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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 June 2025 (19.06.2025)

WIPO | PCT

(10) International Publication Number
WO 2025/128992 A1

(51) International Patent Classification:
C03B 37/04 (2006.01) *D21H 13/40* (2006.01)
D04H 1/4218 (2012.01) *D21H 21/52* (2006.01)
D04H 1/4226 (2012.01) *D21H 27/10* (2006.01)

(21) International Application Number:
PCT/US2024/060026

(22) International Filing Date:
13 December 2024 (13.12.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PCT/US2023/084231
15 December 2023 (15.12.2023) US
PCT/US2023/084235
15 December 2023 (15.12.2023) US

(71) Applicant: **OWENS CORNING INTELLECTUAL CAPITAL, LLC** [US/US]; One Owens Corning Parkway, Toledo, Ohio 43659 (US).

(72) Inventors: **GAWRYLA, Matthew Daniel**; 3008 Granview Road, Granville, Ohio 43023 (US). **SALATA, Ryan Robert**; 5653 Longmire Dr., Westerville, Ohio 43023 (US). **UGOREK, Michael Stephen**; 587 Apple Street, Westerville, Ohio 43082 (US). **JONES, Sarah Beth Warren**; 6462 Ellis Nook Drive, New Albany, Ohio 43054 (US). **SMITH, William Edwin**; 5322 York Rd. SW, Pataskala, Ohio 43062 (US). **PRUZINSKY, Stephanie**; 346 Highbanks Valley Ct., Newark, Ohio 43055 (US). **VERHOFF, Jonathan Michael**; 2086 James Rd., Granville, Ohio 43023 (US).

(74) Agent: **RAULERSON, Billy C.**; Calfee, Halter & Griswold LLP, The Calfee Building, 1405 East Sixth Street, Cleveland, Ohio 44114 (US).

(54) Title: MICROFIBER FILLED NON-WOVEN MAT

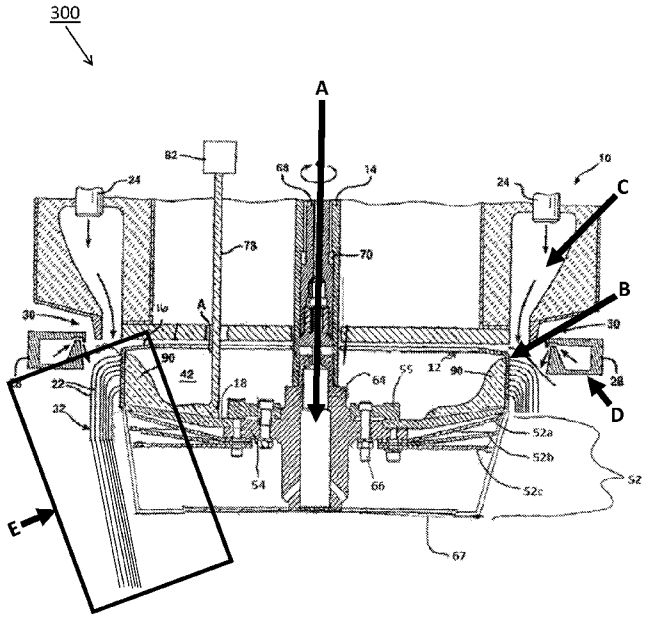


FIG. 3

(57) Abstract: A method of forming rotary fibers (e.g., glass fibers) that have a more uniform or constrained fiber diameter and/or length distribution is disclosed. The rotary fibers, which have the improved property distribution(s) across a volume of the fibers, promote the formation of improved non-woven fibrous mats and products formed from the mats. Additionally, use of the rotary-formed microfibers in a blend with larger fibers leads to the intended creation of fiber bundles, which can also be used to fashion improved non-woven fibrous mats and products formed from the mats. Because the structure of the non-woven mats may be readily tuned to have desired properties (e.g., thickness, air permeability), they are suitable for many applications, such as substrates in roofing materials, composite reinforcements, and facers for gypsum/polyiso boards.

WO 2025/128992 A1

[Continued on next page]

(81) **Designated States** *(unless otherwise indicated, for every kind of 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, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, 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, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

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

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

MICROFIBER FILLED NON-WOVEN MAT

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to and any benefit of International Application No. PCT/US2023/084231, filed on December 15, 2023, and International Application No. PCT/US2023/084235, filed on December 15, 2023, the contents of which are incorporated herein by reference in their entireties.

FIELD

[0002] The general inventive concepts relate to an apparatus and a method of fiberizing mineral fibers, such as glass fibers, from molten mineral material using a rotary process, as well as to the fibers themselves and articles incorporating the fibers.

BACKGROUND

[0003] The production of mineral fibers such as glass fibers by a rotary process is well known. See, for example, U.S. Patent Nos. 5,582,841; 7,856,853; 8,087,265; and 8,250,884, the disclosure of each being incorporated herein in its entirety by reference. In such a process, molten glass is fed at a high temperature into a metallic spinner which revolves at a high rotation rate. The spinner has a peripheral wall containing a multiplicity of orifices. The molten glass flows by centrifugal force through the orifices and forms small diameter molten glass streams. The streams are directed downward toward a collection surface by an annular blower which surrounds the spinner. The flow generated by the blower attenuates the molten glass streams into a finer diameter, and the streams are cooled to form glass fibers. An annular burner is also positioned around the spinner, and combustion gases and heat from the burner are directed downward to provide a fiber attenuating environment suitable for allowing the initial streams of glass to be attenuated to the desired final diameter. The downward annular flow of hot gases facilitates attenuation of the streams of molten mineral material into mineral fibers by the blower, and also maintains the spinner at a temperature suitable for fiberizing.

[0004] As one example, as shown in FIG. 1, a fiber manufacturing apparatus or fiberizer 10 includes a centrifuge or spinner 12 fixed to a rotatable hollow shaft or spindle 14. In particular, the spinner 12 is fixed to a hub 54 of a quill 64 at the lower end of the rotatable

shaft or spindle 14. Rotating the spinner 12 by rotating spindle 14 is known in the art. The spinner 12 includes a base 16 extending from hub 54 to the peripheral wall 18. Disposed around the outer periphery of the peripheral wall 18 is a plurality of orifices 20 for centrifuging fibers 22 of a molten material, for example, glass.

[0005] The spinner 12 is supplied with a stream 78 of a molten glass. Conventional supply equipment 82 can be used to supply stream 78 of molten glass. Such molten glass supply equipment is well known in the industry and, therefore, will not be discussed in detail herein. The glass in stream 78 drops into the chamber 42 of spinner 12 and through centripetal force is directed against the peripheral wall 18 and flows outwardly to form a build-up or head 90 of glass. The glass then flows through the orifices 20 to form primary fibers 22, which are heated and stretched by burners 24 and annular blower 28.

[0006] The rotation of the spinner 12 (as depicted by the circular arrow (a) in FIG. 1) centrifuges molten glass through orifices 20 in spinner peripheral wall 18 to form primary fibers 22. The primary fibers 22 are maintained in a soft, attainable condition by the heat of an annular burner 24. The annular blower 28 uses induced air through passage 30 to pull primary fibers 22 and further attenuate them into secondary fibers 32 suitable for use in a product, such as wool insulating materials. The secondary fibers 32 are then collected on a conveyor (not shown) for formation into a product, such as a glass wool pack.

[0007] The quill 64, which is hollow, is press fit in a borehole formed through the center of hub 54 and locked in place with three circumferentially spaced locking pins 66. The upper end of the quill 64 is threaded into the lower end of a hollow drawbar 68. The quill 64 is preferably cooled further with water circulated through an annular cooling jacket 70 disposed around spindle 14 and quill 64 and above hub 54. The quill 64 and hub 54 are preferably fabricated from a low thermal expansion alloy to minimize differential thermal expansion between them.

[0008] A radiation shield 52 may include a number of individual plates 52a, 52b, 52c. The plates may be connected to the hub 54 of quill 64. The plates inhibit convection from the base of the spinner and inhibit the infrared energy from escaping from the base of spinner 12 and decreases the thermal gradient along the height of the peripheral sidewall 18 thus inhibit devitrification within the glass head 90 and controls the temperature of the glass as it passes through the orifices 20 at the lower edge of peripheral sidewall 18. The uppermost shield 52a

is preferably frustoconical to follow the base wall 16 of spinner 12. The lower shields 52b, 52c may be frustoconical or planar to allow space between the shields. The shields 52 may be formed of stainless steel or a refractory metal, such as HASTELLOY alloy a transition metal nickel based high temperature alloy. One especially suitable material for the shields is HASTELLOY X alloy, which is available from Haines International of Kokomo, Indiana (USA). HASTELLOY X alloy includes 47 weight % Ni, 22 weight % Cr, 18 weight % Fe, 9 weight % Mo, 1.5 weight % W, 0.1 weight % C, 1 weight % Mn (maximum), 1 weight % Si (maximum) and 0.008 weight % B (maximum).

[0009] The spinner 12 is clamped to the hub 54 on the quill 64 (at the lower end of the spindle 14) by a clamping ring 55. A quill pan 67 can be situated below the radiation shield 52 to provide a stable flow pattern for the air stream containing the attenuated fibers. In this manner, a more stable "veil" (i.e., the annular flow of the fibers and air downward away from the spinner 12) is maintained. The quill pan 67 can have any shape sufficient to cover a substantial portion of the bottom of the spinner 12 and the radiation shield 52. Like the spinner 12, the quill pan 67 can be mounted on hub 54.

[0010] Notwithstanding these (and other) advancements in spinner technology, a problem still exists with reliably and consistently forming glass fibers having a desired fiber diameter and/or fiber length by a rotary-forming process. By way of example, the fiber diameter distribution of various conventional rotary-formed glass fibers is shown in FIGS. 2A-2D.

[0011] In FIG. 2A, a graph 210 of the fiber diameter distribution for a commercially available unbonded loosefill (ULF) fiberglass material is shown. ULF fibers are rotary-formed fibers that are not typically held together by a binder. ULF fibers are commonly used for building insulation applications.

[0012] With reference to the graph 210, various properties for this first ULF material are shown in Table 1.

Peak Index	Peak Type	Area Intg	Area IntgP	Center Grvty	Max Height	FWHM
1	Gaussian	28.94772	29.27843	3.67323	11.68069	2.32842
2	Gaussian	48.03576	48.58455	7.34547	7.89334	5.72536
3	Gaussian	21.88696	22.13701	14.36941	2.87437	7.15502

Table 1

In Table 1, "Peak Index" refers to the peak identifier from left to right, with the peaks being shown with dashed lines; "Peak Type" refers to the type of model used to fit the data; "Area Intg" refers to the integrated area of the fit peak; "Area IntgP" refers to the percentage of total integrated area for each fit peak; "Center Grvty" refers to the center of the fit peak; "Max Height" refers to the maximum value of the fit peak; and "FWHM" refers to the width of the peak at half of its maximum height.

[0013] In the graph 210 of FIG. 2A, the rotary fibers were produced with a target diameter of about 3.1 μm, as measured using the known air flow method. The graph 210 represents the fiber diameter distribution when measured using an ISO 13322-2 compliant method and plotted by fiber volume %. The (Camsizer) data measured according to the ISO 13322-2 compliant approach was analyzed using the Peak Deconvolution App (v2.00) with OriginPro 2023 (constant baseline; fit until converged to obtain displayed results), which is data analysis software sold by OriginLab Corp. of Northampton, Massachusetts.

[0014] In an ideal case, 100% of the fibers produced would have a fiber diameter of about 3.1 μm. However, rotary fiber production is a complex process with many variables, only some of which can be controlled. Consequently, the fiber diameter distribution (i.e., the area under the graph) shows that a large volume of the fibers have a fiber diameter greater than 3.1 μm, with some fibers having a diameter approaching 25 μm being measured. For the target fiber diameter of 3.1 μm, this wide variance in fiber diameters (e.g., about 1 μm to about 25 μm), with a majority of the fibers having a fiber diameter greater than 6 μm, is less than ideal. Stated another way, for many applications, reducing the variance in fiber diameters relative to the target fiber diameter and/or increasing the volume of fibers having a fiber diameter closer to the target fiber diameter could result in improved products/applications using the fibers.

[0015] In FIG. 2B, a graph 220 of the fiber diameter distribution for another commercially available unbonded loosefill (ULF) fiberglass material is shown. ULF fibers are rotary-formed fibers that are not typically held together by a binder. ULF fibers are commonly used for building insulation applications.

[0016] With reference to the graph 220, various properties for this second ULF material are shown in Table 2.

Peak Index	Peak Type	Area Intg	Area IntgP	Center Grvty	Max Height	FWHM
1	Gaussian	30.98	31.26	3.57	12.36	2.35
2	Gaussian	29.96	27.21	7.02	4.52	5.62
3	Gaussian	41.16	41.53	12.26	3.30	11.89

Table 2

In Table 2, "Peak Index" refers to the peak identifier from left to right, with the peaks being shown with dashed lines; "Peak Type" refers to the type of model used to fit the data; "Area Intg" refers to the integrated area of the fit peak; "Area IntgP" refers to the percentage of total integrated area for each fit peak; "Center Grvty" refers to the center of the fit peak; "Max Height" refers to the maximum value of the fit peak; and "FWHM" refers to the width of the peak at half of its maximum height.

[0017] In the graph 220 of FIG. 2B, the rotary fibers were measured as having an effective fiber diameter between 2.8 μm and 3 μm, as measured using the known air flow method. The graph 220 represents the fiber diameter distribution when measured using an ISO 13322-2 compliant method and plotted by fiber volume %. The (Camsizer) data measured according to the ISO 13322-2 compliant approach was analyzed using the Peak Deconvolution App (v2.00) with OriginPro 2023 (constant baseline; fit until converged to obtain displayed results), which is data analysis software sold by OriginLab Corp. of Northampton, Massachusetts.

[0018] In an ideal case, 100% of the fibers produced would have a fiber diameter within this effective range. However, rotary fiber production is a complex process with many variables, only some of which can be controlled. Consequently, the fiber diameter distribution (i.e., the area under the graph) shows that a large volume of the fibers have a fiber diameter greater than this range (i.e., well greater than 3 μm), with some fibers having a diameter approaching 24 μm being measured. For a target fiber diameter of 2.9 μm (i.e., between 2.8 μm and 3 μm), this wide variance in fiber diameters (e.g., about 1 μm to about 24 μm), with a majority of the fibers having a fiber diameter greater than 6 μm, is less than ideal. Stated another way, for many applications, reducing the variance in fiber diameters relative to the target fiber diameter and/or increasing the volume of fibers having a fiber diameter closer to the target fiber diameter could result in improved products/applications using the fibers.

[0019] In FIG. 2C, a graph 230 of the fiber diameter distribution for another commercially available unbonded loosefill (ULF) fiberglass material is shown. ULF fibers are rotary-formed fibers that are not typically held together by a binder. ULF fibers are commonly used for building insulation applications.

[0020] With reference to the graph 230, various properties for this third ULF material are shown in Table 3.

Peak Index	Peak Type	Area Intg	Area IntgP	Center Grvty	Max Height	FWHM
1	Gaussian	31.46178	31.41663	3.74	12.89667	2.29199
2	Gaussian	40.94293	40.88417	6.84211	8.21829	4.68194
3	Gaussian	27.74622	27.7064	10.71563	3.06125	8.52952

Table 3

In Table 3, "Peak Index" refers to the peak identifier from left to right, with the peaks being shown with dashed lines; "Peak Type" refers to the type of model used to fit the data; "Area Intg" refers to the integrated area of the fit peak; "Area IntgP" refers to the percentage of total integrated area for each fit peak; "Center Grvty" refers to the center of the fit peak; "Max Height" refers to the maximum value of the fit peak; and "FWHM" refers to the width of the peak at half of its maximum height.

[0021] In the graph 230 of FIG. 2C, the rotary fibers were measured as having an effective fiber diameter between 2.8 μm and 3 μm, as measured using the known air flow method. The graph 230 represents the fiber diameter distribution when measured using an ISO 13322-2 compliant method and plotted by fiber volume %. The (Camsizer) data measured according to the ISO 13322-2 compliant approach was analyzed using the Peak Deconvolution App (v2.00) with OriginPro 2023 (constant baseline; fit until converged to obtain displayed results), which is data analysis software sold by OriginLab Corp. of Northampton, Massachusetts.

[0022] In an ideal case, 100% of the fibers produced would have a fiber diameter within this effective range. However, rotary fiber production is a complex process with many variables, only some of which can be controlled. Consequently, the fiber diameter distribution (i.e., the area under the graph) shows that a large volume of the fibers have a fiber diameter greater than this range (i.e., well greater than 3 μm), with some fibers having a diameter of 25 μm or more being measured. For a target fiber diameter of 2.9 μm (i.e.,

between 2.8 μm and 3 μm), this wide variance in fiber diameters (e.g., about 1 μm to about 25 μm), with a majority of the fibers having a fiber diameter greater than 6 μm, is less than ideal. Stated another way, for many applications, reducing the variance in fiber diameters relative to the target fiber diameter and/or increasing the volume of fibers having a fiber diameter closer to the target fiber diameter could result in improved products/applications using the fibers.

[0023] In FIG. 2D, a graph 240 of the fiber diameter distribution for a commercially available specialty material, in the form of chopped glass microfibers, is shown. These specialty glass fibers are rotary-formed fibers that are chopped to shorten their length. The specialty glass fibers are not held together by a binder. These specialty glass fibers can be used as a reinforcing agent or filler material.

[0024] With reference to the graph 240, various properties for the specialty glass fiber material are shown in Table 4.

Peak Index	Peak Type	Area Intg	Area IntgP	Center Grvty	Max Height	FWHM
1	Gaussian	47.15786	47.48612	3.58971	18.31426	2.41972
2	Gaussian	27.08211	27.27062	6.82531	4.93582	5.16019
3	Gaussian	25.06876	25.24326	10.77334	3.09928	7.60232

Table 4

In Table 4, “Peak Index” refers to the peak identifier from left to right, with the peaks being shown with dashed lines; “Peak Type” refers to the type of model used to fit the data; “Area Intg” refers to the integrated area of the fit peak; “Area IntgP” refers to the percentage of total integrated area for each fit peak; “Center Grvty” refers to the center of the fit peak; “Max Height” refers to the maximum value of the fit peak; and “FWHM” refers to the width of the peak at half of its maximum height.

[0025] In the graph 240 of FIG. 2D, the rotary fibers were marketed as having an effective fiber diameter of about 3.2 μm. The graph 240 represents the fiber diameter distribution when measured using an ISO 13322-2 compliant method and plotted by fiber volume %. The (Camsizer) data measured according to the ISO 13322-2 compliant approach was analyzed using the Peak Deconvolution App (v2.00) with OriginPro 2023 (constant baseline; fit until converged to obtain displayed results), which is data analysis software sold by OriginLab Corp. of Northampton, Massachusetts.

[0026] In an ideal case, 100% of the fibers produced would have a fiber diameter of about 3.2 μm. However, rotary fiber production is a complex process with many variables, only some of which can be controlled. Consequently, the fiber diameter distribution (i.e., the area under the graph) shows that a large volume of the fibers have a fiber diameter greater than 3.2 μm, with some fibers having a diameter approaching 24 μm being measured. For the target fiber diameter of 3.2 μm, this wide variance in fiber diameters (e.g., about 1 μm to about 24 μm), with a majority of the fibers having a fiber diameter greater than 5 μm, is less than ideal. Stated another way, for many applications, reducing the variance in fiber diameters relative to the target fiber diameter and/or increasing the volume of fibers having a fiber diameter closer to the target fiber diameter could result in improved products/applications using the fibers.

[0027] In view of the above, there is an unmet need for a rotary-fiber production process that is capable of producing glass fibers with an improved fiber diameter and/or length distribution, a collection of fibers having the improved distribution, and products/applications using said fibers.

SUMMARY

[0028] In view of the above, modifications to a rotary fiber forming process allows for the production of fibers having a more uniform fiber diameter and/or length distribution. The general inventive concepts encompass this new method of producing rotary fibers, the new rotary fibers themselves, a sizing formulation suitable for use on the new rotary fibers, a package of the rotary fibers (e.g., having the improved fiber distribution), a non-woven mat made from the new rotary fibers (including a structured/engineered non-woven mat), and downstream applications for the mats (e.g., roofing materials).

[0029] In one exemplary embodiment, a method of manufacturing mineral fibers (microfibers) is disclosed. The method comprises: rotating a spinner having a peripheral wall including a plurality of orifices; supplying molten mineral material to the rotating spinner to centrifuge streams of a molten mineral material through the orifices; mixing combustion air and combustion gas and supplying the mixture to an annular burner positioned around the spinner; creating an annular flow of induced air in a passage positioned between the annular burner and an annular blower; directing hot gases from the annular burner and the annular flow of induced air toward the spinner and the streams of molten mineral material to heat the spinner and attenuate the streams of molten mineral material into a plurality of mineral fibers;

and directing a source of cooling air through a hollow quill extending through the spinner to a quill pan positioned below the spinner, wherein the cooling air is delivered to the quill pan at a rate of about 30 cubic feet per minute to about 60 cubic feet per minute.

[0030] In some exemplary embodiments, the quill pan is cooled to a temperature of less than 750 °F.

[0031] In some exemplary embodiments, the method further comprises controlling the spinner to rotate at a rate of about 900 revolutions per minute to about 2,400 revolutions per minute. In some exemplary embodiments, the method further comprises controlling the spinner to rotate at a rate of about 1,800 revolutions per minute to about 2,400 revolutions per minute.

[0032] In some exemplary embodiments, the hot gases from the annular burner are directed toward the spinner and the streams of molten mineral material at a rate of about 240 cubic feet per minute to about 300 cubic feet per minute.

[0033] In some exemplary embodiments, the annular blower outputs about 410 cubic feet per minute of air to create the annular flow of induced air.

[0034] In some exemplary embodiments, the mineral fibers are glass fibers.

[0035] In some exemplary embodiments, the mineral fibers have an average diameter of less than 9 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 8 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 7 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 6 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 5 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 4 μm. In some exemplary embodiments, the mineral fibers have an average diameter of less than 3 μm.

[0036] In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a mean fiber diameter x; and wherein x is less than a median fiber diameter of the mineral fibers.

[0037] In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter y; wherein

the mineral fibers have a mean fiber diameter x; and wherein $y < 2x$. In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter y; wherein the mineral fibers have a mean fiber diameter x; and wherein $y < 3x$.

[0038] In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter of less than 6.5 μm; wherein the mineral fibers have a mean fiber diameter x; and wherein a standard deviation from x is less than 2.5 μm. In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter of less than 6.5 μm; wherein the mineral fibers have a mean fiber diameter x; and wherein a standard deviation from x is less than 3.0 μm. In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter of less than 6.5 μm; wherein the mineral fibers have a mean fiber diameter x; and wherein a standard deviation from x is less than 3.5 μm. In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter of less than 6.5 μm; wherein the mineral fibers have a mean fiber diameter x; and wherein a standard deviation from x is less than 4.5 μm. In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a target production fiber diameter of less than 6.5 μm; wherein the mineral fibers have a mean fiber diameter x; and wherein a standard deviation from x is less than 5.5 μm.

[0039] In some exemplary embodiments, the mineral fibers comprise at least 10,000 distinct fibers; wherein the mineral fibers have a fiber diameter distribution with two Gaussian peaks; wherein the two Gaussian peaks represent $\geq 85\%$ of a volume of the mineral fibers; and wherein $\geq 40\%$ of the volume of the mineral fibers is represented by the Gaussian peak corresponding to the smallest diameter of the mineral fibers.

[0040] In some exemplary embodiments, the mineral fibers are free of any fibers having a diameter greater than 22 μm. In some exemplary embodiments, the mineral fibers are free of any fibers having a diameter greater than 20 μm. In some exemplary embodiments, the mineral fibers are free of any fibers having a diameter greater than 16 μm. In some exemplary embodiments, the mineral fibers are free of any fibers having a diameter greater than 15 μm.

In some exemplary embodiments, the mineral fibers are free of any fibers having a diameter greater than 14 μm.

[0041] In some exemplary embodiments, the mineral fibers have an average formed (i.e., non-reduced) length greater than 50.8 mm (2 inches). In some exemplary embodiments, the mineral fibers have an average formed length in the range of about 76.2 mm (3 inches) to about 304.8 mm (12 inches). In some exemplary embodiments, the mineral fibers have an average formed length in the range of greater than 50.8 mm (2 inches) to less than or equal 152.4 mm (6 inches).

[0042] In one exemplary embodiment, a package of microfibers is disclosed. The package comprises: at least 10,000 distinct fibers, wherein the fibers have a mean fiber diameter x; and wherein a fiber diameter distribution of the fibers has a standard deviation from x of less than 2.5 μm. In some exemplary embodiments, $x < 3.0$. In some exemplary embodiments, $x < 3.5$. In some exemplary embodiments, $x < 4.5$. In some exemplary embodiments, $x < 5.5$.

[0043] In some exemplary embodiments, the microfibers are rotary formed fibers.

[0044] In some exemplary embodiments, the microfibers have an average diameter of less than 9 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 8 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 7 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 6 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 5 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 4 μm. In some exemplary embodiments, the microfibers have an average diameter of less than 3 μm.

[0045] In some exemplary embodiments, the mineral fibers have an average formed (i.e., non-reduced) length greater than 50.8 mm (2 inches). In some exemplary embodiments, the mineral fibers have an average formed length in the range of about 76.2 mm (3 inches) to about 304.8 mm (12 inches). In some exemplary embodiments, the mineral fibers have an average formed length in the range of greater than 50.8 mm (2 inches) to less than or equal 152.4 mm (6 inches).

[0046] In some exemplary embodiments, x is less than a median fiber diameter of the fibers.

[0047] In some exemplary embodiments, 90% of the microfibers have a diameter ≤ 1.525x.

[0048] In some exemplary embodiments, the microfibers have a curvature greater than 0.043.

[0049] In some exemplary embodiments, the microfibers have a curvature of at least 0.055.

[0050] In some exemplary embodiments, the microfibers have a curvature in the range of 0.050 to 0.060.

[0051] In some exemplary embodiments, the microfibers are glass fibers.

[0052] In some exemplary embodiments, the microfibers comprise at least 10,000 distinct fibers; wherein the microfibers have a fiber diameter distribution with a first Gaussian peak and a second Gaussian peak; and wherein the first Gaussian peak and the second Gaussian peak represent ≥ 85% of a volume of the microfibers.

[0053] In some exemplary embodiments, ≥ 40% of the volume of the microfibers is represented by the first Gaussian peak, which corresponds to the smallest diameter of the microfibers.

[0054] In some exemplary embodiments, the microfibers include a sizing composition applied to a surface of the microfibers; and the sizing composition is an aqueous composition comprising water, a silane coupling agent, at least one organic acid, and a cationic surfactant.

[0055] In some exemplary embodiments, the microfibers include a sizing composition applied to a surface of the microfibers; and the sizing composition is an aqueous composition consisting essentially of or consisting of water, a silane coupling agent, at least one organic acid, and a cationic surfactant.

[0056] In some exemplary embodiments, the sizing composition is free of a film former.

[0057] In some exemplary embodiments, the sizing composition has less than 5% active solids content.

[0058] In some exemplary embodiments, the sizing composition (applied to the mineral fibers) is substantially color-free with an ΔL^* value of -5 to +5.

[0059] In some exemplary embodiments, the at least one organic acid is selected from the group consisting of acetic acid, succinic acid, citric acid, and combinations thereof.

[0060] In some exemplary embodiments, an amount of the sizing composition applied to the microfibers is from about 0.05 wt.% to about 2 wt.% based on the total weight of the sized microfibers.

[0061] In one exemplary embodiment, a package of rotary-formed fibers is disclosed. The package comprises: at least 10,000 distinct fibers, wherein the fibers have a mean fiber diameter x; wherein a fiber diameter distribution of the fibers has a standard deviation from x of less than 3.5 μm; wherein the mineral fibers have a fiber diameter distribution with a first Gaussian peak and a second Gaussian peak; and wherein the first Gaussian peak and the second Gaussian peak represent ≥ 85% of a volume of the mineral fibers.

[0062] In one exemplary embodiment, a package of rotary-formed fibers is disclosed. The package comprises: at least 10,000 distinct fibers, wherein the fibers have a mean fiber diameter x; wherein a fiber diameter distribution of the fibers has a standard deviation from x of less than 3.5 μm; wherein the mineral fibers have a fiber diameter distribution with a first Gaussian peak and a second Gaussian peak; wherein the first Gaussian peak and the second Gaussian peak represent ≥ 85% of a volume of the mineral fibers; and wherein ≥ 40% of the volume of the mineral fibers is represented by the first Gaussian peak, which corresponds to the smallest diameter of the mineral fibers.

[0063] In one exemplary embodiment, a sizing composition for application to microfibers (e.g., rotary-formed glass fibers) is disclosed. The sizing composition comprises, consists essentially of, or consists of water, a silane coupling agent, at least one organic acid, and a cationic surfactant.

[0064] In some exemplary embodiments, the at least one organic acid is selected from the group consisting of acetic acid, succinic acid, citric acid, and combinations thereof.

[0065] In some exemplary embodiments, the sizing composition has a pH in the range of about 3.0 to about 7.5. In some exemplary embodiments, the sizing composition has a pH in the range of about 4.5 to about 5.5.

[0066] In some exemplary embodiments, the sizing composition has less than 5% active solids content.

[0067] In some exemplary embodiments, the cationic surfactant comprises from about 25 wt.% to about 90 wt.% of the dry solids of the sizing composition.

[0068] In some exemplary embodiments, the silane coupling agent comprises from about 15 wt.% to about 45 wt.% solids of the sizing composition; wherein the organic acid comprises from about 1 wt.% to about 20 wt.% solids of the sizing composition; and wherein the cationic surfactant comprises from about 35 wt.% to about 75 wt.% solids of the sizing composition.

[0069] In some exemplary embodiments, the water comprises about 80 wt.% to about 99.9 wt.% of the sizing composition.

[0070] In one exemplary embodiment, a non-woven mat is disclosed. The non-woven mat comprises: a plurality of first fibers; a plurality of second fibers (microfibers); and a binder holding the first fibers and second fibers together in an interspersed arrangement; wherein the first fibers have an effective fiber diameter a; wherein the second fibers have an effective fiber diameter b; wherein $b < a$; wherein the second fibers have a mean fiber diameter x that is less than about 9 μm; and wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 5.5 μm.

[0071] In some exemplary embodiments, $x < 8$. In some exemplary embodiments, $x < 7$. In some exemplary embodiments, $x < 6$. In some exemplary embodiments, $x < 5$.

[0072] In some exemplary embodiments, the standard deviation from x is less than about 4.5 μm. In some exemplary embodiments, the standard deviation from x is less than about 3.5 μm. In some exemplary embodiments, the standard deviation from x is less than about 3.0 μm. In some exemplary embodiments, the standard deviation from x is less than about 2.5 μm.

[0073] In one exemplary embodiment, a non-woven mat is disclosed. The non-woven mat comprises: a plurality of first fibers; a plurality of second fibers (microfibers); and a binder holding the first fibers and second fibers together in an interspersed arrangement; wherein the first fibers have an average fiber diameter greater than about 7 μm; wherein the second fibers

have a mean fiber diameter x that is less than about 6 μm; and wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 5.5 μm.

[0074] In some exemplary embodiments, the standard deviation from x is less than 4.5 μm. In some exemplary embodiments, the standard deviation from x is less than 3.5 μm. In some exemplary embodiments, the standard deviation from x is less than 3.0 μm. In some exemplary embodiments, the standard deviation from x is less than 2.5 μm.

[0075] In some exemplary embodiments, the second fibers have an average diameter of less than 9 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 8 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 7 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 6 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 5 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 4 μm. In some exemplary embodiments, the second fibers have an average diameter of less than 3 μm.

