), can be blended with PE to boost crosslinking in PE only using UV-light. The present disclosure provides for a process in which a blend of PE and PBdE is drawn (draw ratio=25) as a fiber, and afterwards, the fiber is exposed to UV light, creating an interconnected network that can be revealed after burning the material up to about 600° C. At this point, there can be remaining material that is not decomposed because of the presence of a more stable structure bonded together through covalent bonds. The orientation of polymer chains produced during the drawing process can benefit the crosslinking in an interconnected network at least because the reactive species can be more available to create covalent bonds between polyethylene chains. Otherwise an undrawn chain can be mostly entangled, and reactive species may not have neighboring chains with which to create covalent bonds.

[0068] Cross-linked polymers can typically be more rigid than a polymer that is not cross-linked. This is at least because the molecules are not generally considered to be "anchored" to each other by created covalent bonds. Such a result would not generally be desirable in the context of textiles. However, in the present context, the crosslinking does not result in such undesirable rigidness. This may be because the fibers of the present disclosure have more desirable length-to-diameter ratios that allow them to be more flexible. Further, by performing the crosslinking process after the fiber is produced, that further minimizes any resulting rigidness.

[0069] Spin-dyeing of polyethylene fibers can be achieved, for example, with conventional dyes and/or unconventional inorganic nanoparticle colorants. For instance, PE yarns can be spin-dyed with a variety of organic and/or inorganic colorants, which can be chosen to reduce the potential health risks. Use of spin-dyeing technology can reduce environmental footprint and/or improve the fabrics color fastness to washing, drying, and light exposure. In some embodiments, color can be added to the PE fabrics by adding colored particles into the powdered PE before extruding the material into fiber form. In this way particles can be encapsulated within the fibers, successfully importing color to them. The process of adding color to the fibers can be a dry process, which can allow for the melting down and recovering of the particles for reuse at the end of their lifecycle, eliminating the use of harsh chemicals.

[0070] A dry-coloring process contributes to the small ecological footprint of the PE when it is used to make textiles. The smaller footprint can be attributed at least to the lower melting temperature for PE, which allows heating of the PE to lower levels than other synthetic polymers to make yarn. Moreover, synthesis of raw PE can release less greenhouse gas and waste less heat than synthesis of more conventional textile materials such as polyester or nylon. Similarly, cotton takes a lot of resources to grow and is often treated with harsh chemicals, which is a major contributing factor to its large ecological footprint. In contrast, sugar cane can be used as a biomass for PE raw material production, which can result in the negative carbon footprint of bio-derived PE resins.

[0071] PE fabrics of the present embodiments can offer a high-performance sustainable alternative to conventional textiles that extend beyond radiative cooling. As noted above, in some embodiments, the PE fibers can be dry-colored during fabrication, resulting in large water savings without masking the PE molecular fingerprints scanned during the automated recycling process. Further, owing at least in part to the combination of fast capillary moisture wicking followed by a fast moisture evaporation process, the PE fibers can exhibit passive evaporative cooling in addition to passive cooling via either thermal radiation through the textile or a combination of thermal conductance of heat through the textile. This, in turn, can be followed by heat removal via thermal radiation from the textile outer surface and air convection, which can translate into a high level of personal comfort and further HVAC energy savings, among other benefits. For example, stain-resistance and fast-drying functionalities of the PE fabrics can offer significant energy savings in both domestic and industrial use via reduced temperature and/or time of washing and/or tumble-drying cycles. These properties can be achieved without treating PE fabrics with chemicals and without blending PE fibers with other fibers, which compromises the fabric recyclability.

[0072] Use of PE offers significant reduction of environmental footprint of textiles during the use phase **14**. As noted above, in the use phase **14** of the fabric material lifecycle, PE provides superior shipping, washing, and drying capabilities over conventional fabrics, while exhibiting superior weight reduction, stain resistance, and drying capabilities. While the lack of ionic bonds or polar groups in PE structure can prevent traditional dying techniques from applying color to the PE fabric, this feature can also inhibit the accumulation of dirt and/or harmful microorganisms, and can simplify washing procedures. The presently disclosed techniques can result in improved stain removal capabilities, including complete stain removal, without the use of hot water, soap, and/or other cleaning chemicals. The resulting textiles thus provide a high potential for use in off-grid locations and disaster zones, as well as in hospitals and other healthcare institutions. The ease of cleaning, high comfort, light weight, wicking, and/or drying functionalities of the material can find use in everyday clothes, headwear, and athletic apparel, as well as in bedding, tents, vehicle covers, food packaging, bandages, gloves, and face masks, among other uses.