[0076] In some exemplary embodiments, the second fibers have an average formed length greater than 50.8 mm (2 inches).

[0077] In some exemplary embodiments, the second fibers have an average formed length in the range of about 76.2 mm (3 inches) to about 304.8 mm (12 inches).

[0078] In some exemplary embodiments, the second fibers have an average formed length in the range of greater than 50.8 mm (2 inches) to less than or equal 152.4 mm (6 inches).

[0079] In some exemplary embodiments, x is less than a median fiber diameter of the second fibers.

[0080] In some exemplary embodiments, 90% of the second fibers have a diameter $\leq$ 1.525x.

[0081] In some exemplary embodiments, the second fibers have a curvature greater than 0.043.

[0082] In some exemplary embodiments, the second fibers have a curvature of at least 0.055.

[0083] In some exemplary embodiments, the second fibers have a curvature in the range of 0.050 to 0.060.

[0084] In some exemplary embodiments, the first fibers are glass fibers.

[0085] In some exemplary embodiments, the second fibers are glass fibers.

[0086] In some exemplary embodiments, the second fibers are rotary-formed fibers.

[0087] In some exemplary embodiments, the non-woven mat comprises at least 1 wt.% of the second fibers based on the weight of the non-woven mat. In some exemplary embodiments, the non-woven mat comprises at least 10 wt.% of the second fibers based on the weight of the non-woven mat. In some exemplary embodiments, the non-woven mat comprises at least 20 wt.% of the second fibers based on the weight of the non-woven mat.

[0088] In some exemplary embodiments, the second fibers include a sizing composition applied to a surface of the second fibers; wherein the sizing composition is an aqueous composition comprising, consisting essentially of, or consisting of water, a silane coupling agent, at least one organic acid, and a cationic surfactant.

[0089] In some exemplary embodiments, an amount of the sizing composition applied to the second fibers is from about 0.05 wt.% to about 2 wt.% based on the total weight of the sized second fibers.

[0090] In some exemplary embodiments, the binder includes polyvinyl alcohol.

[0091] In some exemplary embodiments, the non-woven mat further comprises an inorganic filler.

[0092] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 10 μm to about 11 μm; and the average fiber diameter of the second fibers is in the range of about 3 μm to about 4 μm.

[0093] In some exemplary embodiments, the second fibers are free of any fibers having a diameter greater than 22 μm. In some exemplary embodiments, the second fibers are free of any fibers having a diameter greater than 20 μm. In some exemplary embodiments, the second fibers are free of any fibers having a diameter greater than 16 μm. In some exemplary embodiments, the second fibers are free of any fibers having a diameter greater than 15 μm.

In some exemplary embodiments, the second fibers are free of any fibers having a diameter greater than 14 μm.

[0094] In some exemplary embodiments, the non-woven mat has a first surface and a second surface opposite the first surface, and each surface comprises less than about 100 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 50 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 25 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 15 flocs per 1,000 m^2 of the non-woven mat.

[0095] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 8 μm to about 13 μm.

[0096] In some exemplary embodiments, the average fiber diameter of the second fibers is in the range of about 3 μm to about 3. 5 μm.

[0097] In some exemplary embodiments, the first fibers comprise about 10% w/w to about 50% w/w of the total weight of the first and second fibers; and the second fibers comprise about 50% w/w to about 90% w/w of the total weight of the first and second fibers.

[0098] In some exemplary embodiments, the non-woven mat includes more of the first fibers than the second fibers by wt.% based on the total weight of the first and second fibers.

[0099] In one exemplary embodiment, a method of manufacturing a non-woven fibrous mat is disclosed. The method comprises: (i) dispersing a plurality of first fibers in a first aqueous solution to form a first slurry; (ii) dispersing a plurality of second fibers (microfibers) in a second aqueous solution to form a second slurry; (iii) mixing the first slurry, the second slurry, and a water-soluble or water-dispersible binder to form a third slurry; (iv) depositing the third slurry to form a wet-laid web made up of the first fibers, the second fibers, and the binder; and (v) drying the wet-laid web to form the non-woven fibrous mat, wherein the first fibers have an average fiber diameter in the range of about 6.5 μm to about 15 μm; wherein the second fibers have a mean fiber diameter x that is less than 6.0 μm; wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 3.5 μm; and wherein the non-woven mat has a first surface and a second surface opposite the first surface, with each surface having less than 100 flocs per 1,000 m^2 of the non-woven mat.

[00100] In some exemplary embodiments, the binder is added to the first slurry.

[00101] In some exemplary embodiments, the binder is added to the second slurry.

[00102] In one exemplary embodiment, a structured non-woven mat is disclosed. The structured non-woven mat comprises: a plurality of first fibers; a plurality of second fibers (microfibers); a plurality of bundles formed from the first fibers and the second fibers; and a binder holding the first fibers, the second fibers, and the bundles together in an interspersed arrangement; wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers, wherein an average diameter of the bundles is greater than the average fiber diameter of the first fibers and the average fiber diameter of the second fibers; wherein a portion of the first fibers is not present in any of the bundles, and wherein a portion of the second fibers is not present in any of the bundles.

[00103] In some exemplary embodiments, the mat includes at least about 150 bundles per square foot. In some exemplary embodiments, the mat includes at least about 300 bundles per square foot. In some exemplary embodiments, the mat includes at least about 450 bundles per square foot.

[00104] In some exemplary embodiments, the first fibers are non-rotary fibers. In some exemplary embodiments, the second fibers are rotary fibers.

[00105] In some exemplary embodiments, the first fibers are glass fibers. In some exemplary embodiments, the second fibers are glass fibers.

[00106] In some exemplary embodiments, the average fiber diameter of the first fibers is about 1.1 to about 6 times greater than the average fiber diameter of the second fibers.

[00107] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 1 μm less than the average fiber diameter of the first fibers.

[00108] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 3 μm less than the average fiber diameter of the first fibers.

[00109] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 5 μm less than the average fiber diameter of the first fibers.

[00110] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 7 μm less than the average fiber diameter of the first fibers.

[00111] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 10 μm less than the average fiber diameter of the first fibers.

[00112] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 13 μm to about 18 μm, and the average fiber diameter of the second fibers is at least 1 μm less than the average fiber diameter of the first fibers.

[00113] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 13 μm to about 18 μm, and the average fiber diameter of the second fibers is at least 3 μm less than the average fiber diameter of the first fibers.

[00114] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 13 μm to about 18 μm, and the average fiber diameter of the second fibers is at least 5 μm less than the average fiber diameter of the first fibers.

[00115] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 13 μm to about 18 μm, and the average fiber diameter of the second fibers is at least 7 μm less than the average fiber diameter of the first fibers.

[00116] In some exemplary embodiments, the average fiber diameter of the first fibers is in the range of about 13 μm to about 18 μm, and the average fiber diameter of the second fibers is at least 10 μm less than the average fiber diameter of the first fibers.

[00117] In some exemplary embodiments, the average fiber diameter of the first fibers is about 16 μm, and the average fiber diameter of the second fibers is at least 1 μm less than the average fiber diameter of the first fibers.

[00118] In some exemplary embodiments, the average fiber diameter of the first fibers is about 16 μm, and the average fiber diameter of the second fibers is at least 3 μm less than the average fiber diameter of the first fibers.

[00119] In some exemplary embodiments, the average fiber diameter of the first fibers is about 16 μm, and the average fiber diameter of the second fibers is at least 5 μm less than the average fiber diameter of the first fibers.

[00120] In some exemplary embodiments, the average fiber diameter of the first fibers is about 16 μm, and the average fiber diameter of the second fibers is at least 7 μm less than the average fiber diameter of the first fibers.

[00121] In some exemplary embodiments, the average fiber diameter of the first fibers is about 16 μm, and the average fiber diameter of the second fibers is at least 10 μm less than the average fiber diameter of the first fibers.

[00122] In some exemplary embodiments, an average fiber length of the first fibers is greater than an average fiber length of the second fibers.

[00123] In some exemplary embodiments, an average length of the bundles is greater than the average fiber length of the first fibers and the average fiber length of the second fibers.

[00124] In some exemplary embodiments, an average aspect ratio of the first fibers is greater than an average aspect ratio of the second fibers.

[00125] In some exemplary embodiments, an average aspect ratio of the first fibers is greater than about 1,200.

[00126] In some exemplary embodiments, a combined average aspect ratio of the first fibers and the second fibers is greater than about 1,000.

[00127] In some exemplary embodiments, an average curvature of the first fibers is less than an average curvature of the second fibers.

[00128] In some exemplary embodiments, the mat comprises about 50 wt.% to about 99 wt.% of the first fibers, based on the total weight of the first fibers and the second fibers.

[00129] In some exemplary embodiments, the mat comprises about 1 wt.% to about 50 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers. In some exemplary embodiments, the mat comprises about 1 wt.% to about 25 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers. In some exemplary embodiments, the mat comprises about 1 wt.% to about 15 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers.

[00130] In some exemplary embodiments, the bundles comprise more of the first fibers than the second fibers.

[00131] In some exemplary embodiments, an average diameter of the bundles is at least 5 times greater than an average diameter of the first fibers.

[00132] In some exemplary embodiments, the bundles constitute between about 5 wt.% to about 90 wt.% of a total fiber content of the mat.

[00133] In some exemplary embodiments, an average binder content of the bundles is less than an average binder content of the mat.

[00134] In some exemplary embodiments, the average binder content of the bundles is at least 50% less than the average binder content of the mat. In some exemplary embodiments, the average binder content of the bundles is at least 66% less than the average binder content of the mat. In some exemplary embodiments, the average binder content of the bundles is at least 75% less than the average binder content of the mat.

[00135] In some exemplary embodiments, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, wherein a majority of the first ends and the second ends have a non-planar shape.

[00136] In some exemplary embodiments, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, wherein a majority of the first ends and the second ends have a tapered shape.

[00137] In some exemplary embodiments, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, wherein a majority of the first ends and the second ends are split into a plurality of separated strands. In some exemplary embodiments, at least one of the strands at a first end or a second end of a

first bundle is entangled with at least one of the strands at a first end or a second end of a second bundle.

[00138] In one exemplary embodiment, a structured non-woven mat is disclosed. The structured non-woven mat comprises: a plurality of first fibers; a plurality of second fibers (microfibers); a plurality of bundles formed from the first fibers and the second fibers; and a binder holding the first fibers, the second fibers, and the bundles together in an interspersed arrangement; wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers, and wherein a thickness of the mat is less than a thickness of a similar mat formed without any of the bundles.

[00139] In some exemplary embodiments, the (average) thickness of the mat is less than about 0.650 mm. In some exemplary embodiments, the normalized (average) thickness of the mat is less than about 0.0070 mm/g/m^2.

[00140] In some exemplary embodiments, an average fiber length of the second fibers is in the range of about 1 mm to about 25 mm.

[00141] In some exemplary embodiments, a ratio of the first fibers to the second fibers is in the range of about 3:1 to about 99.5:1, by total weight of the fibers.

[00142] In some exemplary embodiments, the first fibers are non-rotary fibers. In some exemplary embodiments, the second fibers are rotary fibers.

[00143] In some exemplary embodiments, the first fibers are glass fibers. In some exemplary embodiments, the second fibers are glass fibers.

[00144] In some exemplary embodiments, a combined aspect ratio of the first fibers and the second fibers is greater than 1,000.

[00145] In some exemplary embodiments, the mat has an area weight in the range of about 40 g/m^2 to about 500 g/m^2. In some exemplary embodiments, the mat has an area weight in the range of about 70 g/m^2 to about 250 g/m^2.

[00146] In some exemplary embodiments, the mat has an air porosity in the range of about 500 cfm to about 800 cfm.

[00147] In some exemplary embodiments, the mat has a bundle concentration in the range of about 538 bundles/m^2 to about 8,608 bundles/m^2 (about 50 bundles/ft^2 to about 800 bundles/ft^2). In some exemplary embodiments, the mat has a bundle concentration in the range of about 1,076 bundles/m^2 to about 5,380 bundles/m^2 (about 100 bundles/ft^2 to about 500 bundles/ft^2). In some exemplary embodiments, the mat has a bundle concentration in the range of about 1,614 bundles/m^2 to about 4,303 bundles/m^2 (about 150 bundles/ft^2 to about 400 bundles/ft^2).

[00148] In one exemplary, a shingle is disclosed, wherein the shingle includes a structured non-woven mat as disclosed herein.

[00149] In one exemplary, an underlayment is disclosed, wherein the underlayment includes a structured non-woven mat as disclosed herein. In some exemplary embodiments, the underlayment is a self-adhered underlayment.

[00150] In one exemplary, a polymeric membrane is disclosed, wherein the polymeric membrane includes a structured non-woven mat as disclosed herein.

[00151] In one exemplary embodiment (i.e., Embodiment A), a structured non-woven mat comprises: a plurality of first fibers; a plurality of second fibers; a plurality of bundles formed from the first fibers and the second fibers; and a binder holding the first fibers, the second fibers, and the bundles together in an interspersed arrangement; wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers, wherein an average diameter of the bundles is greater than the average fiber diameter of the first fibers and the average fiber diameter of the second fibers; wherein a portion of the first fibers is not present in any of the bundles, and wherein a portion of the second fibers is not present in any of the bundles.

[00152] In some embodiments of Embodiment A, the mat includes at least about 1,614 bundles per m^2, preferably at least about 3,228 bundles per m^2, and more preferably at least about 4,842 bundles per m^2.

[00153] In some embodiments of Embodiment A, the first fibers are non-rotary fibers.

[00154] In some embodiments of Embodiment A, the second fibers are rotary fibers.

[00155] In some embodiments of Embodiment A, the second fibers have a mean fiber diameter x that is less than about 4 μm; and wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 3.5 μm, preferably of less than 3.0 μm, and more preferably of less than 2.5 μm.

[00156] In some embodiments of Embodiment A, the first fibers are glass fibers.

[00157] In some embodiments of Embodiment A, the second fibers are glass fibers.

[00158] In some embodiments of Embodiment A, the average fiber diameter of the first fibers is about 1.1 to about 6 times greater than the average fiber diameter of the second fibers.

[00159] In some embodiments of Embodiment A, the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and the average fiber diameter of the second fibers is at least 1 μm less than the average fiber diameter of the first fibers, preferably at least 5 μm less than the average fiber diameter of the first fibers, and more preferably at least 10 μm less than the average fiber diameter of the first fibers.

[00160] In some embodiments of Embodiment A, an average length of the bundles is greater than the average fiber length of the first fibers and the average fiber length of the second fibers.

[00161] In some embodiments of Embodiment A, an average aspect ratio of the first fibers is greater than an average aspect ratio of the second fibers.

[00162] In some embodiments of Embodiment A, an average aspect ratio of the first fibers is greater than about 1,200.

[00163] In some embodiments of Embodiment A, a combined average aspect ratio of the first fibers and the second fibers is greater than about 1,000.

[00164] In some embodiments of Embodiment A, an average curvature of the first fibers is less than an average curvature of the second fibers.

[00165] In some embodiments of Embodiment A, the mat comprises about 50 wt.% to about 99 wt.% of the first fibers, based on the total weight of the first fibers and the second fibers.

[00166] In some embodiments of Embodiment A, the mat comprises about 1 wt.% to about 50 wt.% of the second fibers, preferably about 1 wt.% to about 25 wt.% of the second fibers, and more preferably about 1 wt.% to about 15 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers.

[00167] In some embodiments of Embodiment A, the bundles comprise more of the first fibers than the second fibers.

[00168] In some embodiments of Embodiment A, the bundles constitute between about 5 wt.% to about 90 wt.% of a total fiber content of the mat.

[00169] In some embodiments of Embodiment A, an average diameter of the bundles is at least 5 times greater than an average diameter of the first fibers.

[00170] In some embodiments of Embodiment A, an average binder content of the bundles is less than an average binder content of the mat. In some embodiments of Embodiment A, the average binder content of the bundles is at least 50% less than the average binder content of the mat. In some embodiments of Embodiment A, the average binder content of the bundles is at least 66% less than the average binder content of the mat. In some embodiments of Embodiment A, the average binder content of the bundles is at least 75% less than the average binder content of the mat.

[00171] In some embodiments of Embodiment A, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and wherein a majority of the first ends and the second ends have a non-planar shape.

[00172] In some embodiments of Embodiment A, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and wherein a majority of the first ends and the second ends have a tapered shape.

[00173] In some embodiments of Embodiment A, each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and wherein a majority of the first ends and the second ends are split into a plurality of separated strands. In some embodiments of Embodiment A, at least one of the strands at a first end or a second end of a first bundle is entangled with at least one of the strands at a first end or a second end of a second bundle.

[00174] In some embodiments of Embodiment A, a thickness of the mat is less than a thickness of a similar mat formed without any of the bundles.

[00175] In some embodiments of Embodiment A, an average fiber length of the second fibers is in the range of about 1 mm to about 25 mm.

[00176] In some embodiments of Embodiment A, a ratio of the first fibers to the second fibers is in the range of about 3:1 to about 99.5:1, by total weight of the fibers.

[00177] In some embodiments of Embodiment A, the mat has an area weight in the range of about 40 g/m^2 to about 500 g/m^2, preferably in the range of about 50 g/m^2 to about 250 g/m^2.

[00178] In some embodiments of Embodiment A, the mat has an air porosity in the range of about 850 m^3/h to about 1,359 m^3/h.

[00179] In some embodiments of Embodiment A, the mat has a bundle concentration in the range of about 538 bundles/m^2 to about 8,608 bundles/m^2, preferably in the range of about 1,076 bundles/m^2 to about 5,380 bundles/m^2, and more preferably in the range of about 1,614 bundles/m^2 to about 4,303 bundles/m^2.

[00180] In one exemplary embodiment (i.e., Embodiment B), a shingle comprises the structured non-woven mat according to any aspects of Embodiment A.

[00181] In one exemplary embodiment (i.e., Embodiment C), an underlayment comprises the structured non-woven mat according to any aspects of Embodiment A.

[00182] In one exemplary embodiment (i.e., Embodiment D), a polymeric membrane comprises the structured non-woven mat according to any aspects of Embodiment A.

[00183] Other aspects and features of the general inventive concepts will become more readily apparent to those of ordinary skill in the art upon review of the following description of various exemplary embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[00184] The general inventive concepts, as well as embodiments and advantages thereof, are described below in greater detail, by way of example, with reference to the drawings in which:

[00185] Figure 1 is a partial cross-sectional view of a rotary fiber forming apparatus to illustrate various aspects of a conventional rotary fiber production method.

[00186] Figure 2A is a graph illustrating the fiber diameter distribution for a volume of glass fibers produced by one conventional rotary fiber production method.

[00187] Figure 2B is a graph illustrating the fiber diameter distribution for a volume of glass fibers produced by another conventional rotary fiber production method.

[00188] Figure 2C is a graph illustrating the fiber diameter distribution for a volume of glass fibers produced by yet another conventional rotary fiber production method.

[00189] Figure 2D is a graph illustrating the fiber diameter distribution for a volume of glass fibers produced by still another conventional rotary fiber production method.

[00190] Figure 3 is a partial cross-sectional view of a rotary fiber forming apparatus to illustrate various aspects of a rotary fiber production method, according to one exemplary embodiment.

[00191] Figure 4 is a graph illustrating the fiber diameter distribution for a volume of glass fibers produced by the rotary fiber production method of FIG. 3.

[00192] Figures 5A-5C are scanning electron microscopy (SEM) images, at a magnification of 120x of exemplary non-woven mats made from fiber blends in which fiber curvature was measured.

[00193] Figure 6 is a graph illustrating the zeta potential (relative to pH) of several glass sizing formulations.

[00194] Figure 7 is a diagram showing illustrative non-woven mat portions with and without flocs therein.

[00195] Figure 8 is a graph showing the "conversion value" between measuring fibers diameter of various WUCS fibers having different fiber diameters using an SEM microscopy based approach and the ISO 13322-2 compliant approach described herein.

[00196] Figure 9 is a diagram illustrating exemplary processing of the inventive rotary fibers prior to being mixed with other fibers in a wet-laid process.

[00197] Figures 10A-10B present respective SEM images, at a magnification of 120x, to illustrate the visual difference between an exemplary non-woven mat including many visible fiber bundles and a control non-woven mat lacking such bundles.

[00198] Figure 11 is a graph showing the total weight of the bundles in various sample mats, relative to the total weight of the corresponding mat.

[00199] Figure 12 is a graph showing the average bundle weight for various sample mats.

[00200] Figure 13 is a graph showing bundle density, as the number of bundles per square foot, for various sample mats.

[00201] Figure 14 is a graph showing the LOI of the bundles for various sample mats, relative to the LOI of the corresponding mat.

[00202] Figure 15 is a graph showing the binder content (LOI) and glass content making up the bundles in various sample mats, relative to the binder content (LOI) and glass content of the corresponding mat.

[00203] Figure 16 is a graph illustrating the relationship between (a) increasing the amount of the second fibers in a fiber blend used to produce similar sample mats and (b) bundle generation (i.e., increasing bundle density) in the mats.

[00204] Figure 17 is a graph illustrating the relationship between (a) increasing the average fiber length of the second fibers in a fiber blend used to produce similar sample mats and (b) bundle generation (i.e., increasing bundle density) in the mats.

[00205] Figure 18 is a plot of bundle generation (aggregate density/basis weight) for three similar mats, wherein each mat is made from a fiber blend comprising the same concentration

of second fibers but with the second fibers in each mat having a different average fiber diameter (i.e., 3.5 μm, 6.5 μm, 10 μm, respectively).

[00206] Figure 19A is a graph illustrating the relationship between (a) increasing the amount of the second fibers in a fiber blend used to produce similar sample mats and (b) the decreased caliper (thickness) of the corresponding mats.

[00207] Figure 19B is another graph illustrating the relationship between (a) increasing the amount of the second fibers in a fiber blend used to produce similar sample mats and (b) the decreased caliper (thickness) of the corresponding mats.

[00208] Figure 20 is a graph illustrating the relationship between (a) increasing the amount of the second fibers in a fiber blend used to produce similar sample mats and (b) the decreased air permeability of the corresponding mats, when measured using ASTM D737 Standard Test Method for Air Permeability of Textile Fabrics.

[00209] Figure 21 is a plot of the percentage of rotary (second) fibers in an exemplary structured non-woven mat and the quantity of asphalt colored pixels from a back of the mat identified by image processing, as a representation of asphalt penetration.

[00210] Figure 22 is a graph illustrating the Gurley stiffness (mg) of various sample mats, as normalized for the basis weight of the mats.

[00211] Figure 23 is a pair of diagrams (side view and corresponding top plan view) of a portion of an exemplary structured non-woven mat, which illustrate the creation of higher compressive strength regions in the mat.

[00212] Figure 24 is a diagram (side view) of a portion of an exemplary structured non-woven mat, which illustrate the creation of a textured surface on the mat.

[00213] Figure 25 is a pair of diagrams (top plan view and corresponding force plot) of a portion of an exemplary structured non-woven mat, which illustrate the creation of higher cut/tear resistance portions through the mat.

[00214] Figure 26 is a diagram (top plan view) of a portion of an exemplary structured non-woven mat, which illustrates the creation of regions within the mat having improved fastener pull through resistance.

DETAILED DESCRIPTION

[00215] Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art to which this invention belongs. The term "about," as used herein to modify any numerical values, encompasses the specific numerical value(s) without any modification, as well as reasonable deviations therefrom, such as those attributable to measurement methodologies or limitations.

[00216] Several illustrative embodiments will be described in detail with the understanding that the present disclosure merely exemplifies the general inventive concepts. Embodiments encompassing the general inventive concepts may take various forms and the general inventive concepts are not intended to be limited to the specific embodiments described herein.

[00217] In view of the above, modifications to a rotary fiber forming process allows for the production of fibers having a more uniform fiber diameter and/or length distribution. The general inventive concepts encompass this new method of producing rotary fibers, the new rotary fibers themselves, a sizing formulation suitable for use on microfibers (including the new rotary fibers), a package of microfibers (e.g., the new rotary fibers having the improved fiber distribution), a non-woven mat made from microfibers (including the new rotary fibers), and downstream applications for the mat (e.g., roofing materials).

Rotary-Forming Process/System

[00218] It is known to form non-woven materials from glass fibers. For example, composite materials comprised of reinforcing glass fiber mats (known as, e.g., veils, webs, facers) are utilized in a variety of applications.

[00219] One approach to forming glass fibers involves passing molten glass through orifices in the bottom of a stationary bushing, wherein the streams of molten glass attenuate into fibers as they cool. See, e.g., U.S. 3,653,860; U.S. 3,972,702; and U.S. 4,207,086. Another approach to forming glass fibers involves passing molten glass through orifices in

the outer wall of a spinner (via centrifugal force), wherein the streams of molten glass attenuate into fibers as they cool. See, e.g., U.S. 5,582,841. For the rotary-formed fibers, heated air can be used to draw the fibers downward, which helps with attenuation and collection of the fibers.

[00220] The bushing-formed glass fibers can subsequently be chopped to form wet-use chopped strand (WUCS) fibers having a relatively consistent average fiber diameter and average fiber length. However, bushing-formed glass fibers are usually limited to fiber diameters of 6.5 μm or larger, due to health concerns relating to their non-biosolubility. Furthermore, due to factors such as raw material costs and production (melting) costs, bushing-formed glass fibers can be relatively more expensive to produce compared to rotary-formed glass fibers.

[00221] Consequently, for many applications, rotary-formed glass fibers are used instead of or in addition to bushing-formed glass fibers. The rotary-formed glass fibers can have fiber diameters well below 6.5 μm owing to their biosoluble formulations. These so called "microfibers" can provide improved properties at lower add-on weights compared to WUCS fibers. However, it has proven difficult to produce rotary-formed glass fibers having a consistent average fiber diameter and/or average fiber length.

[00222] The term "microfiber," as used herein (including in claims), means fibers that have a target average fiber diameter of about 6.5 μm or less and, more preferably, about 4 μm or less . Typically, but not exclusively, the microfibers will be rotary formed fibers, such as the exemplary fibers presented in Table 6. Typically, but not exclusively, the microfibers will be glass fibers and, more preferably, biosoluble glass fibers. While the microfibers have a target average fiber diameter of 6.5 μm or less, the distribution of a quantity of the fibers produced at the same time may fall outside this range, owing to production variability, particularly in the case of rotary-formed fibers. For example, the average fiber diameter of the distribution of microfibers can be as high as about 8.5 μm. Furthermore, the median (d_{50}) value of the distribution of microfibers can be as high as about 7.5 μm. As shown in Table 6, the standard deviation from the actual mean fiber diameter for the distribution of microfibers can be as high as about 5.5 μm, but more preferably is less than about 3.5 μm.

[00223] One approach to measuring average fiber diameter, such as the average fiber diameters described herein, involves: (1) subjecting the samples to sufficient heat to burn off

any surface chemistry without impacting the underlying fiber morphology; and (2) determining the average fiber diameter for a given quantity of the fibers by measuring an airflow/pressure drop across the quantity of fibers, as commonly performed in the insulation and fiber industries (e.g., Micronaire). Instrumentation used for measuring fiber diameter via airflow resistance are based on theories by Darcy, Les Fontaines Publiques de la Ville de Dijon (1856); Kozeny, Uber Kapillare Leitung des Wassers im Boden (1927); and Carman, Flow of Gases Through Porous Media (1956) among others. The instruments work by measuring the airflow resistance through a known mass of material; as the fiber diameter decreases, the specific surface area increases, which increases the resistance to airflow. The higher the airflow resistance, the smaller the effective fiber diameter, representing the fiber diameter that would be expected to produce the same resistance, if all fibers were the same diameter. This is the primary technique (referred to as the airflow resistance approach) to obtaining the effective fiber diameter values presented herein (as an estimate of the average fiber diameter), including in the claims, unless otherwise noted.

[00224] The aforementioned airflow resistance approach, however, is not suitable for determining the distribution of individual fibers (e.g., fibers with different diameters) from a quantity of fibers or values calculated from the distribution (e.g., mean, median, standard deviation). Thus, another approach to measuring fiber diameter in the context of the overall fiber distribution, such as the fiber diameter distributions described herein, involves (1) subjecting the samples to sufficient heat to burn off any surface chemistry without impacting the underlying fiber morphology; (2) dispersing the plain fibers in water using a high-speed blender; (3) diluting the fibers dispersed in the water to an acceptable concentration suitable for image analysis; and (4) measuring the fiber diameter distribution using image analysis (e.g., in compliance with ISO 13322-2). The image analysis can be performed by an apparatus wherein particles (i.e., the dispersed fibers) pass through the focal planes of two cameras, the apparatus having an image rate of 300 images per second and a resolution of 0.8 μm per pixel. The apparatus used to obtain the data described herein is the Camsizer X2 with the X-Flow Module, which is manufactured by Microtrac MRB of Osaka, Japan. The measured data can be filtered to remove non-fibrous particles (e.g., particles having an aspect ratio (L/D) of less than 5). In general, a minimum of 10,000 fibers are measured to ensure a proper distribution assessment. The results reported are the Martin minimum diameter, bucketed every 0.1 micron, and plotted based on volume (not count), wherein volume requires both the average diameter and average length of each fiber to be measured. This

image processing-based approach, which is referred to herein generally as the ISO 13322-2 compliant approach, is the primary technique to obtaining the mean fiber diameter values presented herein, including in the claims, unless otherwise noted.

[00225] As generally used herein, including in the claims, the term "average fiber diameter" encompasses both the effective fiber diameter and the mean fiber diameter for a sample, unless the context indicates otherwise.

[00226] It is noted that other approaches to identifying mean fiber diameter, as well as other distribution-related properties of a collection of fibers exist, for example, count-based approaches that look at individual fibers identified using scanning electron microscopy (SEM). While these other approaches aren't directly relevant to the values presented herein, it has been determined that measurements taken by one approach might be readily convertible to the approaches disclosed herein by means of multiplying those values by a constant conversion value. By way of example, as shown in the graph 800 of FIG. 8, various samples made up of non-rotary WUCS fibers having different fiber diameters were measured using both an SEM microscopy based approach and the ISO 13322-2 compliant approach described herein (referred to as Camsizer in the graph 800). By calculating the "fit line" between the various measured values, it was determined that conversion between the SEM microscopy based approach values (α) and the ISO 13322-2 compliant approach values (β) could be calculated as follows $\alpha = 0.76 \times \beta$.

[00227] In view of the above, modifications to a rotary fiber forming process allows for the production of microfibers having a more uniform fiber diameter and/or length distribution. Accordingly, a primary drawback of rotary-formed fibers is mitigated and downstream processing of the rotary-formed fibers is improved.

[00228] The modified rotary fiber forming process 300 will be described with reference to a conventional fiber manufacturing apparatus or fiberizer, such as the fiberizer 10 of FIG. 1 (albeit with the radiation shield 52 disclosed therein being an optional component). As shown in FIG. 3, the rotary fiber forming process 300 includes multiple aspects A-E that can be modified to produce the fibers having a more uniform fiber diameter and/or length distribution. The general inventive concepts encompass a modified rotary fiber forming process 300 that uses any one or more of these aspects A-E to obtain a quantity of fibers (produced together) having a more uniform fiber diameter and/or length distribution. The

general inventive concepts encompass any combination of these aspects (e.g., A, A+B, A+C, A+B+C, A+D, A+B+D, A+B+C+D, A+E, etc.). Furthermore, the general inventive concepts are not necessarily limited to these aspects and other features of the invention, such as the sizing formulation(s) described herein, may also contribute to the improved fiber diameter and/or length distribution, in some exemplary embodiments.

[00229] During conventional processing, a surface of a quill pan 67 of the fiberizer 10 can get hot enough to melt fibers that come into contact with the quill pan 67. In one aspect A of the modified rotary fiber forming process 300, the amount of cooling air introduced through the hollow quill 64 is increased, which reduces the temperature of the quill pan 67. By way of example, a conventional rotary fiber forming process will use approximately 5-15 cubic feet per minute (CFM) of air flow to cool the quill pan 67 to a temperature $temp_{conv}$. The inventive rotary fiber forming process (e.g., the process 300) uses approximately 30-60 CFM of air flow to cool the quill plan 67 to a temperature $temp_{inv}$. Consequently, while $temp_{conv}$ is typically much higher than 1,100 °F (e.g., ≥ 1,200 °F), $temp_{inv}$ is kept under 1,100 °F. As a result, fibers being formed that come into contact with the quill pan 67 are less likely to be fused thereto (or with other fibers fused thereto) in a manner likely to damage the fibers or lead to agglomeration of fibers (e.g., flocs), both of which can distort the intended fiber diameter and/or length distribution.

[00230] In another aspect B of the modified rotary fiber forming process 300, a rotational speed of the spinner 12 (via the rotating spindle 14) is decreased, which reduces the likelihood of the fibers contacting a surface of the blower 28. By way of example, a conventional rotary fiber forming process will cause the spinner 12 to run at 2,500 revolutions per minute (rpm) to 3,000 rpm, while the inventive rotary fiber forming process (e.g., the process 300) will cause the same spinner 12 to run at 1,800 rpm to 2,400 rpm. For spinners with different sizes/geometries, these ranges might shift, but the reduction in rotational speed in the modified rotary fiber forming process versus a conventional rotary fiber forming process will hold. As a result, the fibers being formed are less likely to be fused thereto (or with other fibers fused thereto) in a manner likely to damage the fibers or lead to agglomeration of fibers (e.g., flocs), both of which can distort the intended fiber diameter and/or length distribution.

[00231] In another aspect C of the modified rotary fiber forming process 300, an amount of heated air created by the burner 24 is reduced. By way of example, a conventional rotary

fiber forming process will use approximately 360 cubic feet per minute (CFM) of mixed gas flow, while the inventive rotary fiber forming process (e.g., the process 300) will use approximately 240-300 CFM of mixed gas flow. Although reducing the air flow at C helps lower the temperature within the process 300, it has to be balanced against the tendency of the lower temperature to result in larger diameter fibers due to reduced attenuation. Consequently, in some exemplary embodiments, the modified rotary fiber forming process 300 may have a lower limit on its ability to produce smaller diameter and/or length fibers. For example, the lower limit of effective fiber diameter (using the air flow method) would be in the range of 2.5 μm to 3.0 μm, with this lower limit being restricted by the ability to maintain sufficient temperature to attenuate the molten glass into fibers.

[00232] In another aspect D of the modified rotary fiber forming process 300, an amount of air induced through passage 30 by blower 28 is controlled to promote improved attenuation of the primary fibers 22 into the secondary fibers 32. In some exemplary embodiments of the inventive rotary fiber forming process (e.g., the process 300), the blower 28 outputs approximately 410 cubic feet per minute (CFM) of air, which in turn leads to the "induced air" flowing through the passage 30. Here, "improved attenuation" can be considered achieving a reduction in the occurrence of fused fibers and other defects (e.g., shot, flocs), as described herein. Likewise, this improved attenuation (and the resulting reduction in fused fibers) is evidenced by an improved fiber diameter and/or length distribution, such as shown in the graph 400 of FIG. 4.

[00233] The above aspects A-D are particularly important with respect to aspect E of the modified rotary fiber forming process 300, which represents the "attenuation zone" for the secondary fibers 32. The attenuation zone E is an area around the fiberizer 10 where the temperatures are hot enough to fuse the fibers 32. The modified rotary fiber forming process 300 attempts to minimize collisions between two separate fibers 32 and/or between a fiber 32 and a piece of the fiber forming equipment until after the fibers 32 have cooled below their glass transition temperature T_g and, thus, are less likely to fuse. For example, for glass fibers having a Tg in the range of 1,000 °F to 1,250 °F, the modified rotary fiber forming process 300 would attempt to minimize fiber collisions until after the fibers have cooled to a temperature below 1,100 °F.

[00234] In addition to producing a quantity of fibers that have a fiber diameter and/or length distribution closer to a target fiber diameter and/or length, by reducing the number of

fibers that are fused and/or damaged during the production process, the modified rotary fiber forming process 300 produces a quantity of fibers with an improved overall quality (e.g., longer length), as compared to conventional rotary fibers.

[00235] Furthermore, the fibers produced by the modified rotary fiber forming process 300 can be further processed downstream of the process 300, such as by milling/cutting/chopping the fibers into easier to process lengths. For example, the fibers can be milled to have a reduced length in the range of 1/8 inch (3.25 mm) to 1 inch (25.4 mm), which facilitates the use of the fibers in a wet-laid process. Likewise, other applications/processes might benefit from the fibers having a longer length. Thus, because the fibers produced by the modified rotary fiber forming process 300 have a longer initial (formed) length than conventional rotary-formed fibers, the fibers are more likely to start at a length greater than a target length, which in turn provides more flexibility in reducing the fibers to the target (processed) length and more uniformity in products made from such fibers.

[00236] In this manner, a wider range of aspect ratios can be obtained from the processed fibers, with the processed fibers having a more uniform distribution relative to the target aspect ratio. For example, the inventive rotary fibers can be processed to have an average aspect ratio in the range of 850 to 5,000 or in the range of 850 to 2,000. When blended with non-rotary fibers (e.g., WUCS fibers) that have an aspect ratio less than 2,000, the combined average aspect ratio of the fiber blend is less than about 1,000. This is beneficial since controlling the average aspect ratio of the fiber blend was found to help avoid or otherwise reduce the presence of flocs, bundles, strings, or the like, all of which are typically considered undesired forms of the fibers within the blend. However, as described below, the creation of bundles or strings can be desirable in creating a non-woven fibrous mat with enhanced properties. In such cases, a combined average aspect ratio of the fiber blend greater than about 1,000 may be beneficial.

[00237] The average aspect ratio for a quantity of similar fibers (e.g., fiber1 or fiber2) can be calculated by dividing the average diameter d of the fibers (μm) into the average length L of the fibers (μm), so average aspect ratio = L/d. For a blend of two different fibers (e.g., fiber1 and fiber2), the combined average aspect ratio = (wt.% of fiber1 * average aspect ratio of fiber1) + (wt.% of fiber2 * average aspect ratio of fiber2). Additionally, the combined average aspect ratio of the fibers when used to form a non-woven mat, as described herein,

will typically be lower (e.g., in the range of 150 to 500) due to breakage in the non-woven forming process.

[00238] In some exemplary embodiments, the combined average aspect ratio of the fiber blend is less than about 1,100. In some exemplary embodiments, the combined average aspect ratio of the fiber blend is less than about 1,000. In some exemplary embodiments, the combined average aspect ratio of the fiber blend is less than about 900. In some exemplary embodiments, the combined average aspect ratio of the fiber blend is in the range of about 500 to about 1,000.

Improved Rotary-Formed Fibers

[00239] In FIG. 4, a graph 400 of the fiber diameter distribution for a fiberglass material, according to one exemplary embodiment, is shown. The fiberglass material comprises rotary-formed microfibers that are not held together by a binder. The fiberglass material was formed by a modified rotary fiber forming process (e.g., the process 300).

[00240] With reference to the graph 400, various properties for this inventive fiberglass material are shown in Table 5.

Peak Index	Peak Type	Area Intg	Area IntgP	Center Grvty	Max Height	FWHM
1	Gaussian	5.23342	52.85354	3.49237	2.39689	2.05115
2	Gaussian	4.66832	47.14646	7.44389	1.4328	3.06085

Table 5

In Table 5, “Peak Index” refers to the peak identifier from left to right, with the peaks being shown with dashed lines; “Peak Type” refers to the type of model used to fit the data; “Area Intg” refers to the integrated area of the fit peak; “Area IntgP” refers to the percentage of total integrated area for each fit peak; “Center Grvty” refers to the center of the fit peak; “Max Height” refers to the maximum value of the fit peak; and “FWHM” refers to the width of the peak at half of its maximum height.

[00241] In the graph 400 of FIG. 4, the rotary fibers were produced with a target diameter of about 3.5 μm, as measured using the known air flow method. The graph 400 represents the fiber diameter distribution when measured using an ISO 13322-2 compliant method and plotted by fiber volume %. The (Camsizer) data measured according to the ISO 13322-2

compliant approach was analyzed using the Peak Deconvolution App (v2.00) with OriginPro 2023 (constant baseline; fit until converged to obtain displayed results), which is data analysis software sold by OriginLab Corp. of Northampton, Massachusetts.

[00242] In an ideal case, 100% of the fibers produced would have a fiber diameter of about 3.5 μm. However, rotary fiber production is a complex process with many variables, only some of which can be controlled. As described herein, a modified rotary fiber forming process (e.g., the process 300) recognizes and controls one or more production variables to achieve fibers that have improved properties, as compared to conventional rotary fibers.

[00243] The rotary fibers shown in the graph 400 have a more pronounced bi-modal distribution, as compared to the conventional rotary fibers shown in the graphs of FIGS. 2A-2D. In particular, in the graph 400, two distinct peaks are shown, with each peak having an apex higher than 15 %/μm within the distribution. Furthermore, the fiber diameter distribution (i.e., the area under the graph) shows that a larger volume of the fibers are closer to the target fiber diameter (i.e., 3.5 μm), with almost no fibers having a diameter greater than 14 μm being measured. For the target fiber diameter of 3.5 μm, this narrower variance in fiber diameters (e.g., about 1.5 μm to about 13.5 μm), with a majority of the fibers having a fiber diameter less than 6 μm, is closer to the ideal than that achieved by conventional rotary fibers. Stated another way, since the variance in fiber diameters relative to the target fiber diameter is reduced and/or the volume of fibers having a fiber diameter closer to the target fiber diameter is increased, the inventive rotary fibers could result in improved products/applications.

[00244] In Table 6, additional properties for the inventive fiberglass material (shown in the graph 400) are compared to various conventional fibrous materials (shown in the graphs 210, 220, 230, 240).

	conventional rotary-formed glass fibers	conventional rotary-formed glass fibers	conventional rotary-formed glass fibers	conventional rotary-formed glass fibers	inventive rotary-formed glass fibers
	FIG. 2A	**FIG. 2B**	**FIG. 2C**	**FIG. 2D**	**FIG. 4**
d10	3.15 µm	2.92 µm	3.13 µm	2.70 µm	2.96 µm
d50 (median)	7.32 µm	7.08 µm	6.28 µm	5.06 µm	6.05 µm
d90	16.55 µm	15.71 µm	12.58 µm	12.10 µm	9.12 µm
Sample Mean	8.54 µm	8.22 µm	7.18 µm	6.47 µm	5.99 µm
Standard Deviation	5.27 µm	5.01 µm	4.05 µm	3.95 µm	2.45 µm

Table 6

wherein: d10 means that 10% of all particles in the sample are smaller than or equal to the d10 value; d50 means that 50% of all particles in the sample are smaller than or equal to the d50 value (also known as the median particle size); d90 means that 90% of all particles in the sample are smaller than or equal to the d90 value; Sample Mean refers to the mean particle size for the sample; and Standard Deviation refers to the standard deviation from the mean.

[00245] With respect to the values shown in Table 6, while the inventive microfibers do not have a lower median fiber diameter (d50) than all of the sampled conventional microfibers, the inventive microfibers do have a lower mean value than all of the sampled conventional microfibers. This indicates that the amount of larger diameter (i.e., greater than the target fiber diameter) material is less for the inventive microfibers, which can be seen in the graphs of FIGS. 2A, 2B, 2C, 2D, and 4. The smaller standard deviation value also indicates that the inventive microfibers have a more uniform fiber diameter distribution, as described herein.

[00246] Additionally, the inventive microfibers are produced with an increased fiber length relative to conventional microfibers.

[00247] By way of example, a conventional rotary fiber forming process will produce rotary fibers (from the fiberizer 10) having a length of approximately 12.7 mm (0.5 inches) to 50.8 mm (2 inches), while the inventive rotary fiber forming process (e.g., the process 300) will produce rotary fibers (from the fiberizer 10) having a length of approximately 76.2 mm (3 inches) to 304.8 mm (12 inches). In some exemplary embodiments, the inventive rotary fiber forming process will produce rotary fibers having an average formed length in the range of greater than 50.8 mm (2 inches) to less than or equal 152.4 mm (6 inches). The ability to

produce longer fibers provides for increased flexibility in downstream processing of the fibers, as well as more control over final product properties.

[00248] Furthermore, the inventive microfibers contain fewer fused fibers or clumps (e.g., flocs), thus enabling a more uniform dispersion of the fibers when producing non-woven products, as described herein. As used herein, the term "floc" refers to a loosely clumped mass of fibers which is visible to the naked eye. As shown in the diagram 700 of FIG. 7, a sample portion of a non-woven mat 710 is substantially free of any flocs 702 on one side 712 thereof and/or on the side (not shown) opposite the side 712, while a sample portion of another non-woven mat 720 includes several flocs 702 on one side 722 thereof and/or on the side (not shown) opposite the side 722.

[00249] In some exemplary embodiments, the microfibers have an average fiber diameter of less than 6.5 μm. In some exemplary embodiments, the microfibers have an average fiber diameter of less than 5.5 μm. In some exemplary embodiments, the microfibers have an average fiber diameter of less than 4.5 μm.

[00250] In some exemplary embodiments, the microfibers have a fiber diameter distribution with one or two Gaussian peaks that represent ≥ 85% of the fiber volume/mass, with ≥ 40% of the volume/mass being in the peak representing the smallest diameter fibers.

[00251] In some exemplary embodiments, the microfibers are substantially free of any fibers having a diameter larger than 15 μm.

[00252] In some exemplary embodiments, upon formation thereof (e.g., exiting the fiberizer 10), the microfibers are substantially free of or have a substantial reduction in any unfiberized or poorly fiberized material (generally referred to as "shot"), fused fibers, agglomerated fibers (e.g., flocs), and/or other forms of defective fibers, which can contribute to the improved fiber diameter distribution described herein.

[00253] In some exemplary embodiments, the microfibers are made from a bio-soluble composition.

[00254] While non-rotary fibers (e.g., WUCS fibers) are inherently straight when formed, rotary fibers generally have a curvature due to the glass fibers cooling in a less controlled environment. This curvature can also impart benefits to products made from microfibers (e.g.,

the inventive rotary fibers), for example, reducing visual defects (e.g., clouds/mottling; directionality) in ceiling tiles due to more random scattering of light and the inability of the fibers to align with one another.

[00255] As shown in FIGS. 5A-5C, several sample non-woven mats were made using a wet-laid process that combined blends of fibers comprising 11 μm diameter, 6 mm long WUCS fibers as first fibers (Fiber 1) and (i) 6.5 μm diameter, 6 mm long WUCS fibers as second fibers (Fiber 2) in FIG. 5A; (ii) the conventional ULF fibers shown in FIG. 2C as second fibers (Fiber 2) in FIG. 5B; and (iii) the inventive rotary fibers described herein and shown in FIG. 4 as second fibers (Fiber 2) in FIG. 5C.

[00256] FIG. 5A includes an SEM image of a non-woven mat 500 made by a wet-laid process from a combination of 85% first WUCS fibers (Fiber 1) having an average fiber diameter of 11 μm and a processed length of 6 mm and 15% second WUCS fibers (Fiber 2) having an average fiber diameter of 6.5 μm and a processed length of 6 mm, by weight of the glass fibers. FIG. 5B includes an SEM image of a non-woven mat 502 made by a wet-laid process from a combination of 85% first WUCS fibers (Fiber 1) having an average fiber diameter of 11 μm and a processed length of 6 mm and 15% second ULF fibers (Fiber 2) having an average fiber diameter in the range of 2.8 μm to 3 μm and a processed length in the range of 1 mm to 6 mm, by weight of the glass fibers. FIG. 5C includes an SEM image of a non-woven mat 504 made by a wet-laid process from a combination of 85% first WUCS fibers (Fiber 1) having an average fiber diameter of 11 μm and a processed length of 6 mm and 15% second inventive rotary fibers (Fiber 2) having an average fiber diameter of 3.5 μm and a processed length in the range of 1 mm to 6 mm, by weight of the glass fibers.

[00257] The mats 500, 502, and 504 were imaged using scanning electron microscopy to create the SEM images shown in FIGS. 5A-5C, respectively. These SEM images were analyzed using ImageJ version 1.54f open-source software, with the Kappa Curvature Analysis plug-in (Gary Brouhard, 2016) to approximate the curvature of the second fibers (Fiber 2) in each of the mats 500, 502, 504. The WUCS fibers (Fiber 2) in the mat 500 were found to have a curvature of 0.004. The ULF fibers (Fiber 2) in the mat 502 were found to have a curvature of about 0.043. The inventive rotary fibers (Fiber 2) in the mat 504 were found to have a curvature of about 0.055.

[00258] In some exemplary embodiments, the microfibers, which are all produced by one or more fiberizers having essentially the same operating parameters (and, perhaps, at essentially the same time), are packaged together. In some exemplary embodiments, the microfibers may undergo processing (e.g., milling to reduce length (to a "processed length")) prior to packaging. The microfibers in the package may include a sizing composition applied thereto, as described herein. The package of microfibers have an improved fiber diameter and/or length distribution, as described herein.

Sizing Formulation(s)

[00259] As the microfibers (e.g., the inventive rotary fibers are being formed), or soon thereafter, an aqueous sizing composition can be applied thereto. For example, the sizing composition could be sprayed on the fibers using an annular ring with nozzles surrounding the curtain of fibers being directed downward. The surface chemistry imparted to the microfibers by the sizing composition can act to protect the fibers and promote downstream processing thereof.

[00260] In one exemplary embodiment, a sizing composition is provided. The sizing composition comprises water, a silane coupling agent, at least one organic acid, and a cationic surfactant, wherein the sizing composition has less than 5% active solids content and is substantially "color-free." It was surprisingly discovered that the subject sizing composition, which includes a reduced number of components compared to conventional sizing compositions (e.g., conventional sizing compositions used with WUCS fibers), is particularly useful with the inventive fibers. In particular, various exemplary aspects of the sizing compositions disclosed herein are free of a film former. In some aspects, the reduced number of components results in a sizing composition that is more cationic than conventional sizing compositions, which provides improved dispersion of the sized fibers in the white-water solution during formation of mats made from microfibers (e.g., the inventive rotary fibers).

[00261] The exemplary sizing composition includes, at a minimum, a silane coupling agent, at least one organic acid, and a cationic surfactant. In any of the embodiments, the sizing composition may consist essentially of, or consist of a silane coupling agent, at least one organic acid, and a cationic surfactant.

Silane Coupling Agent

[00262] The silane coupling agent may be in a partially or a fully hydrolyzed state or in a non-hydrolyzed state. The silane coupling agent may also be in monomeric, oligomeric, or polymeric form prior to, during, or after its use.

[00263] Suitable silane coupling agents used in the sizing compositions disclosed herein are organosilanes that have silanol functional groups (e.g., after hydrolysis of the alkoxy groups) that bond well with glass. The silane coupling agent also functions to aid in processability, such as by reducing the level of broken fiber filaments during subsequent processing.

[00264] Silane coupling agents which may be used in the present sizing composition may be characterized by the functional groups amino, methacrylate, epoxy, azido, vinyl, methacryloxy, ureido, and isocyanato. Preferably, the organosilane has a functional group that is linked through non-hydrolyzable bonds to a silicon atom.

[00265] Organosilanes for use in the sizing composition include monosilanes containing the structure $Si(OR)_3$, where R is an organic group such as an alkyl group. Lower alkyl groups such as methyl, ethyl, and isopropyl are preferred. Examples of particular silane coupling agents suitable for use in the sizing composition include, but are not limited to, gamma-aminopropyltriethoxysilane (A-1100), gamma-ureidopropyltrimethoxysilane (A-1524), 3-aminopropyltriethoxysilane (KBE-903), γ-glycidoxypropyltrimethoxysilane (A-187), γ-methacryloxypropyltrimethoxysilane (A-174), n-βaminoethyl-γ-aminopropyltrimethoxysilane (A-1120), methyl-trichlorosilane (A-154), methyltrimethoxysilane (A-163), γ-mercaptopropyl-trimethoxy-silane (A-189), γ-chloropropyl-trimethoxy-silane (A-143), vinyl-triethoxy-silane (A-151), vinyl-tris-(2-methoxyethoxy)silane (A-2171), vinyl-triacetoxy silane (A-188), octyltriethoxysilane (A-137), methyltriethoxysilane (A-162), and methyltrimethoxysilane (A-1630). All of the silane coupling agents listed herein are commercially available as Silquest™ products from Momentive Performance Materials, Inc. (Waterford, New York). In certain exemplary embodiments, the silane coupling agent is selected from the group consisting of gamma-aminopropyltriethoxysilane, gamma-ureidopropyltrimethoxysilane, 3-aminopropyltriethoxysilane, and combinations thereof.

[00266] In one exemplary embodiment, the sizing composition comprises Silquest® Y-9669, available from Momentive, which is a N-phenyl-gamma-aminopropltrimethoxy silane, with a solids content of 82% and Silquest® A-1120, which is N(beta-aminoethyl)gamma-

aminopropyltrimethoxy-silane, with a solids content of 81%. An exemplary methacrylate-functional silane for use in the sizing composition disclosed herein is Gamma-methacryloxypropltrimethoxysilane (A-174), which is available commercially from Momentive Performance Materials, Inc. of Waterford, New York. In another exemplary embodiment, the silane coupling agent component of the sizing composition of the present disclosure comprises Silquest® Y-9669 and A-174.

[00267] In certain exemplary embodiments, the sizing composition includes a silane coupling agent in an amount such that the silane coupling agent comprises from 1 wt.% to 60 wt.% of the solids content of the sizing composition. In certain exemplary embodiments, the silane coupling agent comprises from 5 wt.% to 50 wt.% solids, based on the total solids content of the sizing composition, including, for example, from 15 wt.% to 45 wt.%, and also including from 25 wt.% to 35 wt.% of the solids. In certain exemplary embodiments, the silane coupling agent has an active solids content of 25-80%, including from 40-70%, and 60-65%.

Organic Acid

[00268] As mentioned above, the exemplary sizing compositions disclosed herein include at least one organic acid. The organic acid is used to adjust the pH to enable the hydrolysis of the silane coupling agent. The organic acid disclosed herein comprises at least one weak acid. Examples of suitable weak acids that can be used in the sizing compositions disclosed herein include, but are not limited to, acetic acid, succinic acid, citric acid, and combinations thereof. In some exemplary embodiments, the weak acid component comprises or consists of acetic acid. The sizing compositions disclosed herein have a pH of from about 3.0 to about 7.5, preferably from about 4.5 to about 5.5.

[00269] In certain exemplary embodiments, the sizing composition includes an organic acid in an amount such that the organic acid comprises from 0.01 wt.% to 50 wt.% of the solids content of the sizing composition. For example, the organic acid comprises from 0.05 wt.% to 40 wt.% of the solids content of the sizing composition, including from 0.1 wt.% to 30 wt.%, from 0.5 wt.% to 25 wt.%, from 0.75 wt.% to 22 wt.%, from 1.0 wt.% to 20 wt.%, from 1.5 wt.% to 18 wt.%, and from 2.0 wt.% to 15 wt.%, based on the total solids of the sizing composition. In certain exemplary embodiments, the organic acid has an active solids content

of 25-99%, including from 40-90%, and 70-85%. In certain exemplary embodiments, the organic acid has an active solids content of about 80% +/- 3%.

Cationic Surfactant

[00270] The exemplary sizing compositions disclosed herein further include a cationic surfactant. The cationic surfactant acts as a "wet lubricant" and serves to increase dispersion of the glass fibers in the white-water solution during formation of mats made from microfibers (e.g., the inventive rotary fibers).

[00271] Suitable examples of cationic surfactants include, but are not limited to, imidazoline and alkyl imidazoline derivatives, amino ethyl imidazolines, a stearic ethanolamide such as Lubesize K-12 (Alpha/Owens Corning (Ontario, Canada), polyamides of acetic acid, of C5-C9 carboxylic acids and of diethylenetriamine-ethyleneimine, commercially available as Katax® 6760L (Pulcra Chemicals). A preferred cationic softener is the acetic acid salt of the reaction product of tetraethylene pentamine and stearic acid converted in about 91% imidazoline groups, commercially available as LUBESIZE K-12.

[00272] Imidazolines are thermally stable organic nitrogenous bases. Unneutralized imidazolines, being lipophilic, are generally soluble in non-polar solvents and mineral oil but tend to only be dispersible in aqueous systems. The ability of imidazolines to form cations renders them strongly adsorbed onto the negatively charged surface of metals, fibers, plastics, glass and minerals, thereby converting these hydrophilic surfaces to hydrophobic surfaces. Imidazoline salts tend to be much more hydrophilic than their bases and function as acid stable detergents with good wetting agents. The compatibility of imidazolines in aqueous systems may be improved through the use of suitable solubilizers.

[00273] In certain exemplary embodiments, the sizing composition includes a cationic surfactant in an amount such that the cationic surfactant comprises from 25 wt.% to 90 wt.% of the total solids content of the sizing composition. In certain exemplary embodiments, the cationic surfactant comprises from 30 wt.% to 80 wt.% solids, based on the total solids content of the sizing composition, including, for example, from 35 wt.% to 75 wt.%, from 37 wt.% to 72 wt.%, and from 40 wt.% to 70 wt.% solids, including all endpoints and subranges therebetween. In certain exemplary embodiments, the cationic surfactant has an active solids content of 0.5-20%, including from 1-15%, and 5-10%. In certain exemplary embodiments, the cationic surfactant has an active solids content of about 9% +/- 3%.

[00274] As mentioned above, the sizing compositions disclosed herein may be formed without the presence of a film former material, which may comprise a polymer material, such as, for example, an amide-based polymer, acrylic-based polymer, polyester-based polymer, epoxy-based polymer, and the like. Traditionally, film formers are included to coalesce and form a film on a fiber when the sizing composition has been dried. The film former functions to protect the fibers from damage during processing and imparts compatibility of the fibers with other end use materials. However, the sizing compositions disclosed herein are formed using a reduced amount of chemicals and provides sufficient fiber protection without the use of a film former. Nonetheless, the various aspects of the exemplary sizing compositions disclosed herein may optionally include a film former.

[00275] The exemplary sizing compositions disclosed herein also include water. The sizing composition contains an amount of water sufficient to dilute the solids of the sizing composition to a viscosity that is suitable for application to rotary fibers. In accordance with certain exemplary embodiments, the sizing composition comprises water in an amount of from 80 wt.% to 99.9 wt.%, based on the total weight of the sizing composition, including, for example, from 85 wt.% to 98 wt.%, or from 90 wt.% to 99.5 wt.%. The total solids content of the sizing composition may be from 0.5 wt.% to about 20 wt.%, including from 2 wt.% to 10 wt.%. Preferably, the sizing composition has a total solids content of 3 wt.% to 6 wt.%, and more preferably of about 5 wt.%.

[00276] In certain exemplary embodiments, the sizing composition comprises, consists essentially of, or consists of a silane coupling agent in an amount of from 25 wt.% to 35 wt.% solids, an organic acid in an amount of about 2-20 wt.% solids, and a cationic surfactant in an amount of from 50 wt.% to 70 wt.% solids, based on the total solids content of the sizing composition. In any of the exemplary embodiments, the sizing composition may comprise or consist of a γ-aminopropyltriethoxysilane coupling agent in an amount of from 25 wt.% to 35 wt.% solids, based on the total solids content of the sizing composition, acetic acid in an amount of from 2 wt.% to 20 wt.% solids, based on the total solid content of the sizing composition, and an imidazoline derivative coupling agent in an amount of from 50 wt.% to 70 wt.% solids, based on the total solids content of the sizing composition.

[00277] The exemplary sizing compositions disclosed herein may also include other components that are conventionally used in sizing compositions. For example, the sizing compositions may optionally include wetting agents, surfactants, lubricants, antioxidants,

dyes, oils, fillers, thermal stabilizers, antifoaming agents, dust suppression agents, antimicrobial agents, antistatic agents, fungicides, biocides, film forming agents, chopping aids, thickeners and/or other conventional additives. The amount of the foregoing optional components in the sizing composition may range from 0 wt.% to 90 wt.% based on the dry solids content of the sizing composition, including, for example, 0 wt.% to 50 wt.%, or 0 wt.% to 30 wt.%.

[00278] The exemplary sizing compositions disclosed herein may be prepared by combining the ingredients thereof according to any method known to one of ordinary skill in the art. In certain exemplary embodiments, the viscosity of the white water at room temperature is preferably greater than 2.0 cps, and more preferably between 2.0 and 5 cps, and still more preferably about 3.0-3.5 cps.

[00279] Exemplary sizing compositional ranges are provided below in Table 7. It should be appreciated that any of the disclosed ranges of Sizing Compositions A-C in Table 7 may be used in combination with any other disclosed compositional range herein and is not limited to the particular combination of ranges provided therein.

	Sizing Composition A (wt.% solids)	**Sizing Composition B (wt.% solids)**	**Sizing Composition C (wt.% solids)**
Silane coupling agent	1-60	15 – 45	25 - 35
Organic Acid	0.1 – 50	1 – 20	2 - 15
Cationic Surfactant	25 - 90	35 - 75	50 - 70
Film Former	0 - 90	0 - 70	0 - 50
Total	100	100	100

Table 7

[00280] In some exemplary embodiments, the sizing composition is substantially cationic in nature. The charge of the sizing composition may be described in terms of its zeta potential over a range of pH values. The zeta potential is the charge that develops at the interface between a solid surface (such as a particulate material) and its liquid medium. The sizing composition of the subject inventive concepts has a zeta potential with an absolute value that is at least 20 greater than the pH. Particularly, the sizing composition has a zeta potential with an absolute value of greater than 30 at a pH range between 2 and 4. The sizing composition has a zeta potential with an absolute value of greater than 20 at a pH range between 2 and 6.

[00281] For purposes of illustration, an inventive sizing formulation (IF) formed in accordance with the present inventive concepts and with about 70 wt.% solids of a cationic surfactant was compared to a first conventional reference sizing formulation (RF-1) applied to an equivalent fiber and a second conventional reference sizing formulation (RF-2) applied to another equivalent fiber. Both RF-1 and RF-2 included about 20 w% to 40 wt.% of a cationic lubricant. In each instance, the particular size formulation was applied using a roll coating technique on conventional WUCS fibers at the same or lower wt.%. In FIG. 6, a graph 600 of the zeta potential of each formulation is plotted relative to the pH. In general, the greater the magnitude of the zeta potential, the more cationic the formulation.

[00282] As shown in the graph 600, the greater zeta potential of the IF at both high and low pH indicates that the sized fiber exhibits amphoteric behavior, meaning it can act as an acid or a base. This property indicates that fibers sized with the IF disperses well in both acidic and basic environments. To achieve a suitable dispersion, it is generally desirable to have a zeta potential with an absolute value greater than 20 at a pH between 2 and 6.

[00283] Additionally, the overall composition of the size chemistry (e.g., IF) contains more cationic lubricant, about 70 wt.% solids, than traditional size chemistries (e.g., RF-1, RF-2) which typically range from 0-40 wt.% solids.