[0073] The fabric of the present embodiment can combine excellent stain resistance with efficient moisture wicking and fast-drying performance. These properties can be maintained during the use phase, for example via exposure to sunlight and/or friction occurring during washing, drying, and wear processes. For instance, woven PE fabrics can retain stain resistance typical for pristine PE materials. FIG. **6** illustrates dry samples of woven PE **300** compared to polyester **310**, linen **320**, and cotton **330** (I). As shown, the samples are stained with a food colorant (II), and the stained samples are then washed by rinsing with cold tap water (III). As shown in (III), rinsing of the PE textile **300** can result in complete stain removal, while polyester **310**, linen **320**, and cotton **330** fabrics remain stained, with the natural fabrics, e.g., linen **320** and cotton **330**, exhibiting the most persistent stains. This stain-resistance property of PE can also inhibit accumulation of dirt and microorganisms in PE textiles, and can help to reduce the consumption of energy, time, water, and chemical, e.g., detergent, during the use phase **14**. For example, stain resistance of PE fabrics allows for short, low-temperature, and detergent-free washing cycles, which reduces water and energy consumption, while fast drying performance exhibited by PE textiles can be advantageous for reducing the energy consumption and the amount of waste heat generated during a tumble-dry cycle. For comparison, a breakdown of energy consumption during a lifecycle of a cotton T-shirt shows that over 70% of energy is consumed in the use cycle (mostly for high-temperature washing and tumble-drying).

[0074] The passive cooling and stain-resistance functionalities of the PE textiles of the present embodiments can be achieved by engineering the structure of polymer fibers, yarns, and/or fabrics, without blending PE with other materials or covering its surface with chemical coatings. For example, to the extent that nanoparticle colorants are added, the colorants can be removed during the recycling process, e.g., via centrifuging or filtering. By comparison, commercially-available fabrics with evaporative cooling performance are typically composed of two or three layers of different materials, which can complicate or prevent their recycling.

[0075] The cooling performance of the PE fabrics can be attributed to a combination of several passive cooling mechanisms, including thermal radiation through the fabrics and/or heat conduction from the skin into the fabric, followed by convective and/or radiative heat removal from the textile, as well as the evaporative cooling facilitated by efficient moisture wicking and fast drying performance of PE textiles. In turn, the high thermal conductivity of PE yarns can be attributed, at least in part, to the partial alignment of polymer chains during the process of fiber fabrication via melt-spin and/or the drawing process, or the like, which can also increase the material crystallinity. The material crystallinity can be improved by using HDPE-MDPE, LLDPE-HDPE, and/or HDPE-UHMWPE blends (see Table 1 below for the data on some embodiments of the PE fibers), along with the techniques previously described, including an increased draw ratio and/or the post-treatment of drawn fibers as provided for herein.

TABLE 1

Crystallinity, orientation function, and thermal conductivity of PE fibers

	Thermal conductivity, W/mK	Crystallinity, %	Herman's orientation function
LLDPE fiber	0.62	52.3%	0.267
MDPE Fiber	0.92	57.8%	0.17
HDPE Fiber	0.88	68.6%	0.14

[0076] A person skilled in the art will consider the thickness of the fabric while still providing cooling effects to be unexpected. While intuitively thinner fabric can lead to improved cooling, the present disclosure provides for fabrics that can be thicker and still provide cooling effects by virtue of the high thermal conductivity enabling energy transfer through the fabric, larger thermal mass enabling larger heat storage capacity, and/or high porosity enabling efficient heat removal via convection that the disclosed fabrics provide. The fabrics of the present disclosure can have a thickness approximately in the range of about 300 microns to about 1000 microns, although other thicknesses are possible. The fabric can be knit or woven, although knitting may have enhanced benefits due to the resulting fabric typically being thicker and more porous than weaving the same material.

[0077] A yarn denier of the fabric, which can be determined, at least in part, based on fiber diameter and/or a thickness of the fabric resulting from the use of multiple fibers, can be approximately in the range of about 200 to about 2000, and in some instances approximately 300 or higher. The cooling can be a result, at least in part, of optimization of the material crystallinity and chain orientation of the PE polymer chains inside the fibers. More particularly, fiber crystallinity provided for by the present disclosures is approximately in the range of about 10% to about 100%, in some embodiments approximately in the range of about 50% to about 100%, in some embodiments approximately in the range of about 70% to about 100%, and in some embodiments it can be approximately in the range of about 90% to about 100%. In some embodiments in which the range is higher (e.g., approximately in the range of about 90% to about 100%), one or more post-treatment activities may be performed on the fiber(s) in conjunction with achieving the higher crystallinity percentages. A person skilled in the art, in view of the present disclosures, will understand various post-treatment activities that can be performed to enhance fiber crystallinity, including but not limited to fiber drawing and thermal treatment, including both heating and freezing. The foregoing notwithstanding, when designing fabrics in conjunction with the present disclosure, some balance is required to ensure that the level of crystallinity does not lead to a fabric that becomes too brittle and stiff. At the same time, the degree of the polymer chain alignment—as quantified by the Herman's orientation function—provided for by the present disclosures is approximately in the range of about 0.1 to about 1, in some embodiments approximately in the range of about 0.2 to about 1, in some embodiments approximately in the range of about 0.3 to about 1, and in some embodiments it can be approximately in the range of about 0.5 to about 1.