[00284] The exemplary sizing compositions disclosed herein may be substantially "color-free," as compared to traditional sizing compositions. In exemplary embodiments, the sizing compositions disclosed herein exhibit an ΔL^* value of -5 to +5 on the fibers. In certain exemplary embodiments, the sizing compositions disclosed herein exhibit an ΔL^* value of 0 to +2.5, including an ΔL^* value of +2 on the fibers. In exemplary embodiments, the sizing compositions disclosed herein exhibit an Δa^* value of -10 to +10 on the fibers. In certain exemplary embodiments, the sizing compositions disclosed herein exhibit an Δa^* value of -8 to +2, including an Δa^* value of about -6 on the fibers. In exemplary embodiments, the sizing compositions disclosed herein exhibit an Δb^* value of -10 to +10 on the fibers. In certain exemplary embodiments, the sizing compositions disclosed herein exhibit an Δb^* value of -5 to +5, including an Δb^* value of about 0 on the fibers.

[00285] The sizing composition may be applied to the fibers such that the sizing composition is present on the fibers in an amount of from 0.05 wt.% to 2 wt.%, based on the total weight of the sized fibers. The amount of sizing composition present on the fibers is also

referred to as "strand solids content." In certain exemplary embodiments, the sizing composition is present on the fibers in an amount of from 0.08 wt.% to 1.0 wt.%, based on the total weight of the sized fibers, including from 0.1 wt.% to 0.8 wt.%, from 0.2 wt.% to 0.6 wt.%, and also including from 0.35 wt.% to 0.55 wt.%, based on the total weight of the sized fibers. This can be determined by the loss on ignition (LOI) of the sized fibers, which is the reduction in weight experienced by the sized fibers after heating the sized fibers to a temperature sufficient to burn or pyrolyze the sizing composition from the fibers.

[00286] The inventive sizing composition further may be applied at lower levels when evaluated based on surface area of the fiber. For example, the microfibers (e.g., the inventive rotary fibers) described herein may have less than about 4 mg/cm^2 of strand solids applied thereon, including, for example, 0.5 mg/cm^2 – 3.8 mg/cm^2, 0.75 mg/cm^2 – 3.4 mg/cm^2, 1 mg/cm^2 – 3 mg/cm^2, or 1.15 mg/cm^2 – 2.5 mg/cm^2, while traditional WUCS fibers might have from 4-24 mg/cm^2 of strand solids applied thereon.

[00287] In exemplary embodiments, the moisture content of the sized fiber has a final moisture content of less than 10%, including less than 7%, less than 6%, and less than or equal to 5%. The reduction in final moisture content (i.e., increased dryness of the fibers) can provide benefits such as reduced shipping costs, while reducing/avoiding the need for anti-microbial agents in the sizing composition.

General Non-woven Mat

[00288] Microfibers, such as the inventive rotary fibers described herein, can be used to form other materials, such as a non-woven mat. The fibrous mat can be formed by known processes, such as a wet-laid process. In a wet-laid process, discrete fibers are dispersed in a water slurry that contains surfactants, thickeners, defoaming agents, and/or other chemical agents. The water and chemical components are often referred to as a "white water" solution. The slurry containing the fibers is then agitated in a mixing tank so that the fibers become dispersed throughout the slurry. The slurry containing the dispersed fibers is deposited onto a moving screen, wherein a substantial portion of the water is removed to form a web of randomly oriented fibers. A binder is applied to the collection of fibers, which then passes through an oven to dry (i.e., remove any residual water from) the fibers and cure the binder to form the mat. In addition to being applied in an aqueous form, the binder could also be applied in a dry (powered) form. For example, a swellable polyvinyl alcohol (PVA) powder

could be added to the fiber mix, wherein the PVA binder effectively binds the fibers as they pass through the oven/dryer.

[00289] In general, any binder suitable for forming conventional non-woven fibrous mats could be used. Exemplary binder compositions useful in the production of non-woven mats include formaldehyde-free (or no-added formaldehyde ("NAF")) binders, such as carboxyl-based binder compositions, polyvinyl alcohol-based binder compositions, carbohydrate-based binder compositions, and the like. Such binders are free of added formaldehyde and are environmentally friendly, i.e., "green." In some embodiments, the binder may include one or more bio-sourced materials. However, in some exemplary embodiments, the binder composition may include formaldehyde systems, such as urea formaldehyde systems.

[00290] The binder may comprise a thermoset binder or a thermoplastic binder. For example, the binder may comprise a thermoset binder with at least one polycarboxy polymer as the thermoset binder resin. The polycarboxy polymer comprises an organic polymer or oligomer containing more than one pendant carboxy group. The polycarboxy polymer may be a homopolymer or copolymer prepared from one or more unsaturated carboxylic acids including, but not limited to, acrylic acid, methacrylic acid, crotonic acid, isocrotonic acid, maleic acid, cinnamic acid, 2-methylmaleic acid, itaconic acid, 2-methylitaconic acid, α,β-methyleneglutaric acid, and the like. Alternatively, the polycarboxy polymer may be prepared from unsaturated anhydrides including, but not limited to, maleic anhydride, itaconic anhydride, acrylic anhydride, methacrylic anhydride, and the like, as well as mixtures thereof. The polymerization of these acids and anhydrides is considered to be within the abilities of one of ordinary skill in the art.

[00291] In some exemplary embodiments, the binder composition comprises a thermoset acrylic package that includes a blend of thermoset hydrophilic and hydrophobic acrylic binder materials. The thermoset acrylic package may include, but is not limited to, acrylic emulsions, acrylic solutions, or mixtures thereof. The thermoset nature of the acrylic package reduces the stickiness of the binder and thus reduces the binder sticking to processing equipment during the manufacturing process. In some embodiments, the thermoset acrylic package includes a mixture of an acrylic homopolymer and a styrene-acrylic latex. The acrylic homopolymer may be present in an amount from about 50 wt.% to about 80 wt.%, or from about 60 wt.% to about 75 wt.%, based on the total weight of precursor binder solids.

The styrene-acrylic latex may be present in an amount from about 20 wt.% to about 45 wt.%, or from about 25 wt.% to about 40 wt.%, based on the total weight of binder solids.

[00292] The binder composition may further optionally include an antifoam. In some exemplary embodiments, the antifoam includes one or more of siloxanes, mineral oil, and polyoxalkylene, although any antifoam may alternatively be used. An exemplary antifoam includes a polyether siloxane, such as Tego® Foamex 1488 (available commercially from Evonik). In some exemplary embodiments, the antifoam is present in the binder composition in an amount from about 0.001 wt.% to about 1.0 wt.%, including between about 0.01 wt.% to about 0.25 wt.%, based on the total weight of the solids in the precursor binder composition.

[00293] In certain embodiments, the binder composition may optionally contain at least one coupling agent. In certain embodiments, the coupling agent is a silane coupling agent. The coupling agent may be present in the binder composition in an amount from 0.01% to 5% by weight (on a dry weight basis), from 0.01% to 2.5% by weight (on a dry weight basis), from 0.1% to 0.5% by weight (on a dry weight basis), or from 0.15% to 0.25% by weight (on a dry weight basis) of the binder composition.

[00294] Non-limiting examples of silane coupling agents that may be used in the binder composition may be characterized by the functional groups including, but not limited to, alkyl, aryl, amino, epoxy, vinyl, methacryloxy, ureido, isocyanato, and mercapto. In certain embodiments, the silane coupling agent includes silanes containing one or more nitrogen atoms that have one or more functional groups such as amine (primary, secondary, tertiary, and quaternary), amino, imino, amido, imido, ureido, or isocyanato. Specific, non-limiting examples of suitable silane coupling agents include, but are not limited to, aminosilanes (e.g., γ-aminopropyltriethoxysilane and γ-aminopropyl-trihydroxysilane), epoxy trialkoxysilanes (e.g., 3-glycidoxypropyltrimethoxysilane and 3-glycidoxypropyltriethoxysilane), methyacryl trialkoxysilanes (e.g., 3-methacryloxypropyltrimethoxysilane and 3-methacryloxypropyltriethoxysilane), hydrocarbon trialkoxysilanes, amino trihydroxysilanes, epoxy trihydroxysilanes, methacryl trihydroxy silanes, and/or hydrocarbon trihydroxysilanes.

[00295] The binder composition may also include one or more additional additives, such as an extender, a catalyst, a processing aid, anti-dusting agent, viscosity modifier, pH adjusting agent, crosslinking density enhancer, a deodorant, an antioxidant, a moisture resistant agent,

or combinations thereof. Optionally, the binder may comprise, without limitation, dyes, pigments, additional fillers, colorants, UV stabilizers, thermal stabilizers, emulsifiers, preservatives (e.g., sodium benzoate), corrosion inhibitors, and mixtures thereof. Other additives may be added to the binder composition for the improvement of process and product performance. Such additives include lubricants, wetting agents, antistatic agents, and/or water-repellent agents. Additives may be present in the precursor binder composition from trace amounts (such as about 0.1% or less by weight the binder composition) up to about 10% by weight of the total solids in the binder composition.

[00296] In some exemplary embodiments, the binder may constitute a filled binder, which includes one or more primary fillers (e.g., mineral fillers). In this case, the primary filler may be present in the filled binder composition up to about 50% by weight of the total solids in the filled binder composition.

[00297] The binder further includes water to dissolve or disperse the active solids for application onto the fibers. Water may be added in an amount sufficient to dilute the aqueous binder composition to a viscosity that is suitable for its application to the fibers and to achieve a desired solids content on the fibers.

[00298] In some exemplary embodiments, the binder composition is included in the fiber mat in an amount from about 10 wt.% to about 30 wt.%, including between about 15 wt.% and about 27 wt.%, and between about 16 wt.% and about 25 wt.%.

[00299] The uniformity of the arrangement of the fibers in the non-woven, sheet-like mat of fibers contributes to the strength of the mat and to the ultimate end product. Other benefits, such as improved aesthetics, can also result from increased uniformity of the arrangement of the fibers. One problem that exists in preparing a uniform mat of fibers from an aqueous dispersion is that the fibers (e.g., glass fibers) are not easily dispersed in aqueous media. This difficulty in dispersing the fibers occurs initially upon adding the fibers to water. The dispersibility is further complicated by the tendency of the fibers that are scattered somewhat in the aqueous medium, to reagglomerate to some degree. The reagglomerated fibers are very difficult to redisperse. The lack of a good dispersion of the fibers in the aqueous medium hampers the formation of a uniform mat, and adversely affects the properties (e.g., strength, appearance) of the resultant sheet-like mat or end product incorporating the mat. This

dispersibility problem can be exacerbated in the case of mixing smaller diameter fibers (e.g., microfibers) with larger diameter fibers (e.g., non-rotary fibers, such as WUCS).

[00300] The adequate dispersion of the aqueous mixture may be obtained by any suitable means provided a uniform or substantially uniform distribution of the two (or more) groups of different glass fibers in the aqueous medium is produced. In some exemplary embodiments, a uniform distribution of two groups of different glass fibers is produced. In some exemplary embodiments, a substantially uniform distribution of the two groups of glass fibers is produced. The dispersion may be obtained by a high shear mixing apparatus, such as a rotor/stator mixer. Without wishing to be bound by theory, the inventors believe that highly dispersive and distributive mixing contributes to the production of a fibrous non-woven fibrous mat having substantially no or a low number of undispersed or partially dispersed fibers (e.g., flocs) per surface of the bonded non-woven mat.

[00301] In some exemplary embodiments, a significant portion (e.g., at least 10% by weight), but not all, of the fibers used to form the non-woven mat are microfibers, such as the inventive rotary fibers described herein. In some exemplary embodiments, the non-woven mat is formed from a blend of first fibers and second fibers (i.e., microfibers), wherein the first fibers have an average diameter > 6.5 μm and the second fibers have an average diameter < 6.5 μm. In some exemplary embodiments, the first fibers have an average diameter in the range of about 6.5 μm to about 15 μm. In some exemplary embodiments, the second fibers have an average diameter in the range of about 1 μm to about 6 μm. In some exemplary embodiments, the first fibers and the second fibers are both glass fibers. In some exemplary embodiments, the first fibers are not rotary-formed fibers.

[00302] In some exemplary embodiments, the microfibers are subject to pre-processing before being introduced into a mixing tank (with other fibers) of a wet-laid process. The pre-processing may serve to convert the fibers from a stored (e.g., compressed) form to a form more suitable for wet-laid processing, may serve to condition the fibers (e.g., to promote dispersibility) for wet-laid processing, may serve to evaluate the fibers for defects (e.g., remove flocs or potential flocs), etc.

[00303] By way of example, pre-processing associated with the production of a non-woven veil by a wet-laid process that involves mixing the microfibers (e.g., the inventive rotary fibers) with wet use chopped strands (WUCS) of glass will be described with reference to the

diagram 900 of FIG. 9. In this example, the inventive rotary fibers are ultimately mixed with the WUCS in a slurry, wherein a percentage of the microfibers in the total blend of glass fibers can vary between 1% to 99% w/w%. Prior to using this mix of the two glass-based fibers in a wet-laid process to produce a non-woven veil, the microfibers are wetted and dispersed in a separate process before being mixed with the WUCS.

[00304] In a first step 902, a quantity of the microfibers are loaded onto a conveyer to be fed into a mixing tank.

[00305] In a next step 904, the microfibers are fed into the mixing tank, which contains an aqueous solution of surfactants, viscosity modifiers, polymeric binders, and other process chemical aids. The microfibers are added gradually into the mixing tank to ensure wetting of individual fibers with the aqueous solution. The agitator and shape of the tank are designed such that there is adequate shear energy input and volume displacement rate while also breaking any continuous vortices formed. microfibers, with their large surface area to mass ratio, are wetted thoroughly with the aqueous solution. The dosage level of the microfibers in the mixing tank varies between 5-50 g/L.

[00306] In a next step 906, after sufficient dispersion, the microfiber aqueous suspension is pumped through a screening unit to remove any possible large impurities in the raw material. The screening device can be modified according to the required fineness of the microfiber suspension.

[00307] The microfibers may contain agglomerations of fibers which are difficult to wet and disperse thoroughly with the initial mixing process (step 904). These agglomerations can manifest as defects (e.g., “flocs”) in the non-woven mat. Accordingly, in a next (optional) step 908, a device such as a high shear mixer may be employed to break up these fiber flocs. In the high shear mixer, the microfiber suspension passes through a slotted rotor/stator system which homogenizes the fiber suspension, thereby aiding in the breaking up of fiber flocs.

[00308] Finally, in step 910, the pre-processed microfibers are delivered to a mixing tank of a wet-laid process, wherein the microfibers can be more effectively dispersed in a white water solution with other fibers.

[00309] In view of the above, in one inventive method of producing a non-woven mat using a blend of fibers including the microfibers (wherein a percentage of the microfibers in the

total blend of glass fibers can vary between 1% to 99% w/w%), the method comprises dispersing the microfibers in a first white water solution and then adding the dispersed microfibers to a second white water solution containing non-rotary fibers. In some exemplary embodiments, the non-rotary fibers are WUCS fibers. In some exemplary embodiments, the non-rotary fibers have a larger average fiber diameter than the microfibers.

[00310] In some exemplary embodiments, separate aqueous mixtures of the first and second groups of glass fibers are respectively prepared, and are then combined with agitation (e.g., high intensity mixing) to provide a uniform or nearly uniform dispersion of the fiber blend.

[00311] In some exemplary embodiments, the first and second groups of glass fibers are combined to form a dry mixture of glass fibers. The dry mixture is then formed into an aqueous mixture with agitation (e.g., high intensity mixing) to provide a uniform or substantially uniform dispersion of the fiber blend.

[00312] Because the microfibers (e.g., made by the process 300 or a conventional process) can be substantially free of or have a substantial reduction in any unfiberized or poorly fiberized material (generally referred to as "shot"), fused fibers, agglomerated fibers (e.g., flocs), and/or other forms of defective fibers, as noted above, a non-woven mat (e.g., the non-woven mat including the portion 710) made from the microfibers (e.g., the inventive rotary fibers) can likewise have fewer defects and, thus, improved properties (e.g., surface smoothness, surface appearance).

[00313] For example, a non-woven mat has a first surface 712 and a second surface (not shown) opposite the first surface 712. In some exemplary embodiments, at least one surface of the non-woven mat has less than about 100 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 100 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, at least one surface of the non-woven mat has less than about 50 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 50 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, at least one surface of the non-woven mat has less than about 25 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 25 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, at least one

surface of the non-woven mat has less than about 15 flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven mat has less than about 15 flocs per 1,000 m^2 of the non-woven mat.

[00314] In some exemplary embodiments, at least one surface of the non-woven mat is substantially free of any flocs per 1,000 m^2 of the non-woven mat. In some exemplary embodiments, each surface of the non-woven is substantially free of any flocs per 1,000 m^2 of the non-woven mat.

[00315] One method for assessing or otherwise estimating the number of flocs in a non-woven mat is to (1) unwind a roll of the non-woven mat that represents a total surface area of about 500 m^2, (2) manually count the loosely clumped mass of fibers which are visible to the naked eye under standard or ambient lighting, and (3) convert (extrapolate) the result of the counting into a number of flocs for a larger surface area (e.g., 1,000 m^2). Other suitable methods for counting the number of flocs in a given surface area are also contemplated. For example, image processing techniques could be used to generate an image corresponding to a relatively large portion (e.g., $\geq$ 500 m^2) of a non-woven mat and then automatically evaluate the image for instances of flocs therein. In general, evaluating smaller portions (e.g., $<$ 500 m^2) of a non-woven mat material were found to produce less reliable estimates of floc counts, likely due to flocs often being distributed over larger portions of the produced (roll of) mat.

[00316] In general, the non-woven mat is designed to have sufficient strength to withstand the processing steps and speeds required to produce the non-woven mat for application in various end uses. In addition, the strength of the non-woven mat must be sufficient to permit the mat to be stored in any desirable form, possibly for an extended period of time, without loss of its cohesive properties. In certain exemplary embodiments, the improved fiber diameter and/or fiber length distribution of the inventive rotary fibers is expected to enhance the structure and homogeneity or uniformity of the arrangement of the glass fibers in the non-woven mat, which should lead to more consistent and defined strength properties for the mat.

Structured Non-woven Mat

[00317] In other exemplary embodiments, microfibers (e.g., the inventive rotary fibers) can be used to form a structured non-woven mat. The structured non-woven mat takes advantage of interactions between two or more different fiber types in a blend of fibers being used to form the mat. Furthermore, by controlling properties (e.g., diameter, length) of at least one of

the fiber types, by controlling the concentration of at least one of the fiber types in the blend, and/or by controlling the white water chemistry, the structure of the mat formed from the blend of fibers can be controlled. The ability to tune the architecture of the non-woven mat can lead to beneficial results in certain applications and products (e.g., roofing materials) that use the structured mat.

[00318] Using a standard wet-laid process, two different fiber types (comprising first fibers and second fibers (i.e., microfibers)) are combined in a slurry. In some exemplary embodiments, the first fibers and the second fibers are dispersed simultaneously into a single mix tank. In some exemplary embodiments, the first fibers and the second fibers are dispersed sequentially into the mix tank. In some exemplary embodiments, the first fibers and the second fibers are dispersed separately (in different tanks) before the two mixes are combined. Significantly, the second fibers have characteristics that cause them to entangle with the first fibers (when mixed together) and form fiber bundles comprised primarily of the first fibers. As used herein, the term "bundle" refers to a collection of first fibers and second fibers that are joined together to form a unitary string-like structure, typically comprising many more of the first fibers than the second fibers. For example, in some exemplary embodiments, the first fibers will on average constitute between about 98% to about 99.8% by volume of the bundles. In some exemplary embodiments, the first fibers will on average constitute greater than about 95 wt.% of the bundles. In some exemplary embodiments, a ratio of the first fibers to the second fibers on average will fall within the range of 10:1 to 200:1.

[00319] By virtue of their construction, an average diameter of the bundles is greater than the average fiber diameter of the first fibers and the average fiber diameter of the second fibers. When examined under a Keyence digital microscope, the bundles were observed to have varied numbers of the first fibers therein and to have varied diameters. In some exemplary embodiments, a majority of the bundles in the mat comprise between 40 and 400 of the first fibers therein. In some exemplary embodiments, a majority of the bundles in the mat have a diameter in the range of about 200 μm to about 900 μm. In some exemplary embodiments, an average diameter of the bundles is at least 5 times greater than an average diameter of the first fibers.

[00320] Due to turbulent mixing in the wet-laid process, the bundles are distributed randomly within the slurry. This slurry is then processed in accordance with the wet-laid

process to form a structured non-woven mat. For example, the mixture is passed through a headbox that separates/distributes the first fibers, the second fibers, and the bundles onto a porous conveyor in the form of a relatively wet mat. The bundles are typically distributed randomly through the mat (e.g., in the width and/or thickness direction). In some exemplary embodiments, the bundles can be substantially aligned in the machine (length) direction. A majority of the water drains from the wet mat through the conveyor, and suction can be applied to facilitate this dewatering. Next, the less wet mat is saturated with a binder composition. In some exemplary embodiments, the binder is applied to the mat by curtain coating (i.e., conveying the mat through a curtain of the binder). Thereafter, a portion of the binder is removed (e.g., via suction) to control the average LOI of the mat. The mat with binder then passes through an oven where it is dried to remove any residual moisture and cured to set/cross-link the binder. Further downstream processing of the mat might include cutting the mat to size and/or packaging the mat on a roll for storage and transport.

[00321] In some exemplary embodiments, the first fibers are non-rotary (e.g., WUCS) fibers. In some exemplary embodiments, the second fibers are rotary fibers (e.g., the inventive rotary fibers). In some exemplary embodiments, the first fibers are glass fibers. In some exemplary embodiments, the second fibers are glass fibers.

[00322] In some exemplary embodiments, the first fibers are coarser (i.e., have a larger average diameter) than the second fibers. For example, the first fibers have an average (or effective or mean) fiber diameter in the range of about 11 μm to about 23 μm, while the second fibers have an average (or effective or mean) fiber diameter in the range of about 2 μm to about 10 μm.

[00323] In some exemplary embodiments, the first fibers have an average fiber diameter that is about 1.1 to about 6 times greater than an average fiber diameter of the second fibers. In some exemplary embodiments, the first fibers have an average fiber diameter of about 16 μm and the second fibers have an average fiber diameter at least 1 μm less than the first fibers. In some exemplary embodiments, the first fibers have an average fiber diameter of about 16 μm and the second fibers have an average fiber diameter at least 3 μm less than the first fibers. In some exemplary embodiments, the first fibers have an average fiber diameter of about 16 μm and the second fibers have an average fiber diameter at least 5 μm less than the first fibers. In some exemplary embodiments, the first fibers have an average fiber diameter of about 16 μm and the second fibers have an average fiber diameter at least 7 μm

less than the first fibers. In some exemplary embodiments, the first fibers have an average fiber diameter of about 16 μm and the second fibers have an average fiber diameter at least 10 μm less than the first fibers.

[00324] In some exemplary embodiments, the first fibers are longer (i.e., have a greater average length) than the second fibers. For example, the first fibers have an average fiber length in the range of about 18 mm to about 40 mm, while the second fibers have a target fiber length in the range of about 1 mm to about 24 mm. In some exemplary embodiments, an average length of the bundles is greater than the average fiber length of the first fibers and the average fiber length of the second fibers.

[00325] In some exemplary embodiments, an average aspect ratio of the first fibers is greater than an average aspect ratio of the second fibers. In some exemplary embodiments, an average aspect ratio of the first fibers is less than an average aspect ratio of the second fibers. In some exemplary embodiments, an average aspect ratio of the first fibers is greater than 1,200. In some exemplary embodiments, an average aspect ratio of the second fibers is greater than 1,200. In some exemplary embodiments, the first fibers have an average aspect ratio in the range of about 1,000 to about 2,500, while the second fibers have an average aspect ratio in the range of about 280 to about 1,700. Additionally, in some exemplary embodiments, the ratio of the wt.% of the first fibers and the wt.% of the second fibers results in a combined average aspect ratio for the fiber blend that is greater than 1,000.

[00326] In some exemplary embodiments, the first fibers are straighter (i.e., have a lower average curvature) than the second fibers. In some exemplary embodiments, the first fibers have an average curvature in the range of 0 μm to 0.01 μm, while the second fibers have an average curvature in the range of 0.03 μm to 0.1 μm.

[00327] In some exemplary embodiments, more of the first fibers are included in the blend of fibers than the second fibers. For example, from about 50 wt.% to about 99 wt.% of the first fibers are present in the fiber blend, based on the total weight of the fibers, while from about 1 wt.% to about 50 wt.% of the second fibers are present in the fiber blend, based on the total weight of the fibers. In some exemplary embodiments, from about 1 wt.% to about 25 wt.% of the second fibers are present in the fiber blend. In some exemplary embodiments, from about 1 wt.% to about 15 wt.% of the second fibers are present in the fiber blend.

[00328] The differences in properties between the first fibers and the second fibers can be controlled so as to promote entanglement of a quantity x of the first fibers by a quantity y of the second fibers, wherein x > y. For example, in some exemplary embodiments, the first fibers will on average constitute between about 98% to about 99.8% by volume of the bundles. In some exemplary embodiments, the first fibers will on average constitute greater than about 95 wt.% of the bundles. In some exemplary embodiments, a ratio of the first fibers to the second fibers on average will fall within the range of 10:1 to 200:1. While such an agglomeration of fibers may be undesirable in many applications (c.f., the discussion of flocs herein), it was surprisingly found that their controlled creation could be used to form a more structured mat having desirable properties. These fiber bundles result in a mat having a distinct visible appearance. For example, as shown in FIG. 10A, an exemplary structured mat formed from a blend of about 85 wt.% of the first fibers (16 μm average fiber diameter and 35 mm average fiber length) and about 15 wt.% of the second fibers (3.5 μm average fiber diameter and 1-6 mm target fiber length) includes many bundles that appear as randomly oriented string-like structures in the image 1000. Conversely, as shown in FIG. 10B, a control mat formed entirely from the first fibers (16 μm average fiber diameter and 35 mm average fiber length) does not appear to include any bundles that are readily visible in the image 1010.

[00329] As noted above, some of the characteristics of the second fibers that may impact their ability to bundle with the first fibers include fiber diameter, fiber length, and fiber curvature. Additionally, the relationship between the fiber diameter and the fiber length of the second fibers (i.e., the aspect ratio of the second fibers) may also impact their ability to bundle with the first fibers. Furthermore, the quantity of the second fibers in the fiber blend may also impact their ability to bundle with the first fibers. Of course, other factors could also contribute to the generation and/or control of the fiber bundles, such as processing conditions (e.g., the white water composition).

[00330] In a trial, the impact of varying the diameter and/or the concentration of the second fibers on bundle formation was investigated. In the trial, the bundles were formed by combining first fibers and second fibers during the dispersion step of a wet-laid process. While the properties of the first fibers (16 μm average fiber diameter and 35 mm average fiber length) remained the same across all four sample mats (i.e., Example 1, Example 2, Example 3, and Example 4), the properties of the second fibers were varied across the sample

mats. In particular, the second fibers of Example 1 were the inventive rotary fibers having an average fiber diameter of about 3.5 μm and a target (processed) length of about 3 mm, the second fibers of Example 2 were the inventive rotary fibers having an average fiber diameter of about 3.5 μm and a target (processed) length of about 3 mm, the second fibers of Example 3 were the inventive rotary fibers having an average fiber diameter of about 10 μm and a target (processed) length of about 6 mm, and the second fibers of Example 4 were commercially available rotary fibers having a target fiber diameter of about 3.0 μm and a target length of about 3 mm. Additionally, the mat of Example 1 was formed from 95 wt.% of its first fibers and 5 wt.% of its second fibers, based on the total weight of the fibers; the mat of Example 2 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers; the mat of Example 3 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers; and the mat of Example 4 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers.

[00331] For each sample mat (i.e., Example 1, Example 2, Example 3, and Example 4), the bundles were manually removed from the 12" x 12" sample mat, with the bundles then being counted and weighed, and also having their LOI (all based on the same modified UF resin) measured. The total weight of the bundles for each sample mat, relative to the total weight of the corresponding mat, is shown in the graph 1100 of FIG. 11. Based on this data, it was concluded that selecting second fibers with a smaller average fiber diameter results in a higher % of bundles. Likewise, it was concluded that using an increased amount of the second fibers results in a higher % of bundles.

[00332] Additionally, this data was evaluated to determine the impact of varying the diameter and/or the concentration of the second fibers on average bundle weight for each sample mat (i.e., Example 1, Example 2, Example 3, and Example 4). The average bundle weight in grams was calculated by dividing the total bundle weight for each sample mat by the count of bundles for that mat. The average bundle weight for each sample mat is shown in the graph 1200 of FIG. 12. It was confirmed that average bundle size (represented by its weight) varies with the diameter and the concentration of the second fibers.

[00333] The data was also evaluated to determine the impact of varying the diameter and/or the concentration of the second fibers on the number of bundles per square foot (ft^2) for each sample mat (i.e., Example 1, Example 2, Example 3, and Example 4). Since the size of each

sample mat was 12" x 12" (i.e., 1 ft^2), was simply the count of the bundles removed from each sample mat. Thus, the number of bundles per square foot for each sample mat is shown in the graph 1300 of FIG. 13. This data also supports the finding that as aspect ratios for the fiber blend get closer to (and go below) about 1,000, the number of bundles per ft^2 decreases.

[00334] When viewing the graphs 1200 and 1300 together, it was determined that increasing the concentration of the second fibers (see Example 1 and Example 2) or decreasing the average fiber diameter of the second fibers (see Example 3 and Example 4) would increase the number of bundles present in the sample, neither of these changes resulted in a change in the average weight of the bundles.

[00335] Additionally, this data was evaluated to determine the impact of varying the diameter and/or the concentration of the second fibers on the LOI of the bundles relative to the LOI of the overall mat for each sample mat (i.e., Example 1, Example 2, Example 3, and Example 4). In each instance, the LOI of the bundles (formed of the first fibers and the second fibers) was significantly less than the LOI of the overall mat (sample), as shown in the graph 1400 of FIG. 14 and the graph 1500 of FIG. 15. It was determined that the LOI of the bundles is independent of bundle size or bundle concentration when processed with a binder curtain. Thus, it was found that the bundles would allow for creation of glass rich/low LOI areas in the structured non-woven mat. See FIG. 15.

[00336] Based on the aforementioned trial, mechanisms for generating a structured non-woven mat with an approximate bundle density, distribution, and/or properties (e.g., bundle size) were discovered. The influence of the bundles on the properties of the structured non-woven mat were also observed. For example, as shown in the pair of graphs 1600 of FIG. 16, it was found that increasing the amount of the second fibers resulted in an increase in the entanglement with the first fibers and, thus, an increase in the total bundle content. To generate the data in the graphs 1600, images of structured mat samples were taken using a 4k resolution monochrome line-scan camera from Teledyne Dalsa and using a GigE standard for data and network communications. Pixel sizes were 150 μm in the cross and machine directions. The system utilizes off the shelf proprietary software for image collection, inspection, and storage from Active Inspection. For image processing and inspection, the product was backlit using a 240W 24" line light. The wattage output was adjustable through the system, to accommodate changes in mat basis weight and fiber composition. This was done to achieve the desired contrast between the dense strings and the less dense mat

background. Once the appropriate light settings were in place the image was binarized into "strings" and "not strings" to isolate and measure the string properties of interest. The density was measured as summing the identified bundle pixels in mm^2 within a standard 30 cm x 30 cm sheet. To achieve these measurements, at every identified "string" location within a 30 cm segment the width of the string was captured. The average of these widths was then taken and output in mm for that 1-foot segment. For string density, this was achieved by summing the number of string pixels within the standard 1-foot segment and calibrated to a standard of mm^2. String "length" is effectively the number of measured locations and can be derived from string density and width. Locations below a certain width measurement were not considered to filter out noise generated in the binarization process.

[00337] As also shown in FIG. 16, it was found that increasing the average fiber diameter of the second fibers decreased the aforementioned response to increases in second fiber concentration.

[00338] As another example, as shown in the pair of graphs 1700 of FIG. 17, it was found that increasing the average fiber length of the second fibers resulted in an increase in the entanglement with the first fibers and, thus, an increase in the total bundle content. As also shown in FIG. 17, it was found that increasing the average fiber length of the second fibers from a relatively short length (approximately 3 mm) to a relatively long length (approximately 18 mm) decreased the aforementioned response to increases in second fiber concentration.

[00339] As still another example, as shown in the graph 1800 of FIG. 18, it was found that the average fiber diameter of the second fibers (at a blend concentration of 5 wt.%) influenced string density in a non-linear manner, with a highest string density seen around an average fiber diameter of 3.5 μm, a lowest string density seen around an average fiber diameter of about 6.5 μm, and a string density somewhat in the middle for an average fiber diameter of about 10 μm. This same trend was observed when the blend concentration of the second fibers was increased to 10 wt.%.

[00340] As another example, as shown in the graph 1900 of FIG. 19A, it was found that increasing the concentration of the second fibers (average fiber diameter of about 3.5 μm) for certain lengths (e.g., 3 mm) decreased the caliper (thickness) of the structured non-woven mat. It was also found that the average (processed) fiber length of the second fibers

contributed to the thickness reduction of the mat (at a given concentration of the second fibers), with longer (approximately 9 mm) second fibers providing a greater thickness reduction than shorter (approximately 3 mm) second fibers, as can be seen in the graph 1900.

[00341] It was also found, as shown in the graph 1910 of FIG. 19B, that the thickness of the non-woven mat can be reduced by approximately 5% for every additional 5% to 8% of the second fibers that go into the mat, while normalizing for basis weight and binder concentration and maintaining the same composition of binder. The extent of thickness reduction is also dependent on the diameter of the second fibers, whereas the reduction in thickness is greatest at lower diameters of the second fibers (e.g., about 2 μm to about 6 μm).

[00342] As another example, as shown in the graph 2000 of FIG. 20, it was found that increasing the concentration of the second fibers (average fiber diameter of about 3.5 μm) decreased the air permeability of the structured non-woven mat.

[00343] In one exemplary embodiment, a structured non-woven mat is formed from a blend of first fibers and second fibers (microfibers), which are held together by a cured binder, including but not limited to urea-formaldehyde (UF) resin, acrylic emulsions, styrenic emulsions, polyvinyl alcohol, and combinations thereof, wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers, wherein a plurality of bundles are dispersed throughout the mat, and wherein an average diameter of the bundles is greater than the average fiber diameter of the first fibers and the average fiber diameter of the second fibers. In some exemplary embodiments, the mat includes at least about 150 bundles per square foot. In some exemplary embodiments, the mat includes at least about 300 bundles per square foot. In some exemplary embodiments, the mat includes at least about 450 bundles per square foot.

[00344] In some exemplary embodiments, the first fibers are non-rotary (e.g., WUCS) fibers. In some exemplary embodiments, the second fibers are rotary fibers (e.g., the inventive rotary fibers). In some exemplary embodiments, the first fibers are glass fibers. In some exemplary embodiments, the second fibers are glass fibers.

[00345] In some exemplary embodiments, the bundles constitute between about 5 wt.% to about 90 wt.% of the fiber in the structured non-woven mat.

[00346] In some exemplary embodiments, the bundles have a lower average binder content (LOI) than the average binder content (LOI) of the structured non-woven mat. In some exemplary embodiments, the average binder content of the bundles is at least 50% less than the average binder content of the mat. In some exemplary embodiments, the average binder content of the bundles is at least 66% less than the average binder content of the mat. In some exemplary embodiments, the average binder content of the bundles is at least 75% less than the average binder content of the mat.

[00347] In some exemplary embodiments, a majority of the bundles do not have a flat/planar first end or second end, wherein the first end and the second end define the length of the bundle.

[00348] In some exemplary embodiments, a majority of the bundles have a tapered/pointed first end and second end, wherein the first end and the second end define the length of the bundle.

[00349] In some exemplary embodiments, a majority of the bundles have a first end or second end that splits into multiple fiber strands, wherein the first end and the second end define the length of the bundle. In some exemplary embodiments, one or more split strands belonging to the end of a first bundle are connected to and form part of a second bundle.

[00350] In another exemplary embodiment, a structured non-woven mat is formed from a blend of first fibers and second fibers (microfibers), which are held together by a cured binder, wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers, wherein a plurality of bundles are dispersed throughout the mat, and wherein a thickness of the composite mat is less than a thickness of an equivalent weight mat formed solely from the first fibers or the second fibers, and the binder.

[00351] It was discovered that increasing the average fiber length of the second fibers contributes to producing a thinner structured non-woven mat.

[00352] It was discovered that increasing the concentration of the second fibers relative to the first fibers contributes to producing a thinner structured non-woven mat.

[00353] Non-limiting examples of binder systems include urea-formaldehyde (UF) resin, acrylic emulsions, styrenic emulsions, polyvinyl alcohol, and combinations thereof.

[00354] In some exemplary embodiments, the first fibers are non-rotary (e.g., WUCS) fibers. In some exemplary embodiments, the second fibers are rotary fibers (e.g., the inventive rotary fibers). In some exemplary embodiments, the first fibers are glass fibers. In some exemplary embodiments, the second fibers are glass fibers.

[00355] In some exemplary embodiments, the second fibers have an average (processed) length in the range of about 1 mm to about 25 mm.

[00356] In some exemplary embodiments, a combined aspect ratio of the first fibers and the second fibers is greater than 1,000.

[00357] In some exemplary embodiments, the structured non-woven mat has an area weight in the range of about 40 g/m^2 to about 500 g/m^2. In some exemplary embodiments, the structured non-woven mat has an area weight in the range of about 70 g/m^2 to about 250 g/m^2.

[00358] In some exemplary embodiments, the structured non-woven mat has an air porosity of in the range of about 850 m^3/h (about 500 cfm) to about 1,359 m^3/h (about 800 cfm.)

[00359] In some exemplary embodiments, the structured non-woven mat has an air porosity in the range of about 0.25 $(L/s/m_2)/(g/m_2)$ to about 0.40 $(L/s/m_2)/(g/m_2)$. See FIG. 20.

[00360] In some exemplary embodiments, the structured non-woven mat has a bundle concentration in the range of about 538 bundles/m^2 to about 8,608 bundles/m^2 (about 50 bundles/ft^2 to about 800 bundles/ft^2). In some exemplary embodiments, the structured non-woven mat has a bundle concentration in the range of about 1,076 bundles/m^2 to about 5,380 bundles/m^2 (about 100 bundles/ft^2 to about 500 bundles/ft^2). In some exemplary embodiments, the structured non-woven mat has a bundle concentration in the range of about 1,614 bundles/m^2 to about 4,303 bundles/m^2 (about 150 bundles/ft^2 to about 400 bundles/ft^2).

Exemplary Applications

[00361] There are numerous applications for a non-woven fibrous mat, particularly a structured non-woven mat, produced using the microfibers (e.g., the inventive rotary fibers) described herein. Advantageously, the structured non-woven mat can be produced with desired properties that are suited for its intended use.

[00362] In general, the structured non-woven mat may prove suitable as a replacement for a conventional non-woven fibrous mat, as well as for other reinforcing materials (e.g., a gun roving material), fibrous or otherwise, across a wide range of applications.

[00363] In some exemplary embodiments, the structured non-woven mat is impregnated with a mineral filled coating to form a facer material (e.g., a coated glass facer).

[00364] In some exemplary embodiments, the structured non-woven mat is embedded within a polymer matrix to form a glass-reinforced composite (e.g., a wind turbine blade).

[00365] In some exemplary embodiments, the structured non-woven mat is used in a traction-related product (e.g., slip-resistant flooring).

[00366] In some exemplary embodiments, the structured non-woven mat is used as a surface (e.g., wall) covering, with the bundles in the structured non-woven mat contributing to an aesthetic textured surface.

[00367] In some exemplary embodiments, the structured non-woven mat is used to form a surface conditioning material (e.g., sandpaper, grinding disc), wherein the bundles in the structured non-woven mat contribute to or otherwise support a roughened surface.

[00368] In some exemplary embodiments, the structured non-woven mat serves as the reinforcement/substrate (precursor mat) for a roofing shingle or membrane.

[00369] For purposes of further illustration only and not by way of limitation, possible benefits from the use of the structured non-woven mat (including bundles) as a substrate in a roofing product, such as a shingle or underlayment, will be described in more detail.

Coating Penetration Resistance

[00370] As an initial matter, a trial was conducted to assess the ability of the structured non-woven mat to allow sufficient impregnation of the mat with an asphaltic coating without allowing the asphaltic coating to penetrate all the way through the mat.

[00371] For the trial, several sample mats were produced using a blend of first fibers (average fiber diameter of 16 μm and average fiber length of 35 mm), second fibers (average fiber diameter of 3.5 μm and target fiber length in the range of 1 mm to 6 mm), and an acrylic modified UF resin binder. The sample mats differed from one another by the concentration of

the second fibers in the fiber blend, with the samples ranging from 0 wt.% of the second fibers to 25 wt.% of the second fibers, by total weight of the fibers. Each sample mat was single side (i.e., top side) coated with a mineral filled asphalt coating, followed by granule application to mimic an asphalt shingles. Thus, each sample mat was intended to represent a mock asphalt shingle.

[00372] A digital camera was used to image the back side of each shingle mimic, and the aforementioned ImageJ version 1.54f open-source software was used to measure the percentage of asphalt colored pixels as an approximation of the amount of the analyzed mat covered by the asphalt coating. A value of 100% would indicate full coverage of the mat fibers and only asphalt visible in the image.

[00373] With reference to the graph 2100 of FIG. 21, the concentration of the second fibers (x-axis) was plotted again the measured quantity (%) of the asphalt colored pixels (y-axis). From the graph 2100, it was concluded that increasing the concentration of the second fibers in the fiber blends used to form the sample mats led to a decrease in the amount of the asphalt coating able to penetrate through the mat. Thus, forming a structured non-woven mat to reduce the amount of coating the penetrates through the mat or to otherwise limit the depth that the coating penetrates provides many benefits. For example, such a structured mat would enable the use of different top and bottom coating formulations that could be applied to the mat without substantially mixing with one another. As another example, such a structured mat could enable the exclusion of any back coating and, thus, elimination of the requirement for back dust, thereby decreasing the overall weight of the shingle.

Gurley Stiffness

[00374] Another trial was conducted to assess the stiffness of the four example structured mats. The stiffness is important to wall products (e.g., house wrap, wallpaper) and roofing products (shingles, membranes, underlayments) that are required to bend into/around corners and valleys or over hips and ridges. For rolled products that are required to lay flat when installed, a lower stiffness value is preferred to reduce roll memory, which is the tendency of a rolled material to want to retain its curved shape. While the properties of the first fibers (16 μm average fiber diameter and 35 mm average fiber length) remained the same across all four sample mats (i.e., Example 1, Example 2, Example 3, and Example 4), the properties of the second fibers were varied across the sample mats. In particular, the second fibers of Example

1 were the inventive rotary fibers having an average fiber diameter of about 3.5 μm and a target (processed) length of about 3 mm, the second fibers of Example 2 were the inventive rotary fibers having an average fiber diameter of about 3.5 μm and a target (processed) length of about 3 mm, the second fibers of Example 3 were the inventive rotary fibers having an average fiber diameter of about 10 μm and a target (processed) length of about 6 mm, and the second fibers of Example 4 were commercially available rotary fibers having a target fiber diameter of about 3.0 μm and a target length of about 3 mm. Additionally, the mat of Example 1 was formed from 95 wt.% of its first fibers and 5 wt.% of its second fibers, based on the total weight of the fibers; the mat of Example 2 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers; the mat of Example 3 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers; and the mat of Example 4 was formed from 90 wt.% of its first fibers and 10 wt.% of its second fibers, based on the total weight of the fibers.

[00375] In the trial, a stiffness of each structured mat (i.e., Example 1, Example 2, Example 3, and Example 4) was measured, in accordance with the TAPPI T 543 om-22 standard test method for determining bending resistance of paper (Gurley-type tester), which is used to measure the stiffness of a non-woven material, to generate the stiffness measurements (mg) normalized for the basis weight of each corresponding sample, as shown in the graph 2200 of FIG. 22. From these measurements, it was observed that the inventive structured mats (i.e., Example 1, Example 2, Example 3, and Example 4) each has a reduced stiffness as compared to a similar mat made solely from the first fibers and having the same basis weight. Thus, roofing products (e.g., shingles, underlayment) made using the inventive structured mats would more easily adapt to non-planar and/or complex surfaces.

Improved Traction

[00376] It was also found that the structured non-woven mat, having bundles contained within the thickness of the mat, could provide a material with improved traction (e.g., walkability). The presence of the bundles of fibers provides a mat that has non-uniform compressive resistance across its area (through its thickness). Where bundles overlap with one another, a high concentration of glass provides a localized region of higher compressive strength, while the surrounding area has less glass (i.e., fiber) and therefore is more compressive. This is illustrated generally in the pair of diagrams 2300 (side view and top plan view) shown in Figure 23. When walking on such a surface, the high compressive regions

will act like ridges as the areas around them compress and provide a walking surface with higher traction than a uniform mat (e.g., a conventional non-woven mat).

[00377] Similarly, when at least some of the bundles of fibers are raised or otherwise extend above a surface of the structured non-woven mat, as shown generally in the diagram 2400 (side view) of Figure 24, the bundles create a more textured surface (e.g., less smooth surface) than a conventional non-woven mat's more uniform surface. In this manner, traction (e.g., walkability) can be improved through physical interaction with the exposed bundles. In some exemplary embodiments, a coating can be applied to the surface to bind the bundles into place and/or add additional traction enhancing properties.

Cutting/Tear Resistance and Strength

[00378] The presence of the bundles of fibers in the structured non-woven mat can also be used to enhance or better control the cutting/tear resistance and strength of a product incorporating the mat. In particular, when cutting or tearing through the mat, the bundles of fiber create localized areas of increased resistance due to the size/density of the bundle compared to the surrounding area without the bundles of fiber. Increased resistance to tear is important for many applications, such as roofing, flooring, and wall coverings. When the tear path runs parallel to a bundle, the length of the bundle being longer than the fibers that make up the bundle increases the total tear length and, therefore, the amount of energy (force) needed to tear through the material, as shown in the pair of diagrams 2500 of FIG. 25.

Nail/Staple Pull Through Performance

[00379] The presence of the bundles of fibers in the structured non-woven mat can also be used to enhance or better control the pull through resistance of fasteners (e.g., nails used to fasten shingles to a roof) due to the high fiber count and localized high density provided by the bundles, as shown in the diagram 2600 of FIG. 26. Controlling the concentration and size of the bundles in combination with the area weight and LOI of the mat results in a product (e.g., shingle) with improved fastener pull through performance. When combined with a coating/impregnation such as asphalt or an organic polymer based formulation, the bundles further improve the nail/staple pull through performance as they are better incorporated into the composite.

Impact Resistance

[00380] The presence of the bundles of fibers in the structured non-woven mat can also be used to enhance or better control the impact resistance of products (e.g., shingles) by providing localized reinforcement with the relatively long bundles that are hard to break. When incorporated into a composite product, such as a shingle, coated/impregnated mat, or glass fiber reinforced plastic (GFRP), the bundles impart increased impact performance as compared to a similar mat of the same base fiber without bundles.

[00381] The examples provided above are merely intended to illustrate the increased design flexibility and potential performance improvements afforded by using the inventive structured non-woven mat in a product, such as a roofing shingle.

[00382] In some embodiments, it may be possible to utilize the various inventive concepts in combination with one another. Additionally, any particular element recited as relating to a particularly disclosed embodiment should be interpreted as available for use with all disclosed embodiments, unless incorporation of the particular element would be contradictory to the express terms of the embodiment. The scope of the general inventive concepts presented herein are not intended to be limited to the particular exemplary embodiments shown and described herein. From the disclosure given, those skilled in the art will not only understand the general inventive concepts and their attendant advantages, but will also find apparent various changes and modifications thereto. For example, notwithstanding the illustrative embodiments often disclosing the use of glass fibers, the general inventive concepts may encompass fibers made of materials other than glass, such as mineral wool or stone wool. It is sought, therefore, to cover all such changes and modifications as fall within the spirit and scope of the general inventive concepts, as described and/or claimed herein, and any equivalents thereof.

CLAIMS

What is claimed is:

1. A structured non-woven mat comprising:

a plurality of first fibers;

a plurality of second fibers;

a plurality of bundles formed from the first fibers and the second fibers; and

a binder holding the first fibers, the second fibers, and the bundles together in an interspersed arrangement;

wherein an average fiber diameter of the first fibers is greater than an average fiber diameter of the second fibers,

wherein an average diameter of the bundles is greater than the average fiber diameter of the first fibers and the average fiber diameter of the second fibers;

wherein a portion of the first fibers is not present in any of the bundles; and

wherein a portion of the second fibers is not present in any of the bundles.

2. The structured non-woven mat of claim 1, wherein the mat includes at least about 150 bundles per square foot.

3. The structured non-woven mat of claim 1, wherein the mat includes at least about 300 bundles per square foot.

4. The structured non-woven mat of claim 1, wherein the mat includes at least about 450 bundles per square foot.

5. The structured non-woven mat of any of claims 1-4, wherein the first fibers are non-rotary fibers.

6. The structured non-woven mat of any of claims 1-5, wherein the second fibers are rotary fibers.

7. The structured non-woven mat of claim 6, wherein the second fibers have a mean fiber diameter x that is less than about 4 μm; and

wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 3.5 μm.

8. The structured non-woven mat of claim 6, wherein the second fibers have a mean fiber diameter x that is less than about 4 μm; and

wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 3.0 μm.

9. The structured non-woven mat of claim 6, wherein the second fibers have a mean fiber diameter x that is less than about 4 μm; and

wherein a fiber diameter distribution of the second fibers has a standard deviation from x of less than 2.5 μm.

10. The structured non-woven mat of any of claims 1-9, wherein the first fibers are glass fibers.

11. The structured non-woven mat of any of claims 1-10, wherein the second fibers are glass fibers.

12. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is about 1.1 to about 6 times greater than the average fiber diameter of the second fibers.

13. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and

wherein the average fiber diameter of the second fibers is at least 1 μm less than the average fiber diameter of the first fibers.

14. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and

wherein the average fiber diameter of the second fibers is at least 3 μm less than the average fiber diameter of the first fibers.

15. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and

wherein the average fiber diameter of the second fibers is at least 5 μm less than the average fiber diameter of the first fibers.

16. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and

wherein the average fiber diameter of the second fibers is at least 7 μm less than the average fiber diameter of the first fibers.

17. The structured non-woven mat of any of claims 1-11, wherein the average fiber diameter of the first fibers is in the range of about 11 μm to about 23 μm, and

wherein the average fiber diameter of the second fibers is at least 10 μm less than the average fiber diameter of the first fibers.

18. The structured non-woven mat of any of claims 1-17, wherein an average fiber length of the first fibers is greater than an average fiber length of the second fibers.

19. The structured non-woven mat of any of claims 1-18, wherein an average length of the bundles is greater than the average fiber length of the first fibers and the average fiber length of the second fibers.

20. The structured non-woven mat of any of claims 1-19, wherein an average aspect ratio of the first fibers is greater than an average aspect ratio of the second fibers.

21. The structured non-woven mat of any of claims 1-20, wherein an average aspect ratio of the first fibers is greater than about 1,200.

22. The structured non-woven mat of any of claims 1-21, wherein a combined average aspect ratio of the first fibers and the second fibers is greater than about 1,000.

23. The structured non-woven mat of any of claims 1-22, wherein an average curvature of the first fibers is less than an average curvature of the second fibers.

24. The structured non-woven mat of any of claims 1-23, wherein the mat comprises about 50 wt.% to about 99 wt.% of the first fibers, based on the total weight of the first fibers and the second fibers.

25. The structured non-woven mat of any of claims 1-24, wherein the mat comprises about 1 wt.% to about 50 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers.

26. The structured non-woven mat of any of claims 1-24, wherein the mat comprises about 1 wt.% to about 25 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers.

27. The structured non-woven mat of any of claims 1-24, wherein the mat comprises about 1 wt.% to about 15 wt.% of the second fibers, based on the total weight of the first fibers and the second fibers.

28. The structured non-woven mat of any of claims 1-27, wherein the bundles comprise more of the first fibers than the second fibers.

29. The structured non-woven mat of any of claims 1-28, wherein the bundles constitute between about 5 wt.% to about 90 wt.% of a total fiber content of the mat.

30. The structured non-woven mat of any of claims 1-29, wherein an average diameter of the bundles is at least 5 times greater than an average diameter of the first fibers.

31. The structured non-woven mat of any of claims 1-30, wherein an average binder content of the bundles is less than an average binder content of the mat.

32. The structured non-woven mat of any of claims 1-31, wherein the average binder content of the bundles is at least 50% less than the average binder content of the mat.

33. The structured non-woven mat of any of claims 1-31, wherein the average binder content of the bundles is at least 66% less than the average binder content of the mat.

34. The structured non-woven mat of any of claims 1-31, wherein the average binder content of the bundles is at least 75% less than the average binder content of the mat.

35. The structured non-woven mat of any of claims 1-34, wherein each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and

wherein a majority of the first ends and the second ends have a non-planar shape.

36. The structured non-woven mat of any of claims 1-34, wherein each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and

wherein a majority of the first ends and the second ends have a tapered shape.

37. The structured non-woven mat of any of claims 1-34, wherein each of the bundles has a first end and a second end, with a length of the bundle extending between the first end and the second end, and

wherein a majority of the first ends and the second ends are split into a plurality of separated strands.

38. The structured non-woven mat of claim 37, wherein at least one of the strands at a first end or a second end of a first bundle is entangled with at least one of the strands at a first end or a second end of a second bundle.

39. The structured non-woven mat of any of claims 1-38, wherein a thickness of the mat is less than a thickness of a similar mat formed without any of the bundles.

40. The structured non-woven mat of any of claims 1-39, wherein an average fiber length of the second fibers is in the range of about 1 mm to about 25 mm.

41. The structured non-woven mat of any of claims 1-40, wherein a ratio of the first fibers to the second fibers is in the range of about 3:1 to about 99.5:1, by total weight of the fibers.

42. The structured non-woven mat of any of claims 1-41, wherein the mat has an area weight in the range of about 40 g/m^2 to about 500 g/m^2.

43. The structured non-woven mat of any of claims 1-41, wherein the mat has an area weight in the range of about 50 g/m^2 to about 250 g/m^2.

44. The structured non-woven mat of any of claims 1-43, wherein the mat has an air porosity in the range of about 850 m^3/h (about 500 cfm) to about 1,359 m^3/h (about 800 cfm).

45. The structured non-woven mat of any of claims 1-44, wherein the mat has a bundle concentration in the range of about 538 bundles/m^2 to about 8,608 bundles/m^2 (about 50 bundles/ft^2 to about 800 bundles/ft^2).

46. The structured non-woven mat of any of claims 1-44, wherein the mat has a bundle concentration in the range of about 1,076 bundles/m^2 to about 5,380 bundles/m^2 (about 100 bundles/ft^2 to about 500 bundles/ft^2).

47. The structured non-woven mat of any of claims 1-44, wherein the mat has a bundle concentration in the range of about 1,614 bundles/m^2 to about 4,303 bundles/m^2 (about 150 bundles/ft^2 to about 400 bundles/ft^2).