[0078] One exemplary embodiment of a fabric **400** configured to use thermal conduction to provide cooling is illustrated in FIG. **7**. The thickness of the illustrated fabric **400** is about 820 microns and it has a weight (mass per unit area) of about 500 grams per square meter. A total yarn denier of the illustrated fabric is 994 (double-plied 497 denier yarn). The fiber crystallinity of the illustrated fabric is about 52% and it has an orientation factor of about 0.26. At an orientation factor of about 0.26, the fabric provides a "cool touch sensation" and measurable cooling performance. Even larger alignment values (and/or higher crystallinity values) can have further enhanced performance. A stitch count of the fabric can be approximately in the range of about 280 stitches per square inch to about 600 stitches per square inch (i.e., the number of wales times the number of courses per square inch for knitted fabrics). For example, the stitch count of the illustrated fabric is 352 stitches per square inch, stemming from 16 wales and 22 courses per square inch.

[0079] With reference back to FIG. **2**, the end of life phase **16** of the fabric lifecycle **10** favors textiles that promote ease of disposal. The use of PE for wearable fabrics and textiles also offers promising opportunities for easy recycling of fabrics through well-established industrial processes, as well as their fabrication from recycled materials, including but not limited to the use of colored plastics frequently discarded from the recycling process.

[0080] A person skilled in the art will recognize that a recycling pathway for PE fabrics and garments will reduce the probability of these materials ending up in landfills and contributing to the microplastic pollution. It can also offer an opportunity to recycle the previously accumulated large amounts of PE waste, whose recycling is currently not economically viable due to the lack of added-value products.

Examples

[0081] The PE fibers and yarns discussed in the embodiments of the present disclosure can be fabricated by the standard fiber melt spinning process from the linear low-density polyethylene (LLDPE), medium density polyethylene (MDPE), and high-density polyethylene (HDPE) granules and pellets (or blends thereof). The monofilament fibers of varying diameters provided for herein have been fabricated at the US Army CCDC Soldier Center (Natick, MA) by using a conical miniature twin-screw extruder (Micro-Compounder, DACA Instruments). The multi-filament LLDPE yarns have been fabricated by the MiniFibers Inc. (Johnson City, TN) on an industrial-scale melt-spin extruder. In some non-limiting embodiments, the yarns can be composed of 247 individual filaments with 2 dpf (denier per filament). The yarns can be woven into a plain-weave textile, for instance on an industrial-scale loom at the Shingora Textile Ltd. (Ludhiana, Punjab, India). The monofilament fibers can be dry-colored via the spin-dyeing process, and/or by mixing the colorants with the PE material prior to the fiber melt extrusion. The colorants that can be used include, but are not limited to, commercial disperse dyes (Millipore Sigma) and silicon nano-powders (US Research Nanomaterials Inc.).

[0082] Examples of the above-described embodiments can include the following:

[0083] 1. A hydrophilic fabric, comprising:

[0084] at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene, the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene being at least one of spun, woven, or knitted together to form the fabric,

[0085] wherein the at least one of the multi-filament yarns comprising polyethylene or the continuous fibers comprising polyethylene have a modified surface that causes the respective yarns and/or fibers to be at least partially-hydrophilic,

[0086] wherein the continuous fibers are aligned substantially in parallel with respect to each other, and

[0087] wherein the fabric is devoid of non-polyethylene yarns and non-polyethylene fibers that mechanically reinforce the fabric.

[0088] 2. The hydrophilic fabric of claim **1**, wherein the modified surface comprises at least one of a changed fiber size, a changed fiber density, or a changed cross-section of the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene.

[0089] 3. The hydrophilic fabric of claim **1** or **2**, wherein the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene comprises a pattern arrangement thereof having at least one of a regular triangular arrangement or a square arrangement.