48. A shingle comprising the structured non-woven mat of any of claims 1-47.

49. An underlayment comprising the structured non-woven mat of any of claims 1-47.

50. A polymeric membrane comprising the structured non-woven mat of any of claims 1-47.

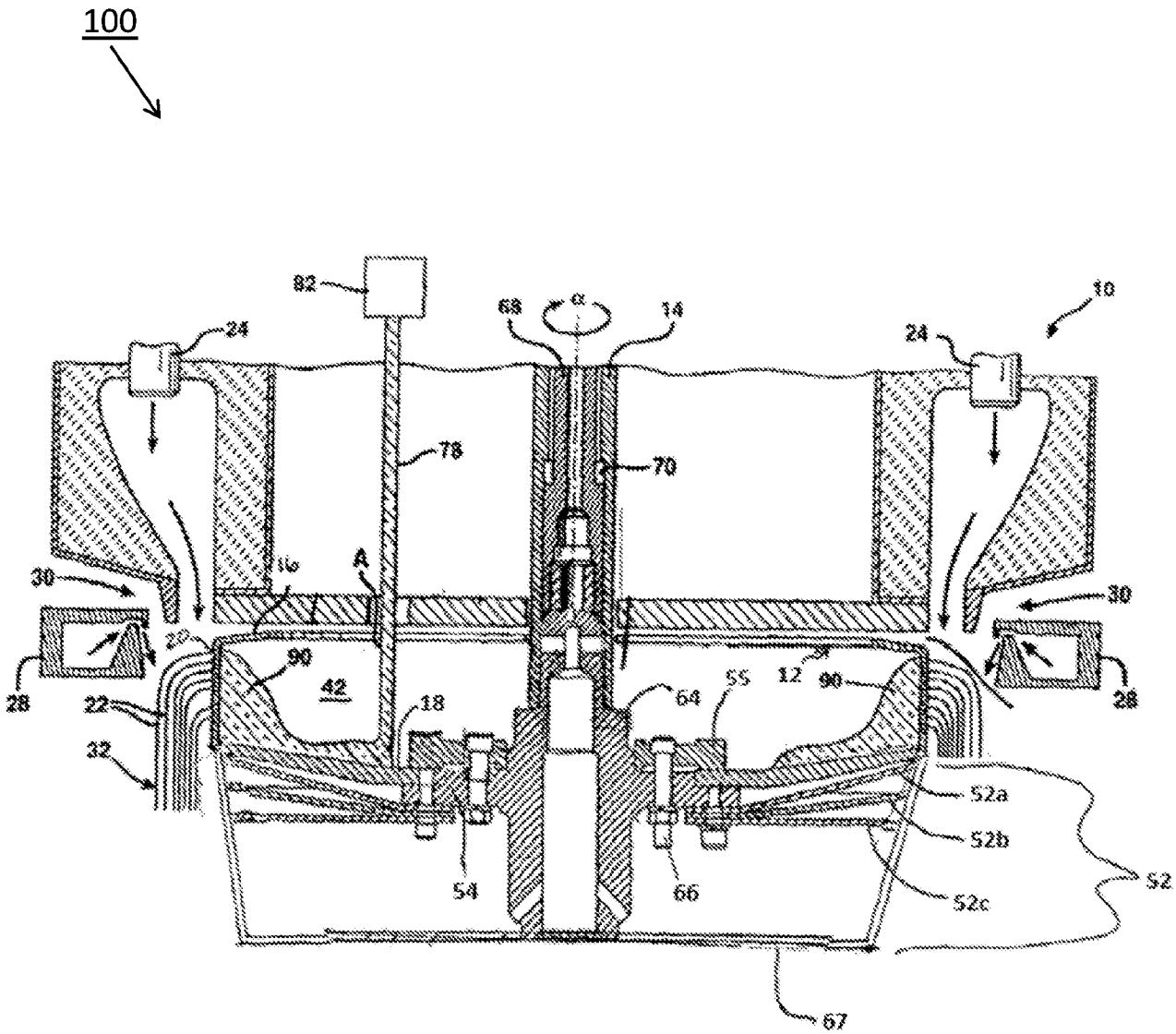


FIG. 1

PRIOR ART

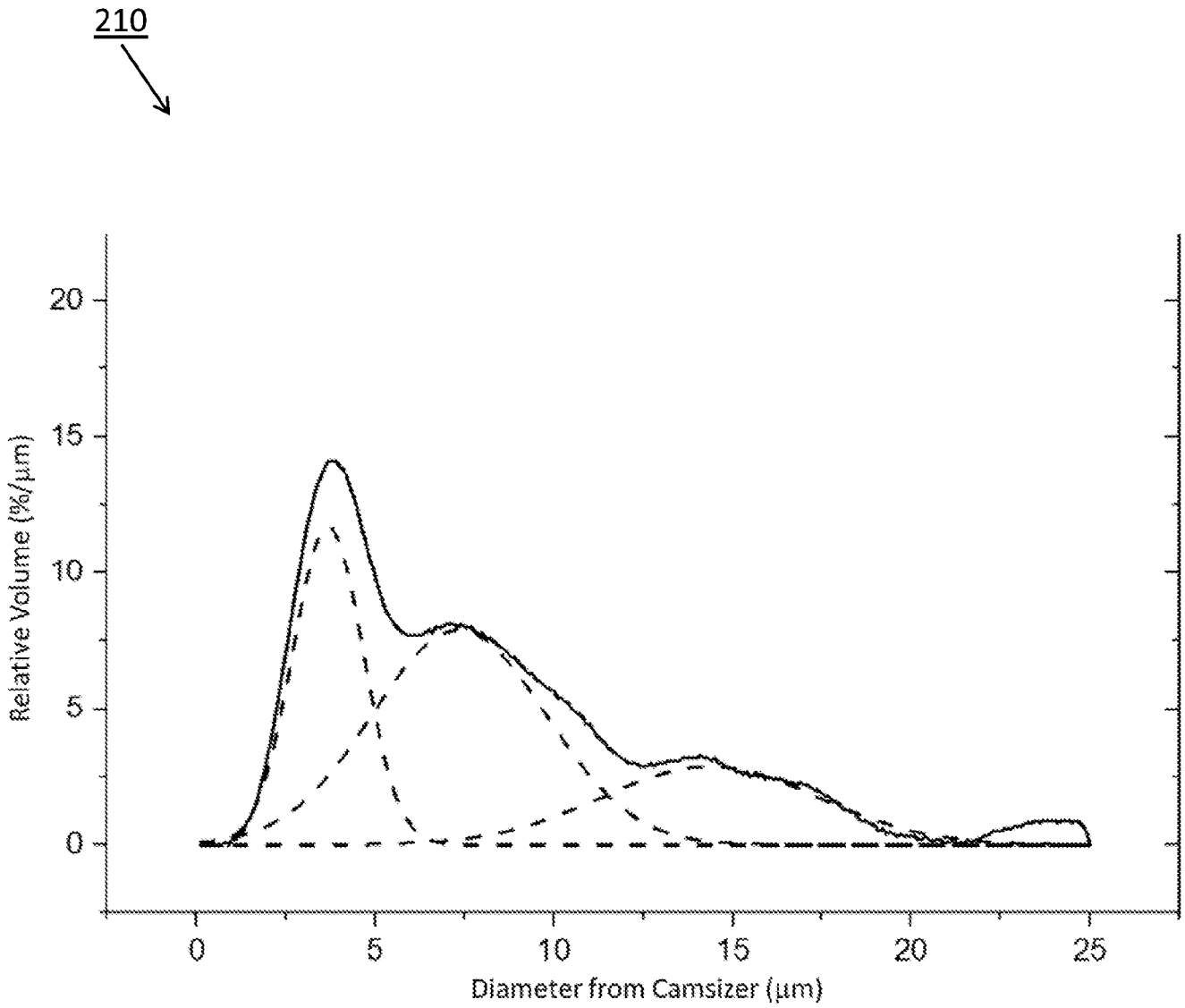


FIG. 2A
PRIOR ART

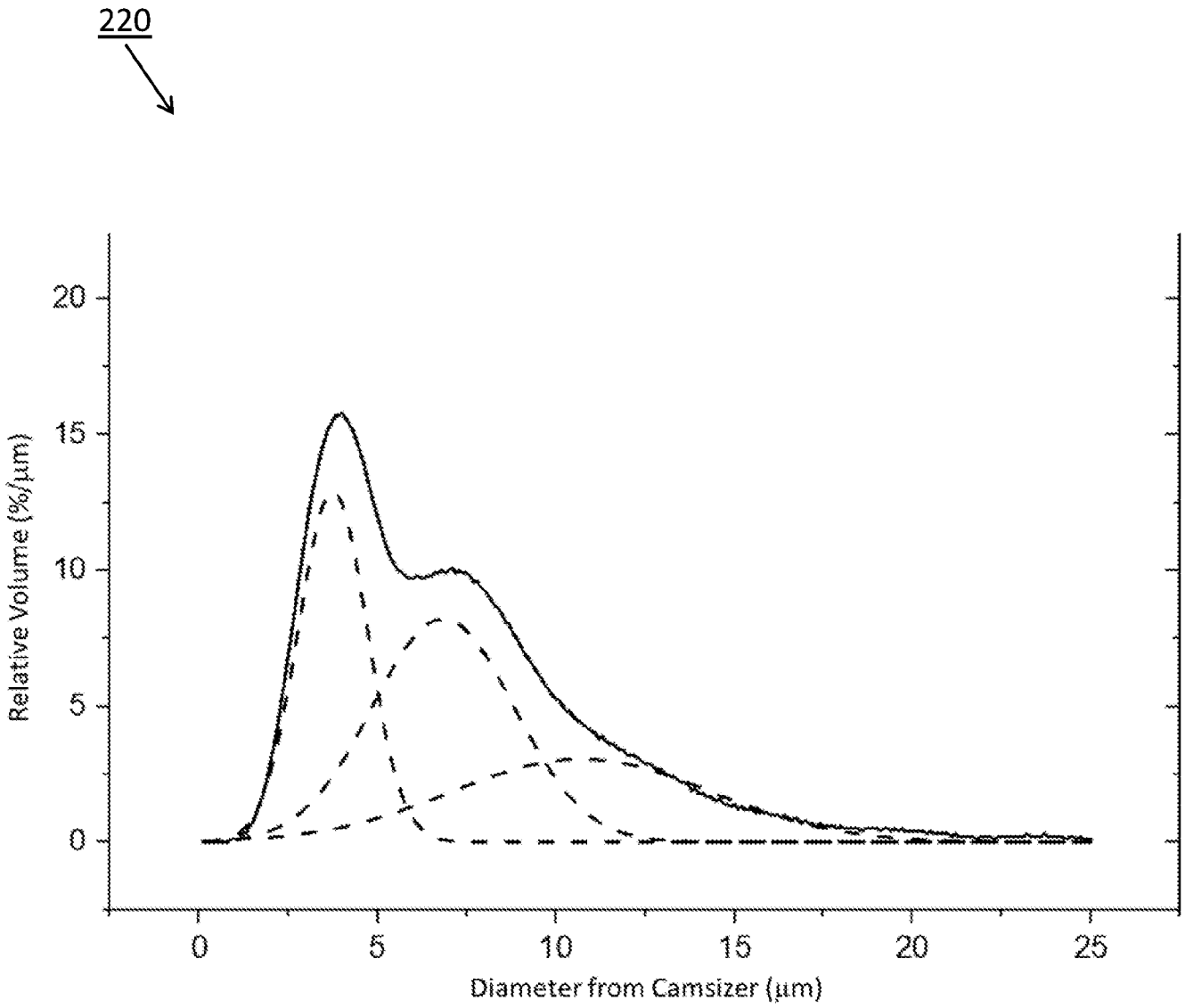


FIG. 2B

PRIOR ART

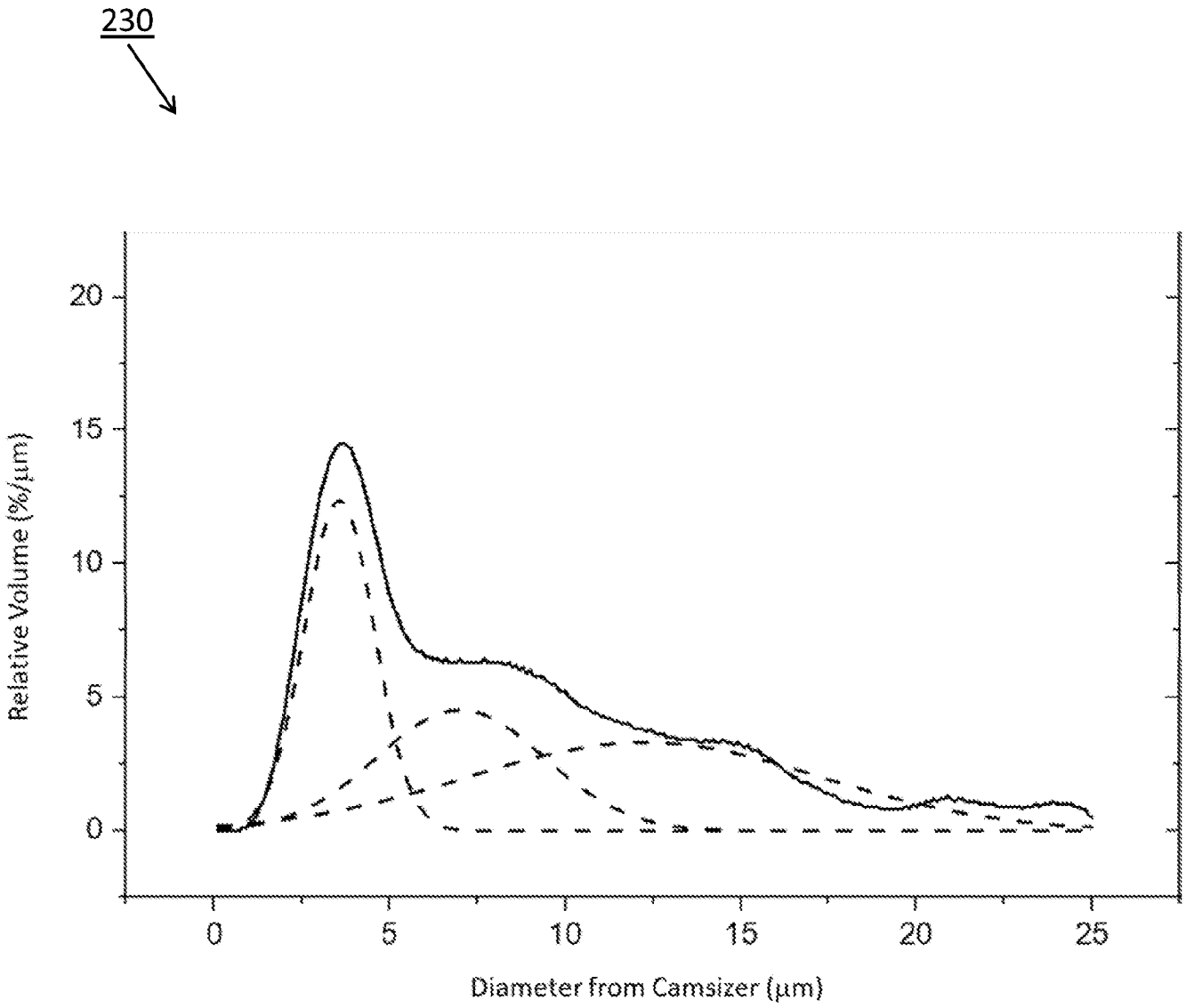


FIG. 2C
PRIOR ART

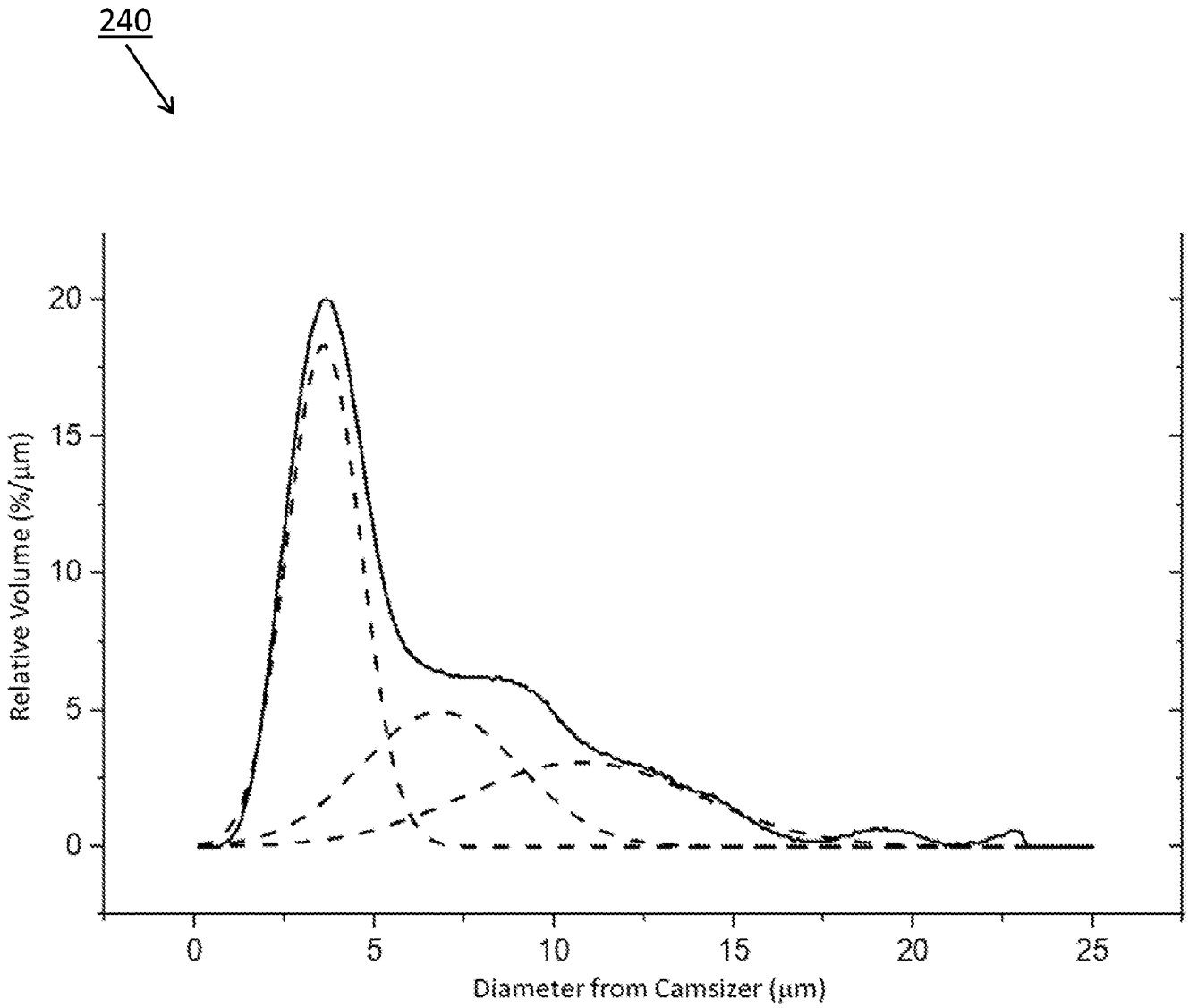


FIG. 2D

PRIOR ART

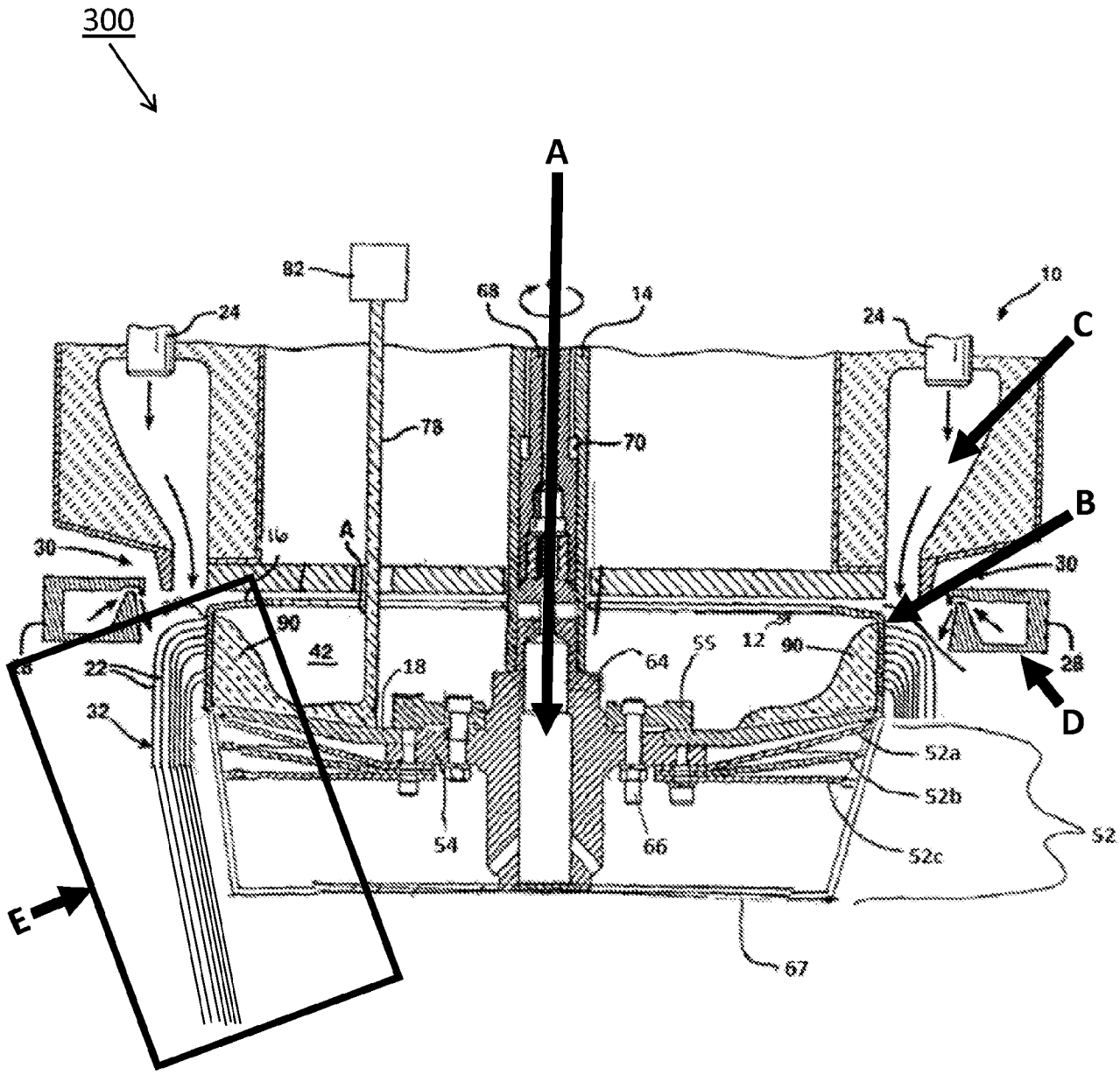

300
A
B
C
D
E
82
68
14
10
24
24
78
70
30
16
A
30
90
42
22
18
64
55
12
90
28
32
52a
52b
52c
52
54
66
67

FIG. 3

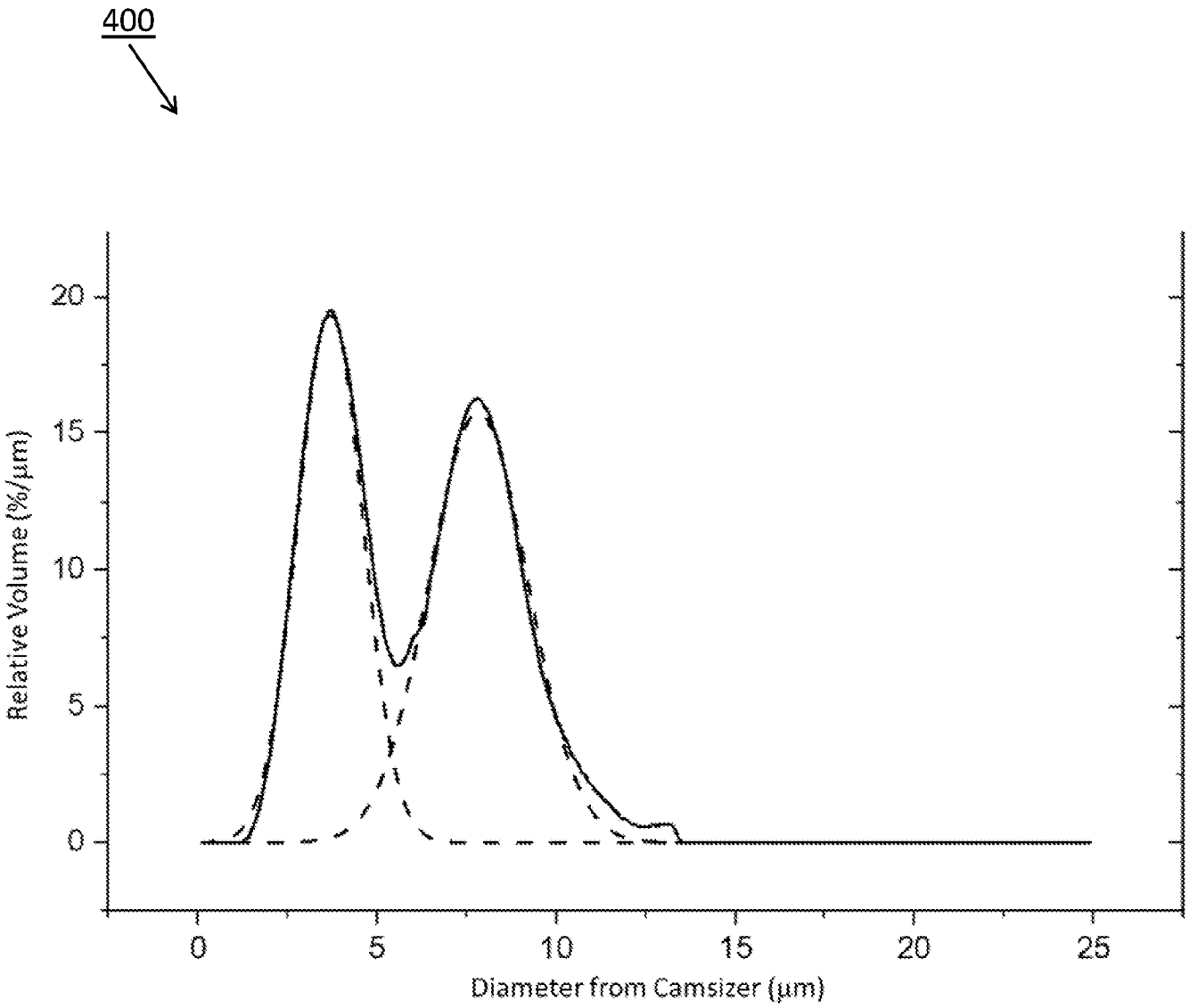
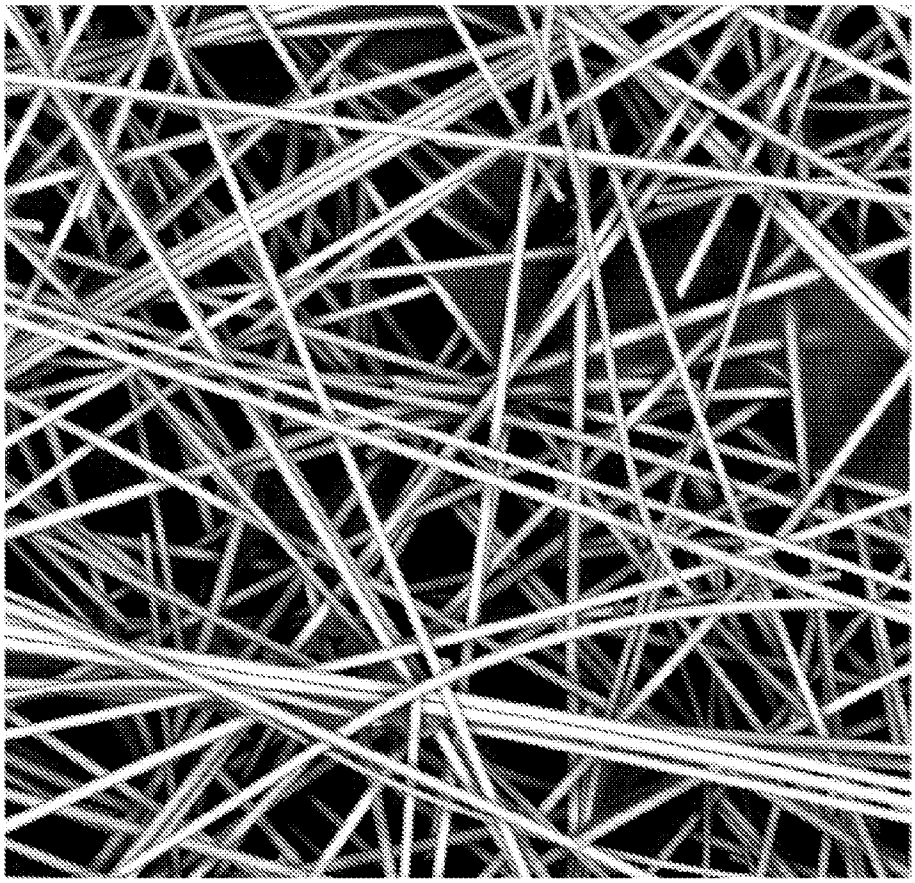

400
Relative Volume (%/µm)
20
15
10
5
0
0
5
10
15
20
25
Diameter from Camsizer (µm)

FIG. 4

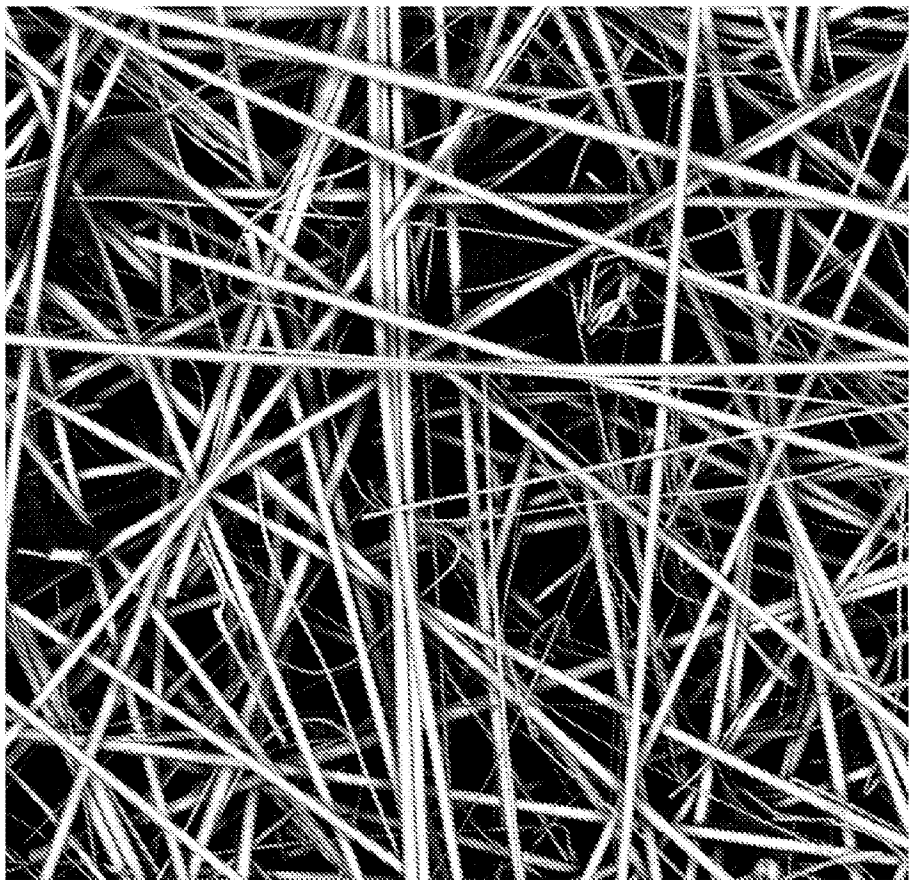
500



	Fiber 1	Fiber 2
	WUCS	WUCS
Target Diameter (μm)	11	6.5
Processed Length (mm)	6	6
Fiber Concentration	85%	15%
Fiber Curvature (μm^{-1})		0.004

FIG. 5A

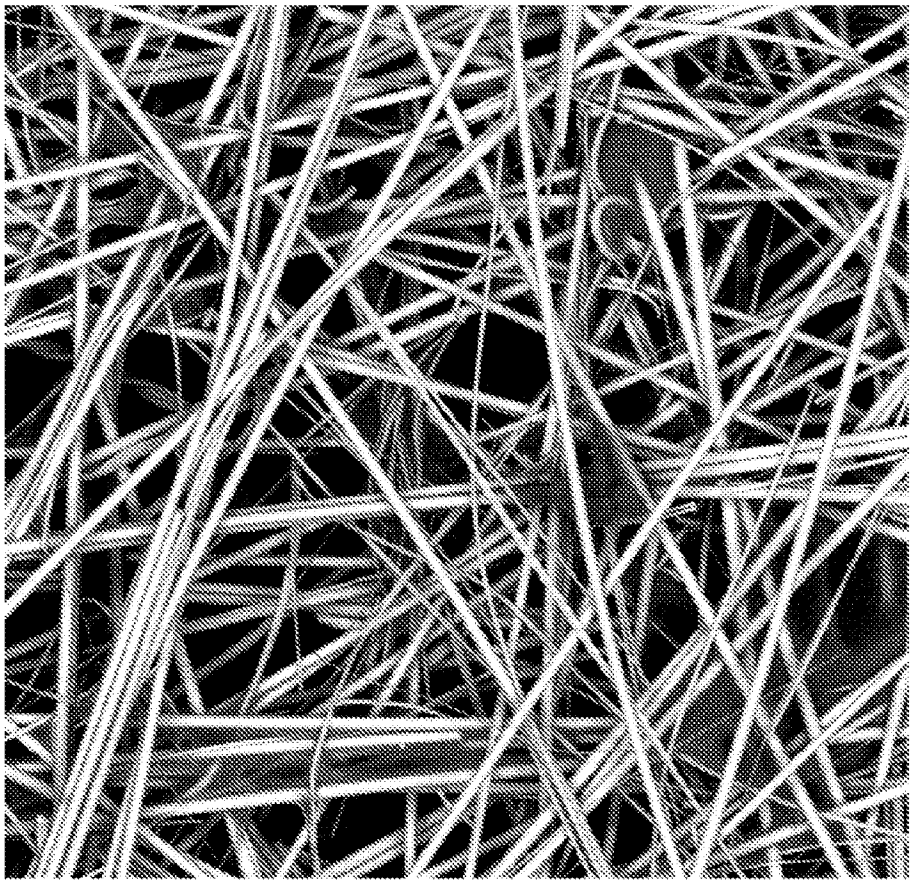
502



	Fiber 1	Fiber 2
	WUCS	ULF
Target Diameter (um)	11	2.8-3
Processed Length (mm)	6	1-6
Fiber Concentration	85%	15%
Fiber Curvature (μm^{-1})		0.043

FIG. 5B

504



	Fiber 1	Fiber 2
	WUCS	Inventive Rotary Fibers
Target Diameter (μm)	11	3.5
Processed Length (mm)	6	1-6
Fiber Concentration	85%	15%
Fiber Curvature (μm^{-1})		0.055

FIG. 5C

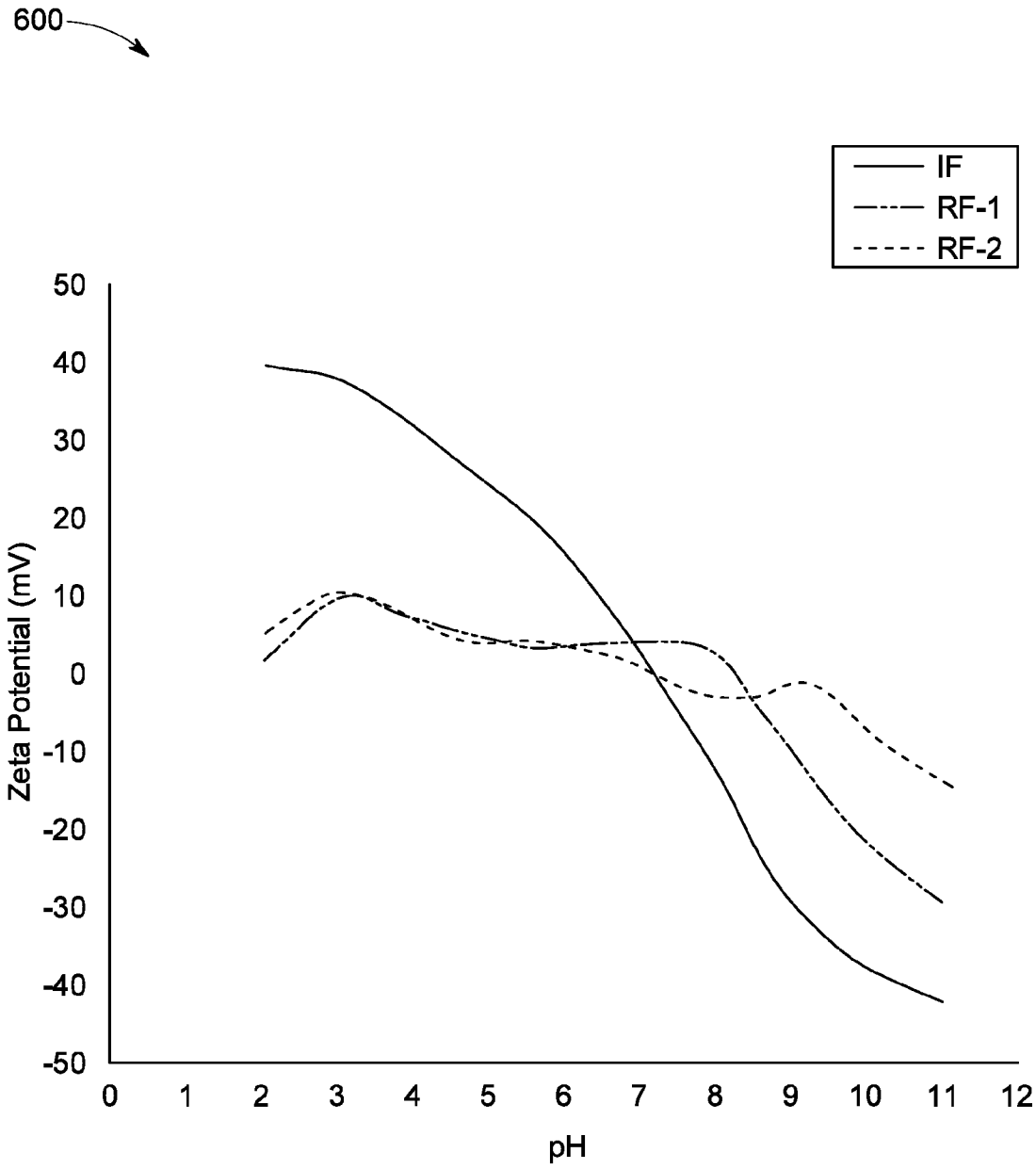

600
IF
RF-1
RF-2
Zeta Potential (mV)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
1
2
3
4
5
6
7
8
9
10
11
12
pH

FIG. 6

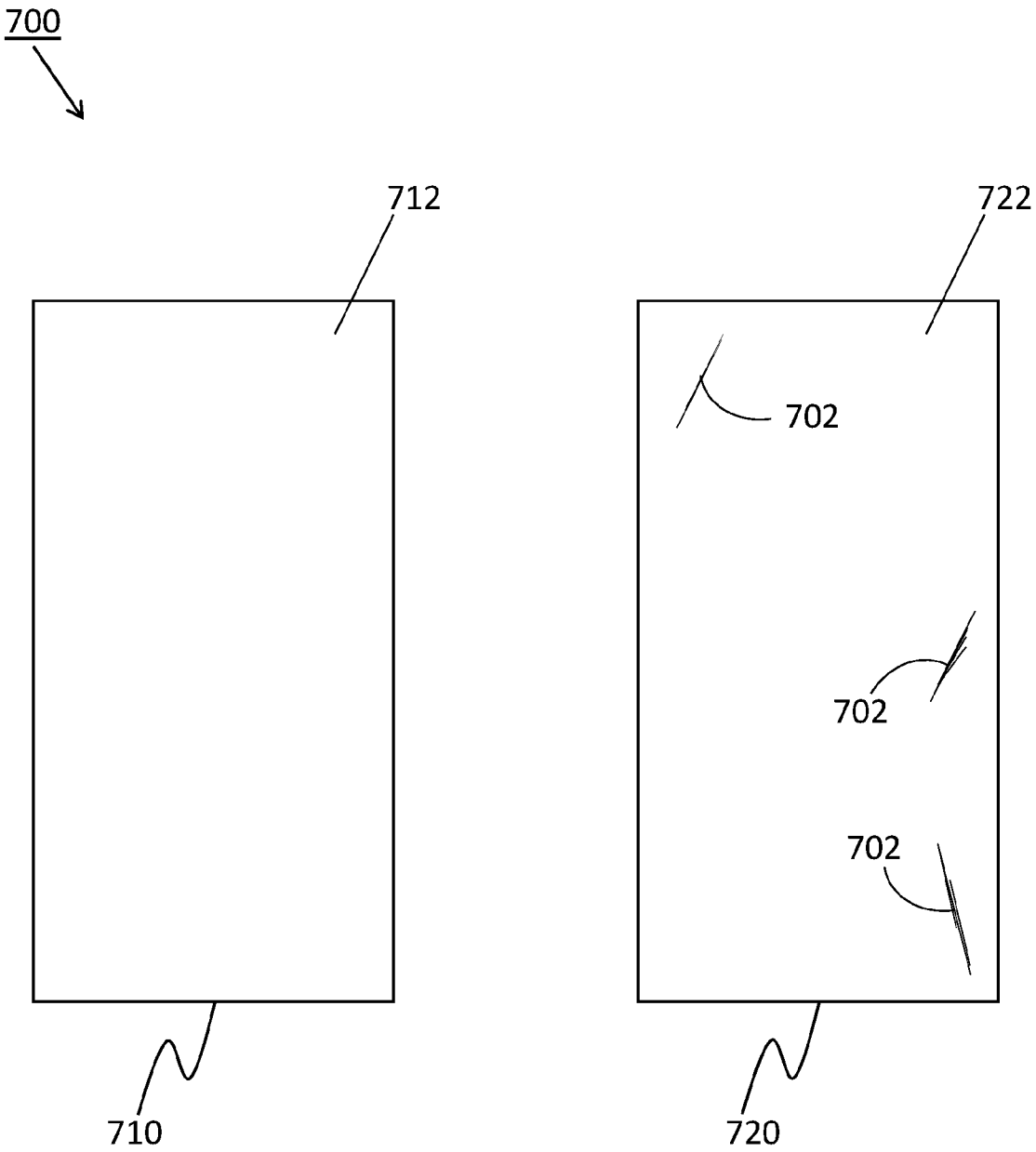


FIG. 7

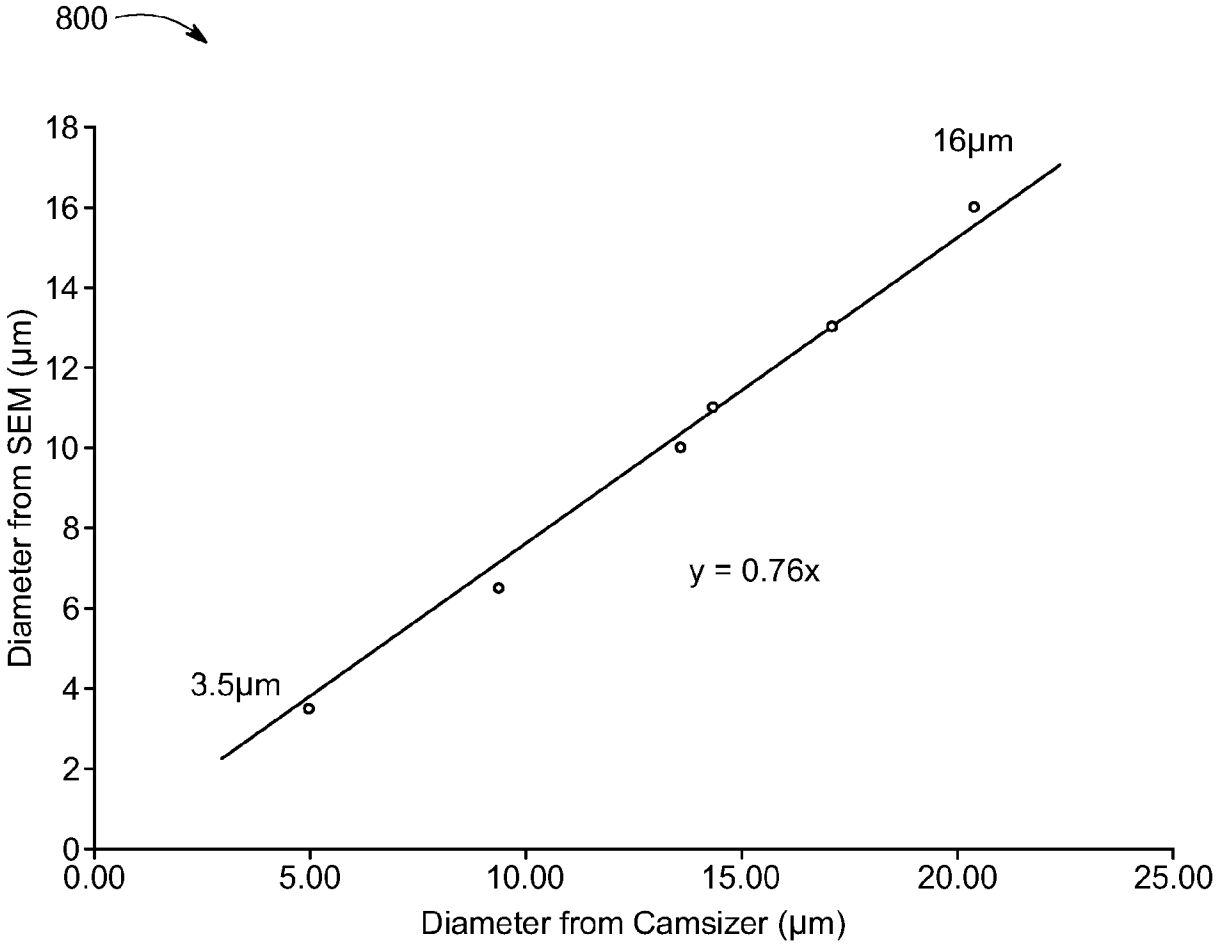

800
18
16
14
12
10
8
6
4
2
0
Diameter from SEM (µm)
16µm
y = 0.76x
3.5µm
0.00
5.00
10.00
15.00
20.00
25.00
Diameter from Camsizer (µm)

FIG. 8

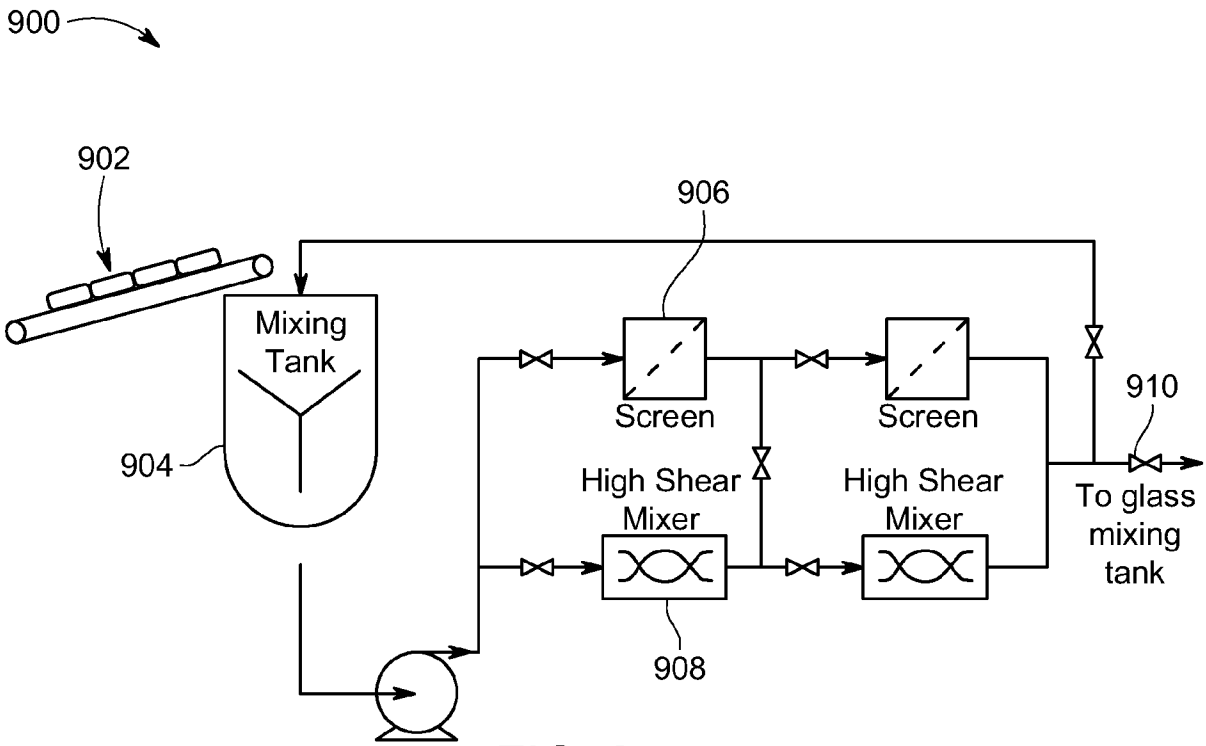

900
902
906
Mixing Tank
904
Screen
Screen
910
High Shear Mixer
High Shear Mixer
To glass mixing tank
908

FIG. 9

1000

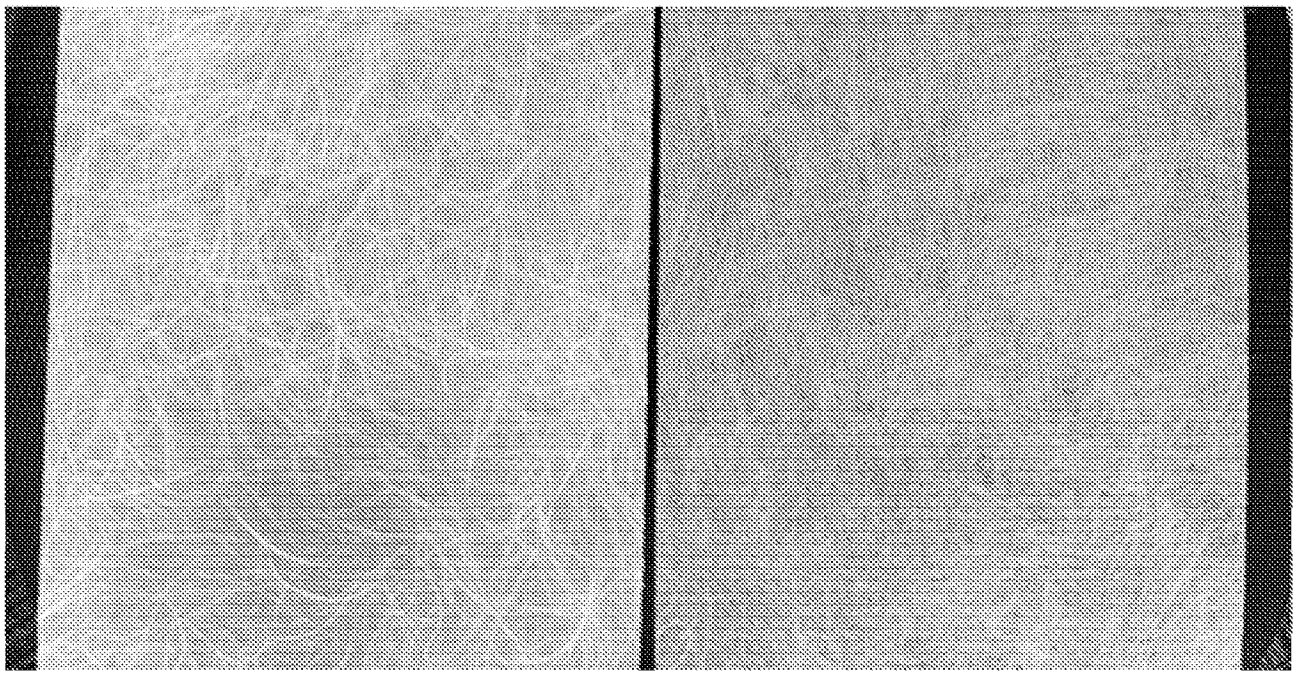


FIG. 10A

1010

FIG. 10B

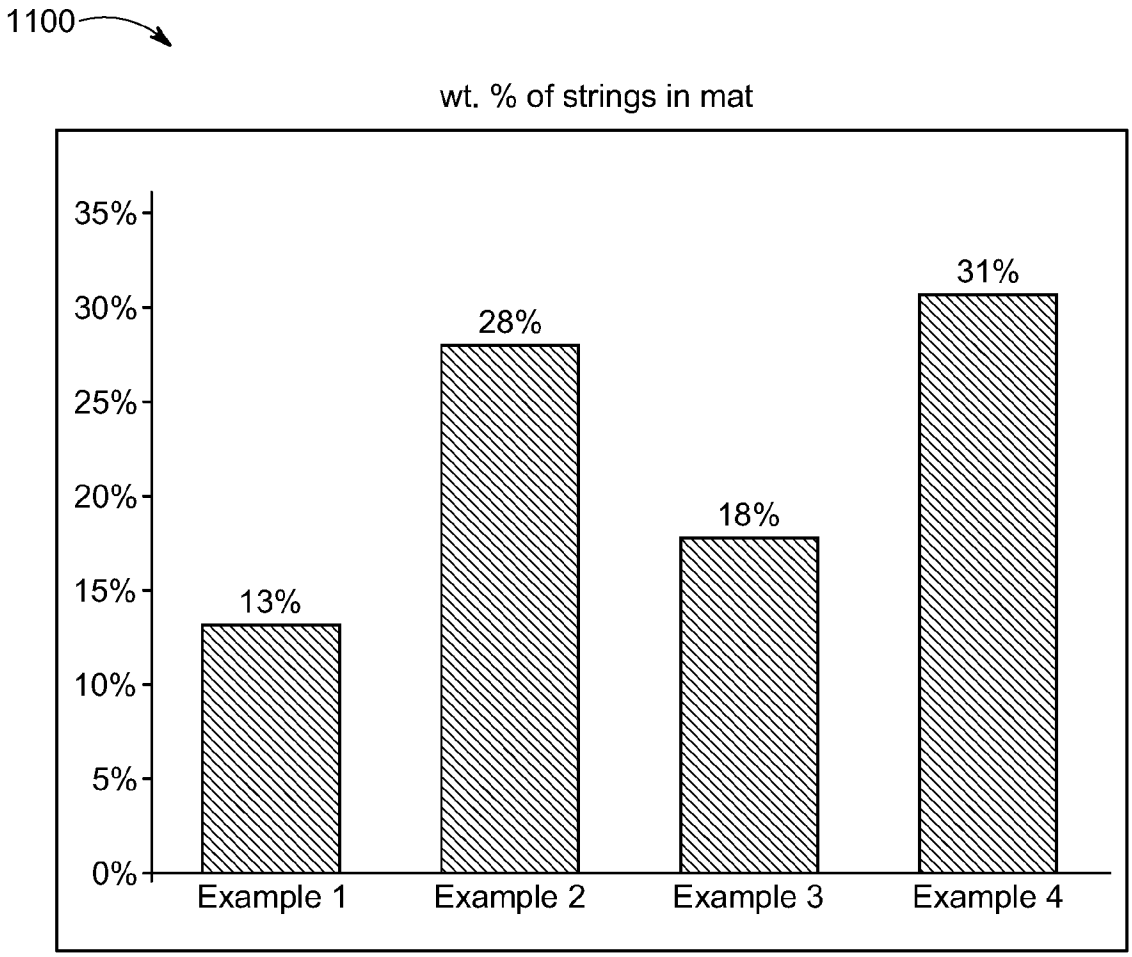

1100
wt. % of strings in mat
35%
30%
25%
20%
15%
10%
5%
0%
13%
28%
18%
31%
Example 1
Example 2
Example 3
Example 4

FIG. 11

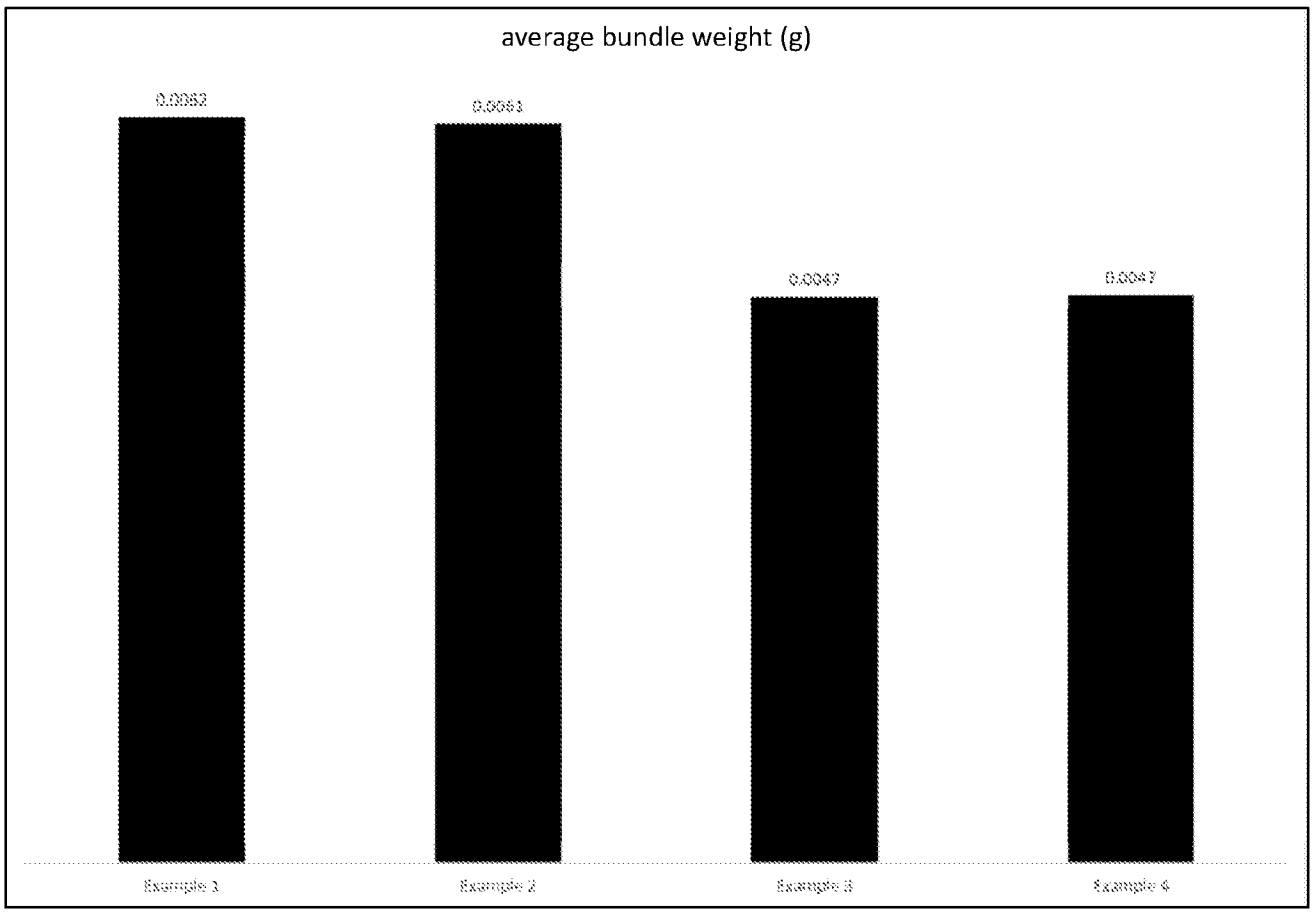

1200
average bundle weight (g)
0.0062
0.0061
0.0049
0.0047
Example 1
Example 2
Example 3
Example 4

FIG. 12

1300

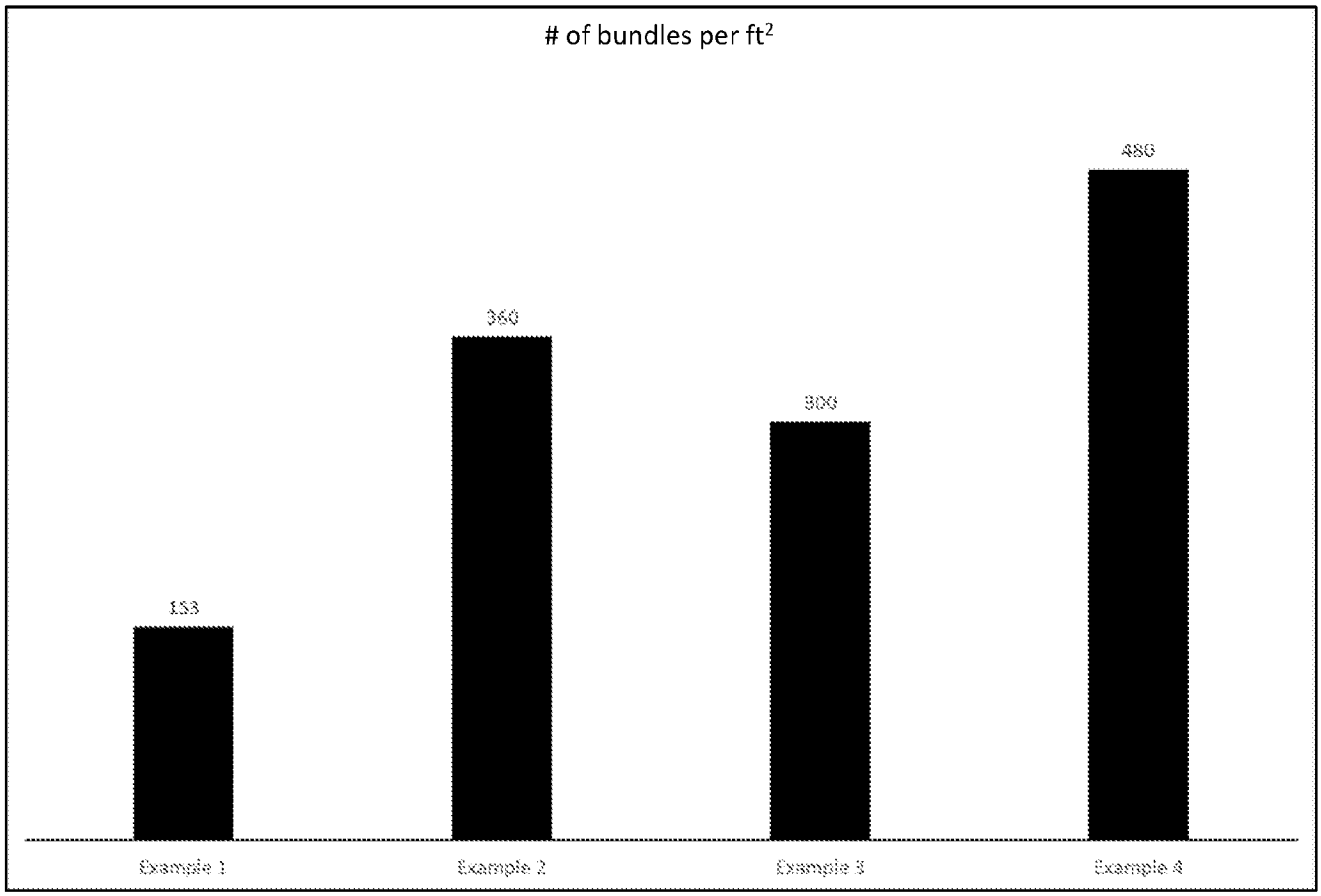

# of bundles per ft²
480
360
300
133
Example 1
Example 2
Example 3
Example 4

FIG. 13

1400

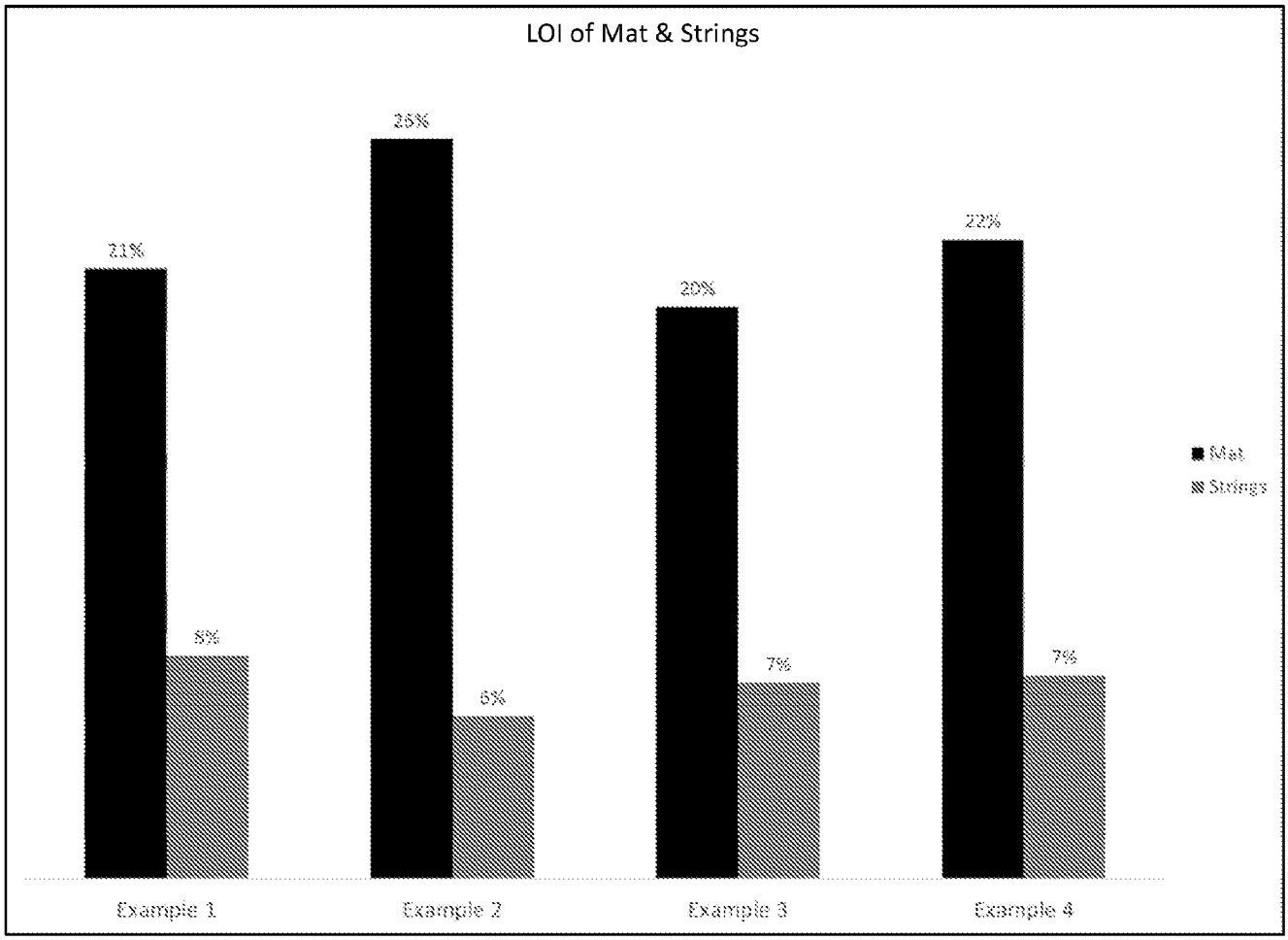

LOI of Mat & Strings
21%
8%
26%
6%
20%
7%
22%
7%
Mat
Strings
Example 1
Example 2
Example 3
Example 4

FIG. 14

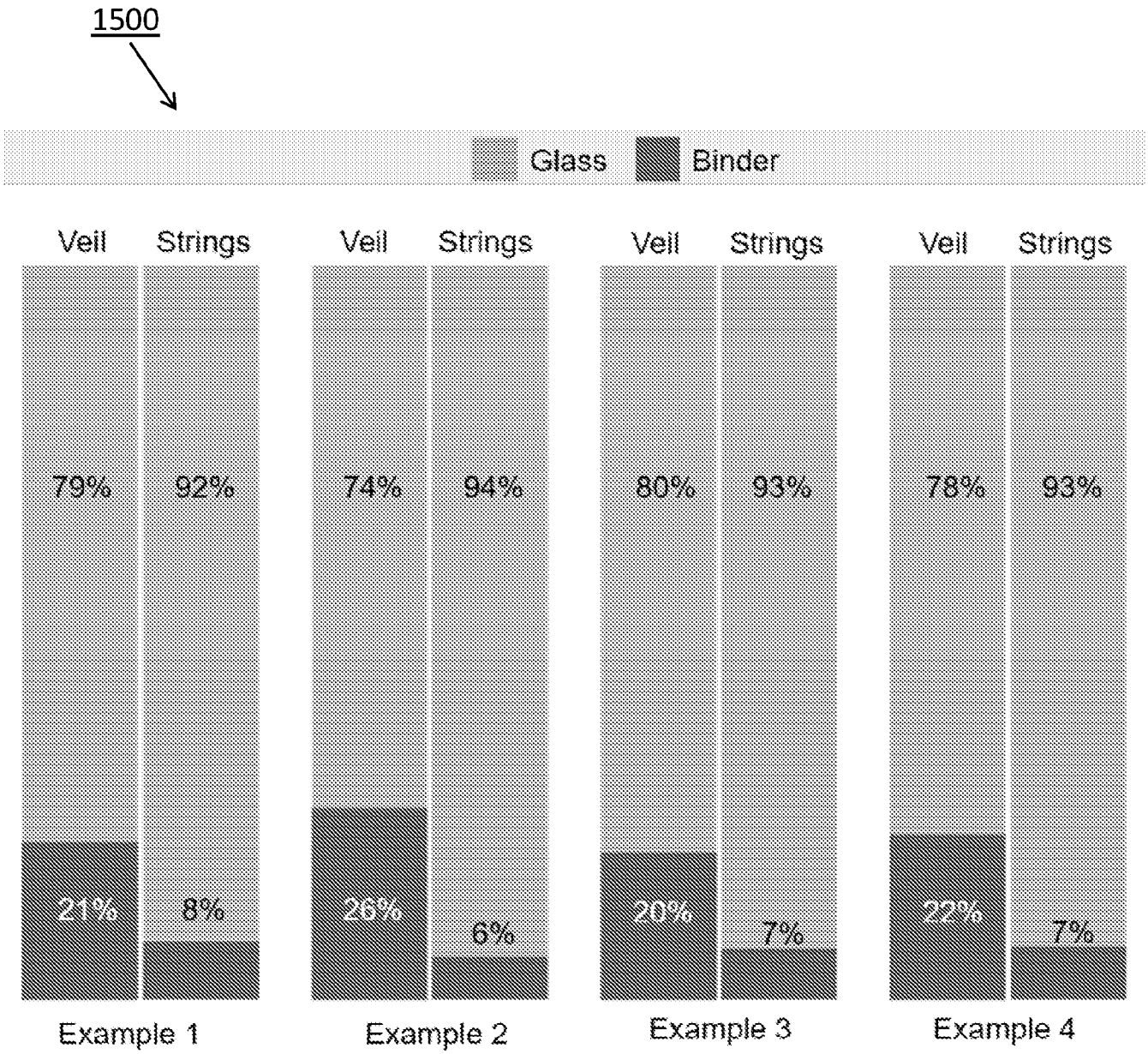

1500
Glass
Binder
Veil
Strings
79%
92%
21%
8%
Example 1
Veil
Strings
74%
94%
26%
6%
Example 2
Veil
Strings
80%
93%
20%
7%
Example 3
Veil
Strings
78%
93%
22%
7%
Example 4