[0090] 4. The hydrophilic fabric of any of claims **1** to **3**, wherein the fabric is devoid of a coating disposed on the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene to make the polyethylene more hydrophilic.

[0091] 5. The hydrophilic fabric of any of claims **1** to **4**, wherein the fabric has a thickness approximately in the range of about 300 microns to about 1000 microns, and

[0092] wherein a thermal conductivity of the continuous fibers comprising the fabric is approximately in the range of about 0.1 Watts per meter Kelvin to about 60 Watts per meter Kelvin.

[0093] 6. The hydrophilic fabric of any of claims **1** to **5**, wherein the polyethylene comprises at least one of low-density polyethylene, linear low-density polyethylene, medium-density polyethylene, high-density polyethylene, low molecular weight polyethylene, or ultra-high molecular weight polyethylene.

[0094] 7. The hydrophilic fabric of any of claims **1** to **6**, wherein an exposed surface thereof is hydrophilic and a portion of the fabric below the exposed surface is hydrophobic.

[0095] 8. The hydrophilic fabric of any of claims **1** to **7**, wherein a fiber crystallinity of the fabric is approximately in the range of about 50% to about 100%.

[0096] 9. The hydrophilic fabric of any of claims **1** to **8**, wherein at least one of a yarn of the multi-filament yarns or a fiber of the continuous fibers has a diameter approximately in the range of about 1 micron to about 150 microns.

[0097] 10. The hydrophilic fabric of any of claims **1** to **9**, wherein the fibers comprise at least one of a single type of polyethylene or a blend of more than one type of polyethylene.

[0098] 11. The hydrophilic fabric of any of claims **1** to **10**, wherein the fabric has a thickness approximately in the range of about 300 microns to about 1000 microns.

[0099] 12. The hydrophilic fabric of any of claims **1** to **11**, wherein a water-fiber contact angle of the hydrophilic fabric is approximately in the range of about 50 degrees to about 80 degrees.

[0100] 13. The hydrophilic fabric of any of claims **1** to **12**, wherein a density of the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene is optimized.

[0101] 14. A method of manufacturing a fabric, comprising:

[0102] extruding one or more continuous fibers comprising polyethylene;

[0103] modifying a surface energy of the one or more continuous fibers comprising polyethylene to change a hydrophilicity thereof;

[0104] bundling the one or more continuous fibers to form a plurality of yarns; and

[0105] one or more of spinning, weaving, or knitting one or more yarns of the plurality of yarns with another yarn of the plurality of yarns to form the fabric.

[0106] 15. The method of claim **14**, wherein modifying a surface energy of the one or more continuous fibers increases the hydrophilicity thereof without either applying a coating thereto or reinforcing the fabric with at least one of non-polyethylene yarns or non-polyethylene fibers.

[0107] 16. The method of claim **14** or **15**, wherein modifying a surface energy of the one or more continuous fibers comprising polyethylene further comprises at least partially oxidizing a surface of the one or more continuous fibers comprising polyethylene.

[0108] 17. The method of any of claims **14** to **16**, further comprising adjusting at least one of a weight fraction, a size, or a drawing ratio of at least one of the one or more continuous fibers comprising polyethylene.

[0109] 18. The method of any of claims **14** to **17**, wherein bundling the one or more continuous fibers further comprises arranging the one or more continuous fibers substantially in parallel to optimize capillary action through the plurality of yarns.

[0110] 19. The method of any of claims **14** to **18**, wherein modifying a surface energy of the one or more continuous fibers further comprises adjusting at least one of one or more of a fiber size, a density, or a cross-section of the one or more continuous fibers or one or more of a size, a density, or a cross section of the bundled one or more continuous fibers.

[0111] 20. The method of any of claims **14** to **19**, further compromising optimizing a chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene.

[0112] 21. The method of claim **20**, wherein optimizing the chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene further comprises post-treating the one or more initially extruded continuous fibers comprising polyethylene.

[0113] 22. The method of any of claims **14** to **21**, further comprising coloring the one or more continuous fibers by at least one of dry-coloring or spin-dying the one or more continuous fibers with one or more of an organic colorant or an inorganic colorant.

[0114] 23. The method of any of claims **14** to **22**, wherein the one or more continuous fibers comprise at least one of low-density polyethylene, linear low-density polyethylene, high-density polyethylene, or ultra-high molecular weight polyethylene.

[0115] 24. The method of any of claims **14** to **23**, further comprising restoring hydrophilicity to the fabric by exposing the surface of the one or more continuous fibers to one or more of an oxygen plasma treatment, ultraviolet radiation, or friction.

[0116] One skilled in the art will appreciate further features and advantages of the disclosures based on the provided for descriptions and embodiments. Accordingly, the inventions are not to be limited by what has been particularly shown and described. All publications and references cited herein are expressly incorporated herein by reference in their entirety.

What is claimed is:

1. A hydrophilic fabric, comprising:

at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene, the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene being at least one of spun, woven, or knitted together to form the fabric,

wherein the at least one of the multi-filament yarns comprising polyethylene or the continuous fibers comprising polyethylene have a modified surface that causes the respective yarns and/or fibers to be at least partially-hydrophilic,

wherein the continuous fibers are aligned substantially in parallel with respect to each other, and

wherein the fabric is devoid of non-polyethylene yarns and non-polyethylene fibers that mechanically reinforce the fabric.

2. The hydrophilic fabric of claim **1**, wherein the modified surface comprises at least one of a changed fiber size, a changed fiber density, or a changed cross-section of the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene.

3. The hydrophilic fabric of claim **1**, wherein the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene comprises a pattern arrangement thereof having at least one of a regular triangular arrangement or a square arrangement.

4. The hydrophilic fabric of claim **1**, wherein the fabric is devoid of a coating disposed on the at least one of multi-filament yarns comprising polyethylene or continuous fibers comprising polyethylene to make the polyethylene more hydrophilic.

5. The hydrophilic fabric of claim **1**, wherein the fabric has a thickness approximately in the range of about 300 microns to about 1000 microns, and

wherein a thermal conductivity of the continuous fibers comprising the fabric is approximately in the range of about 0.1 Watts per meter Kelvin to about 60 Watts per meter Kelvin.

6. The hydrophilic fabric of claim **1**, wherein the polyethylene comprises at least one of low-density polyethylene, linear low-density polyethylene, medium-density polyethylene, high-density polyethylene, low molecular weight polyethylene, or ultra-high molecular weight polyethylene.

7. The hydrophilic fabric of claim **1**, wherein an exposed surface thereof is hydrophilic and a portion of the fabric below the exposed surface is hydrophobic.

8. The hydrophilic fabric of claim **1**, wherein a fiber crystallinity of the fabric is approximately in the range of about 50% to about 100%.

9. The hydrophilic fabric of claim **1**, wherein the fabric has a thickness approximately in the range of about 300 microns to about 1000 microns.

10. The hydrophilic fabric of claim **1**, wherein a water-fiber contact angle of the hydrophilic fabric is approximately in the range of about 50 degrees to about 80 degrees.

11. A method of manufacturing a fabric, comprising:

extruding one or more continuous fibers comprising polyethylene;

modifying a surface energy of the one or more continuous fibers comprising polyethylene to change a hydrophilicity thereof;

bundling the one or more continuous fibers to form a plurality of yarns; and

one or more of spinning, weaving, or knitting one or more yarns of the plurality of yarns with another yarn of the plurality of yarns to form the fabric.

12. The method of claim **11**, wherein modifying a surface energy of the one or more continuous fibers increases the hydrophilicity thereof without either applying a coating thereto or reinforcing the fabric with at least one of non-polyethylene yarns or non-polyethylene fibers.

13. The method of claim **11**, wherein modifying a surface energy of the one or more continuous fibers comprising polyethylene further comprises at least partially oxidizing a surface of the one or more continuous fibers comprising polyethylene.

14. The method of claim **11**, further comprising adjusting at least one of a weight fraction, a size, or a drawing ratio of at least one of the one or more continuous fibers comprising polyethylene.

15. The method of claim **11**, wherein bundling the one or more continuous fibers further comprises arranging the one or more continuous fibers substantially in parallel to optimize capillary action through the plurality of yarns.

16. The method of claim **11**, wherein modifying a surface energy of the one or more continuous fibers further comprises adjusting at least one of one or more of a fiber size, a density, or a cross-section of the one or more continuous fibers or one or more of a size, a density, or a cross section of the bundled one or more continuous fibers.

17. The method of claim **11**, further comprising optimizing a chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene.

18. The method of claim **17**, wherein optimizing the chain orientation and crystallinity of the one or more continuous fibers comprising polyethylene further comprises post-treating the one or more initially extruded continuous fibers comprising polyethylene.

19. The method of claim **11**, further comprising coloring the one or more continuous fibers by at least one of dry-coloring or spin-dying the one or more continuous fibers with one or more of an organic colorant or an inorganic colorant.

20. The method of claim **11**, further comprising restoring hydrophilicity to the fabric by exposing the surface of the one or more continuous fibers to one or more of an oxygen plasma treatment, ultraviolet radiation, or friction.

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