FIG. 15

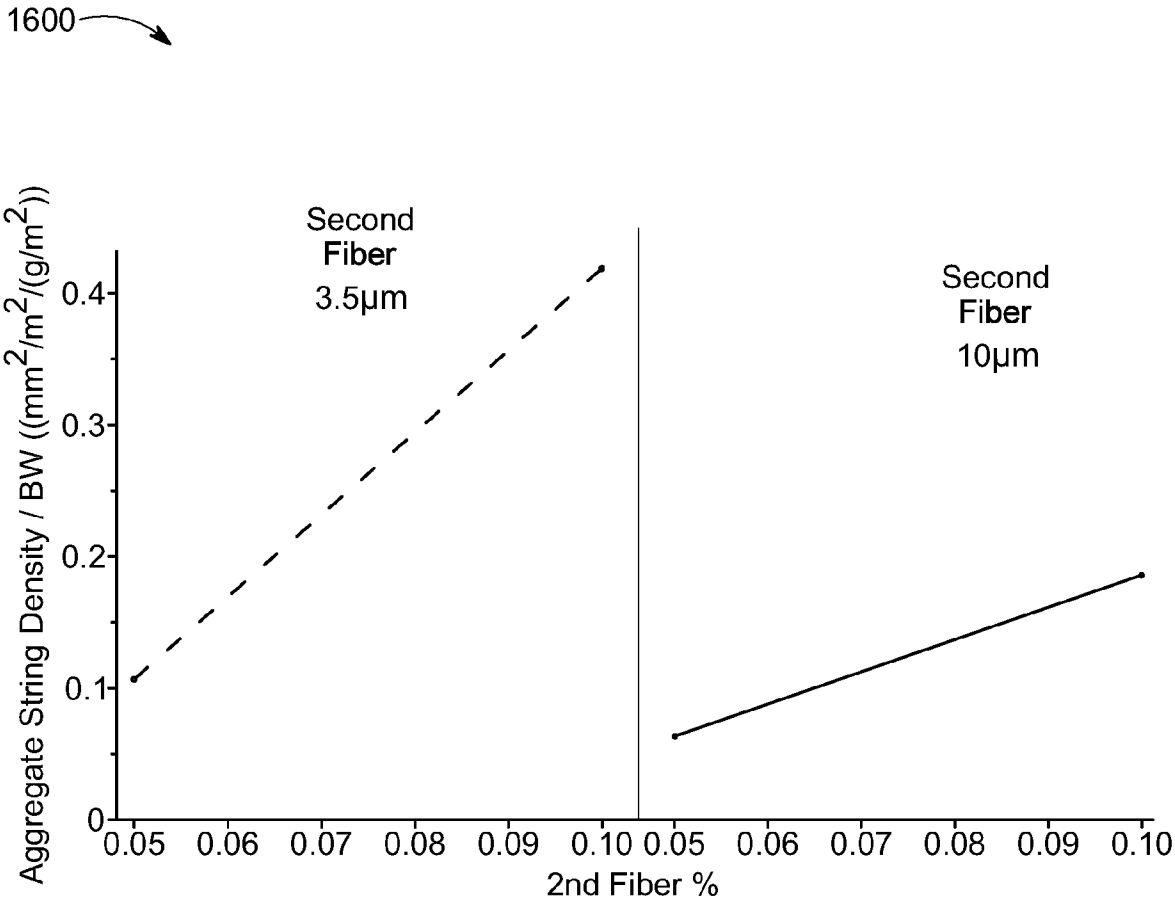

1600
Second
Fiber
3.5µm
Second
Fiber
10µm
Aggregate String Density / BW ((mm2/m2/(g/m2))
0
0.1
0.2
0.3
0.4
0.05 0.06 0.07 0.08 0.09 0.10 0.05 0.06 0.07 0.08 0.09 0.10
2nd Fiber %

FIG. 16

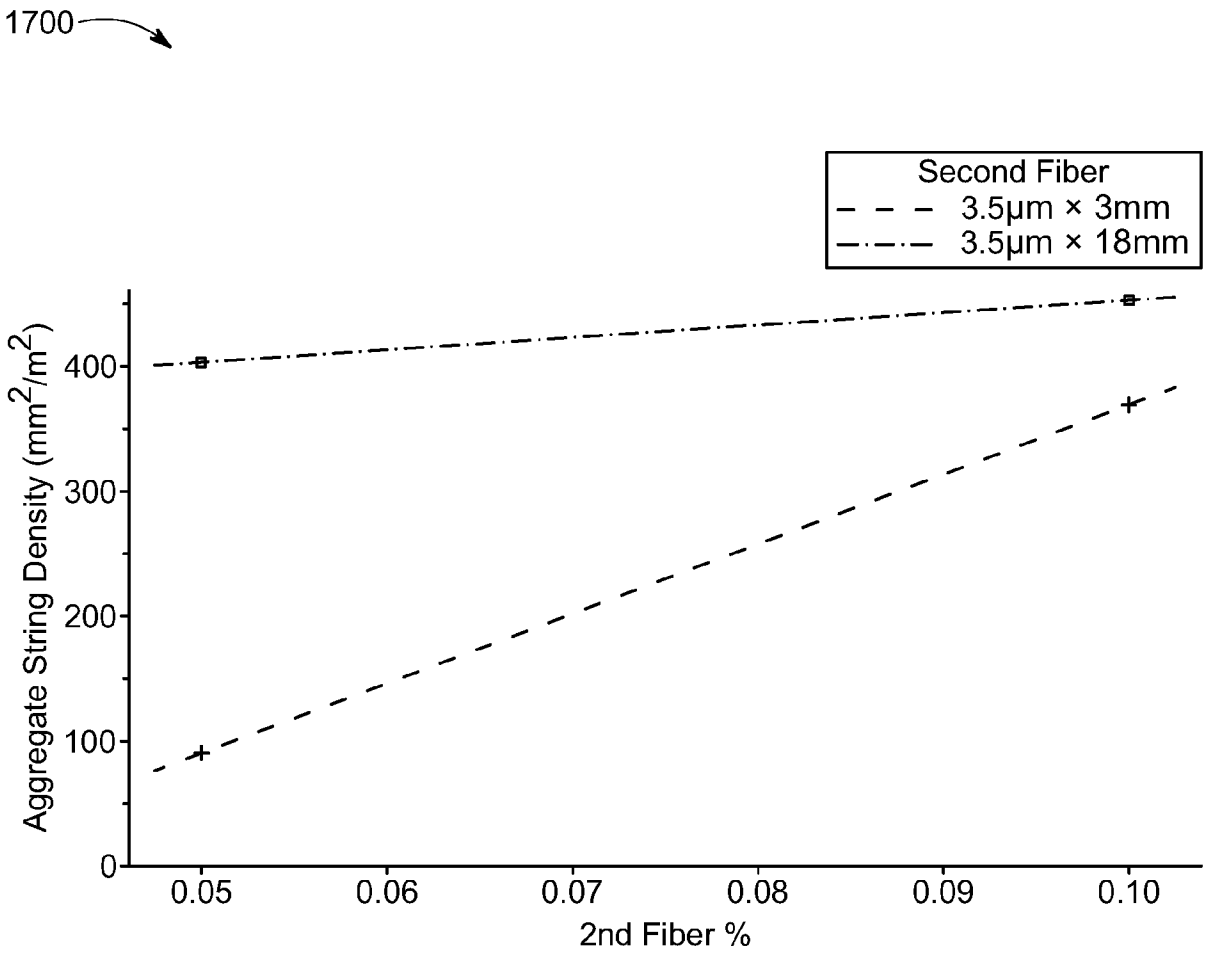

1700
Second Fiber
3.5µm × 3mm
3.5µm × 18mm
Aggregate String Density (mm2/m2)
0
100
200
300
400
0.05
0.06
0.07
0.08
0.09
0.10
2nd Fiber %

FIG. 17

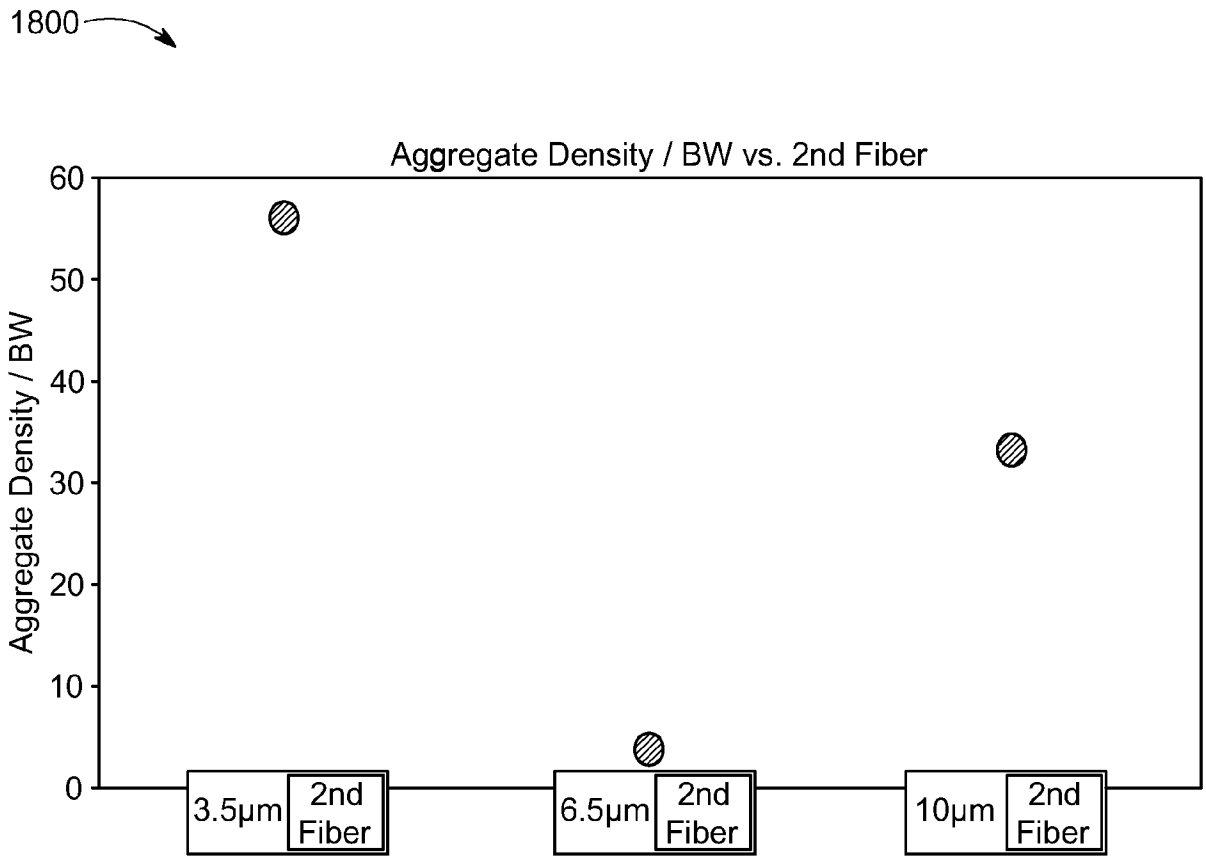

1800
Aggregate Density / BW vs. 2nd Fiber
Aggregate Density / BW
60
50
40
30
20
10
0
3.5µm
2nd Fiber
6.5µm
2nd Fiber
10µm
2nd Fiber

FIG. 18

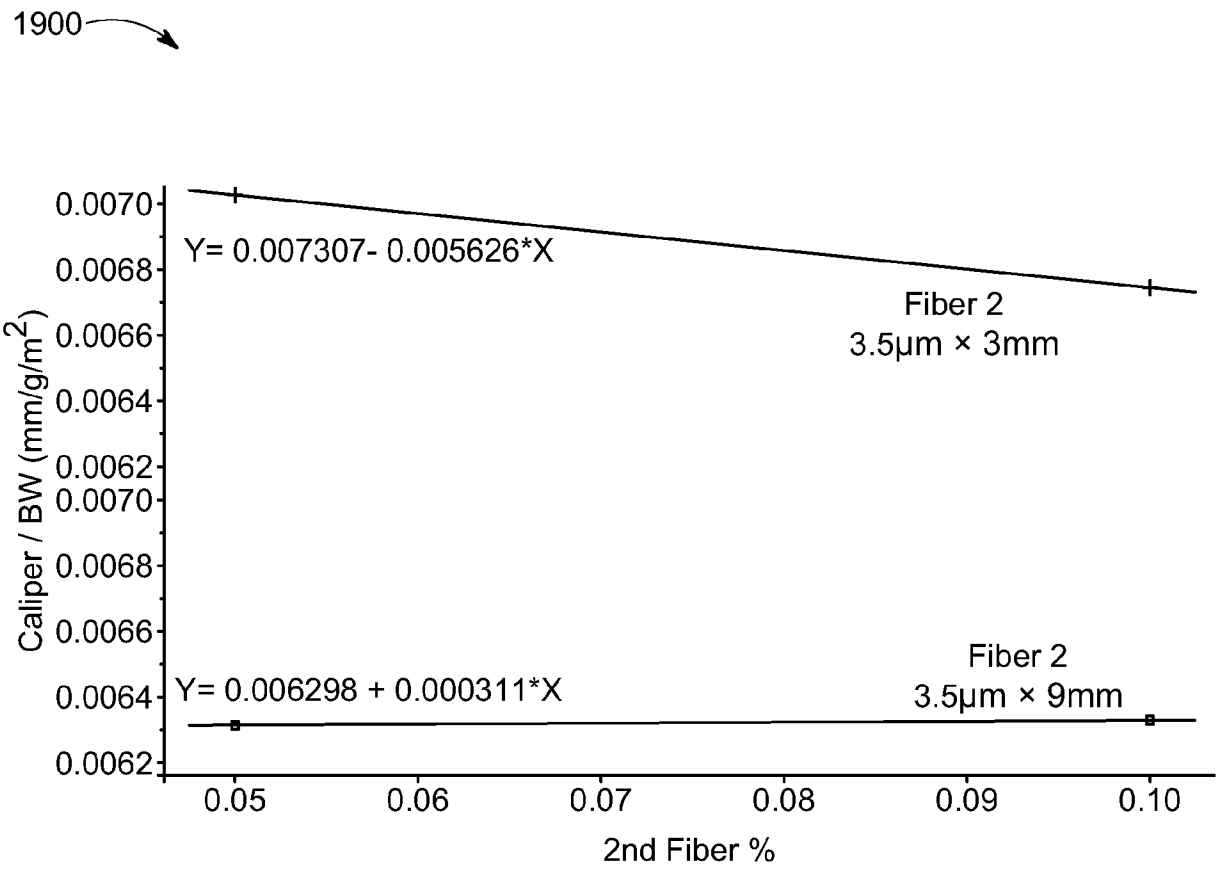

1900
0.0070
0.0068
0.0066
0.0064
0.0062
0.0070
0.0068
0.0066
0.0064
0.0062
Caliper / BW (mm/g/m2)
Y= 0.007307- 0.005626*X
Fiber 2
3.5µm × 3mm
Y= 0.006298 + 0.000311*X
Fiber 2
3.5µm × 9mm
0.05
0.06
0.07
0.08
0.09
0.10
2nd Fiber %

FIG. 19A

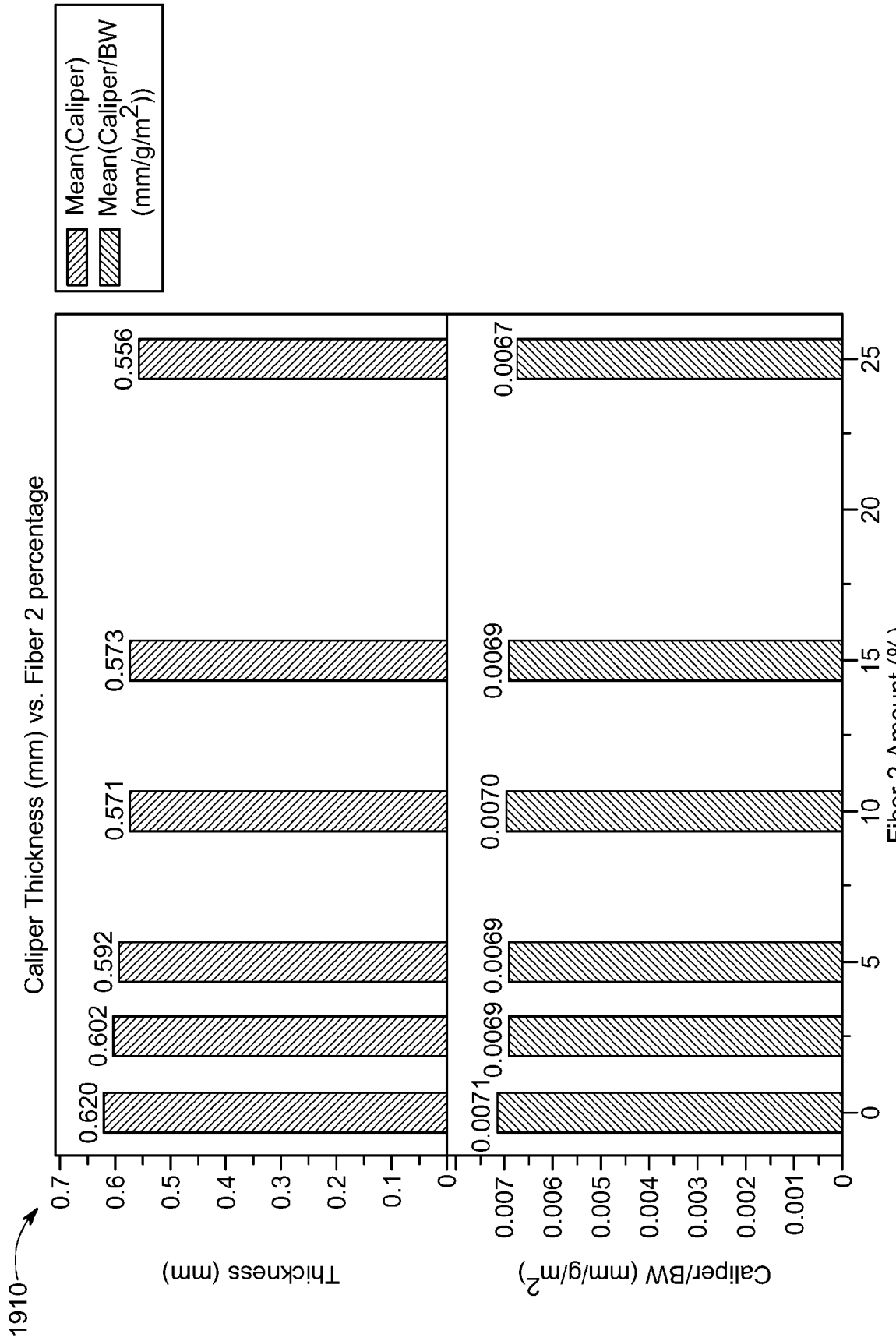

1910
Caliper Thickness (mm) vs. Fiber 2 percentage
Mean(Caliper)
Mean(Caliper/BW (mm/g/m2))
Thickness (mm)
Caliper/BW (mm/g/m2)
Fiber 2 Amount (%)
0.620
0.602
0.592
0.571
0.573
0.556
0.0071
0.0069
0.0069
0.0070
0.0069
0.0067

FIG. 19B

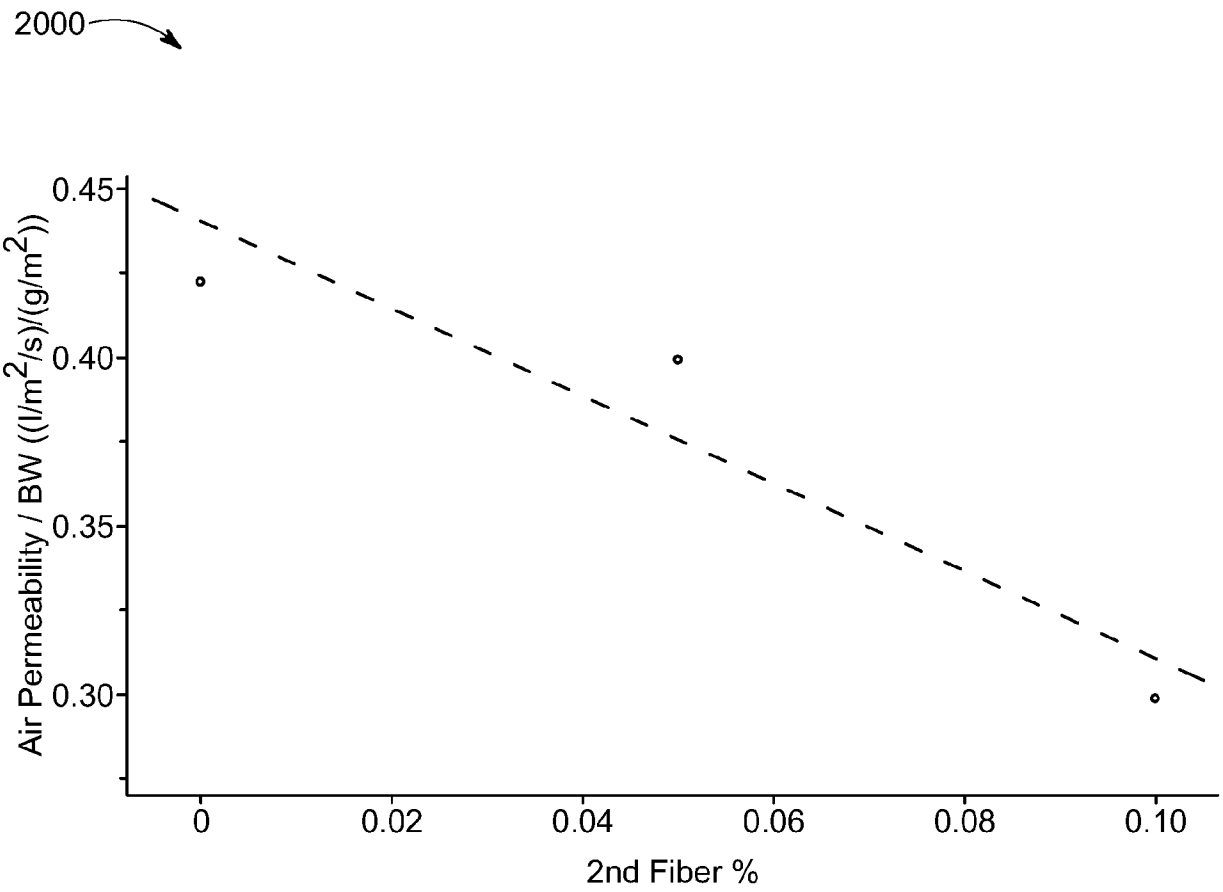

2000
0.45
0.40
0.35
0.30
Air Permeability / BW ((l/m2/s)/(g/m2))
0
0.02
0.04
0.06
0.08
0.10
2nd Fiber %

FIG. 20

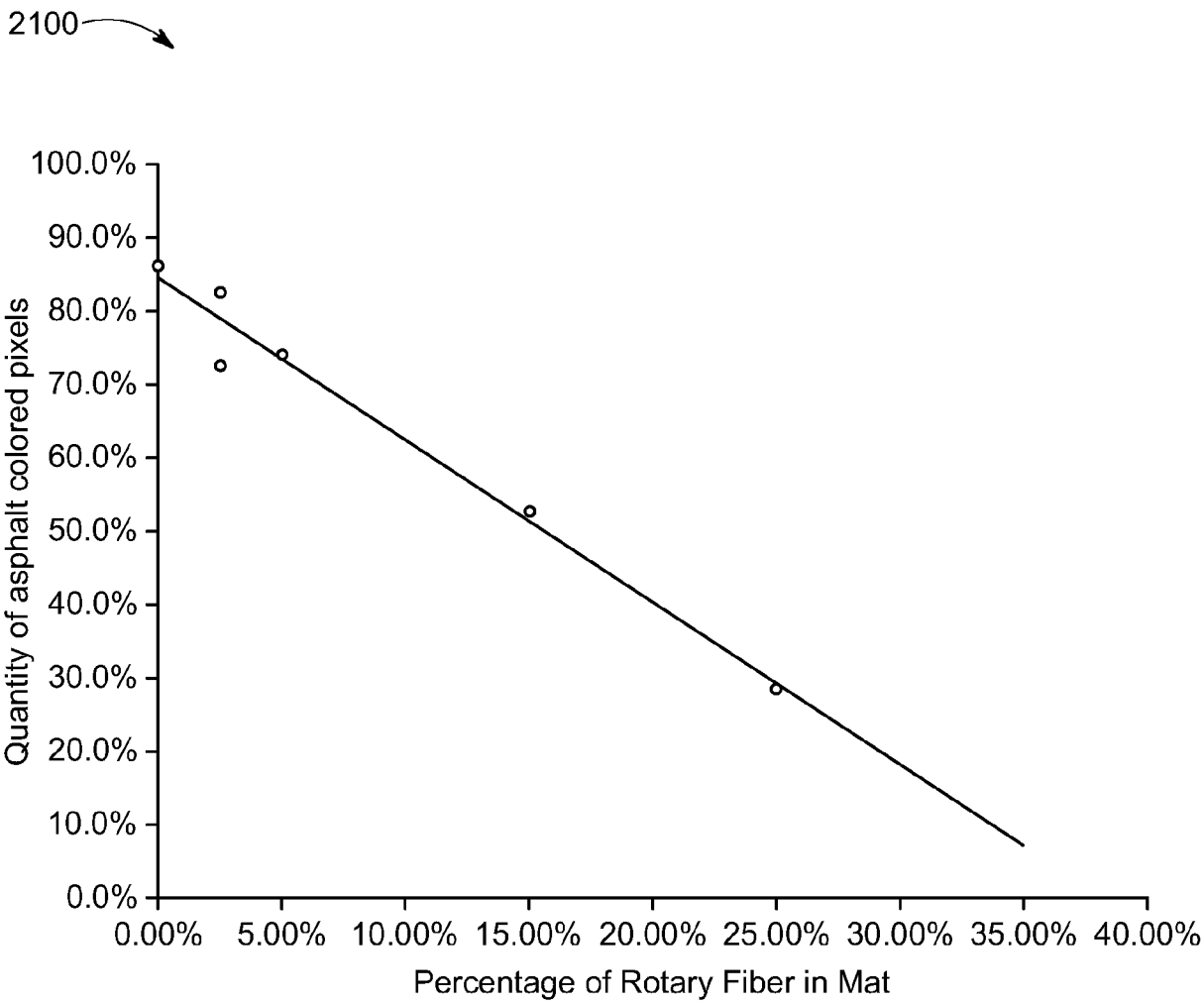

2100
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Quantity of asphalt colored pixels
0.00%
5.00%
10.00%
15.00%
20.00%
25.00%
30.00%
35.00%
40.00%
Percentage of Rotary Fiber in Mat

FIG. 21

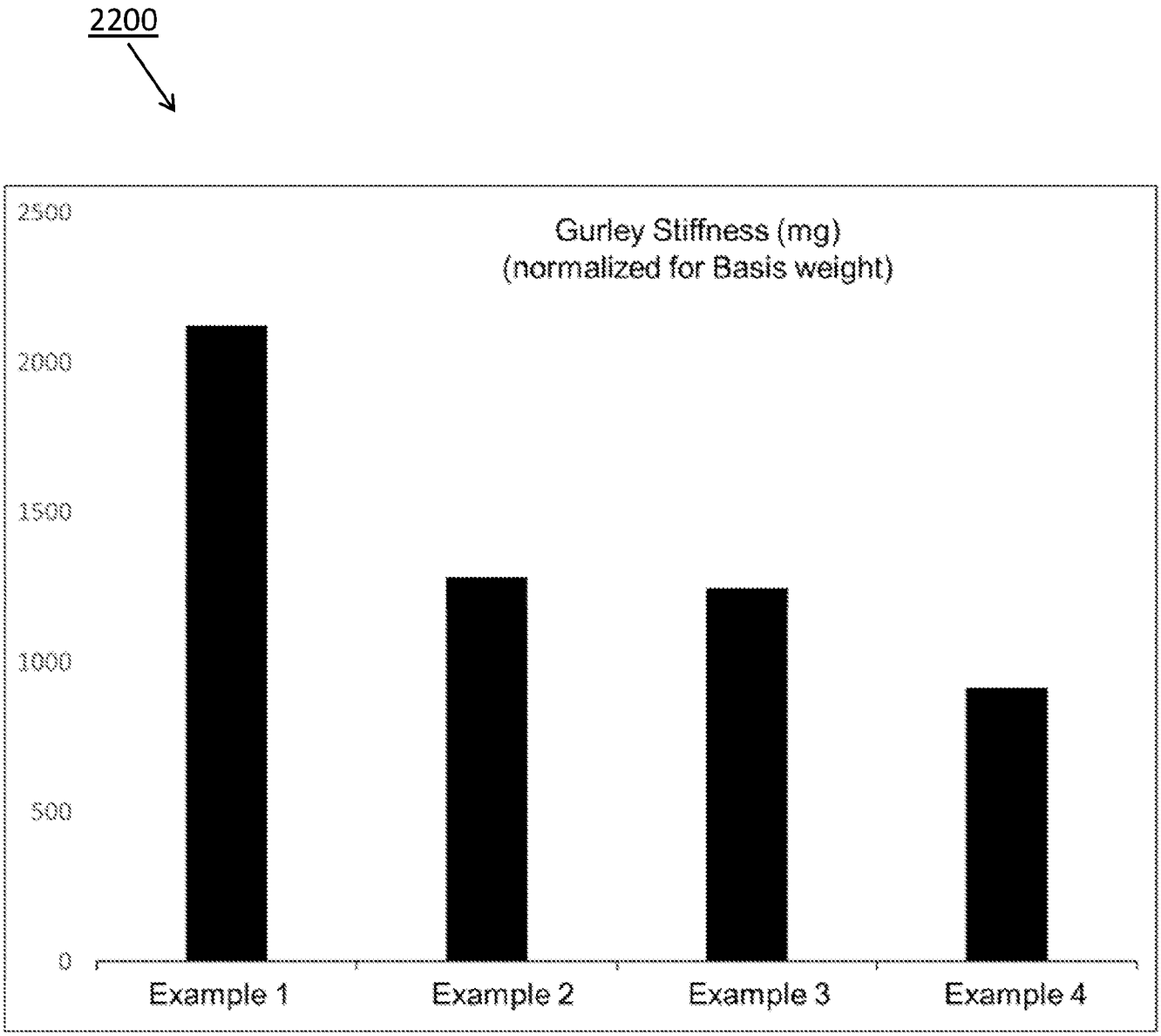

2200
Gurley Stiffness (mg)
(normalized for Basis weight)
2500
2000
1500
1000
500
0
Example 1
Example 2
Example 3
Example 4

FIG. 22

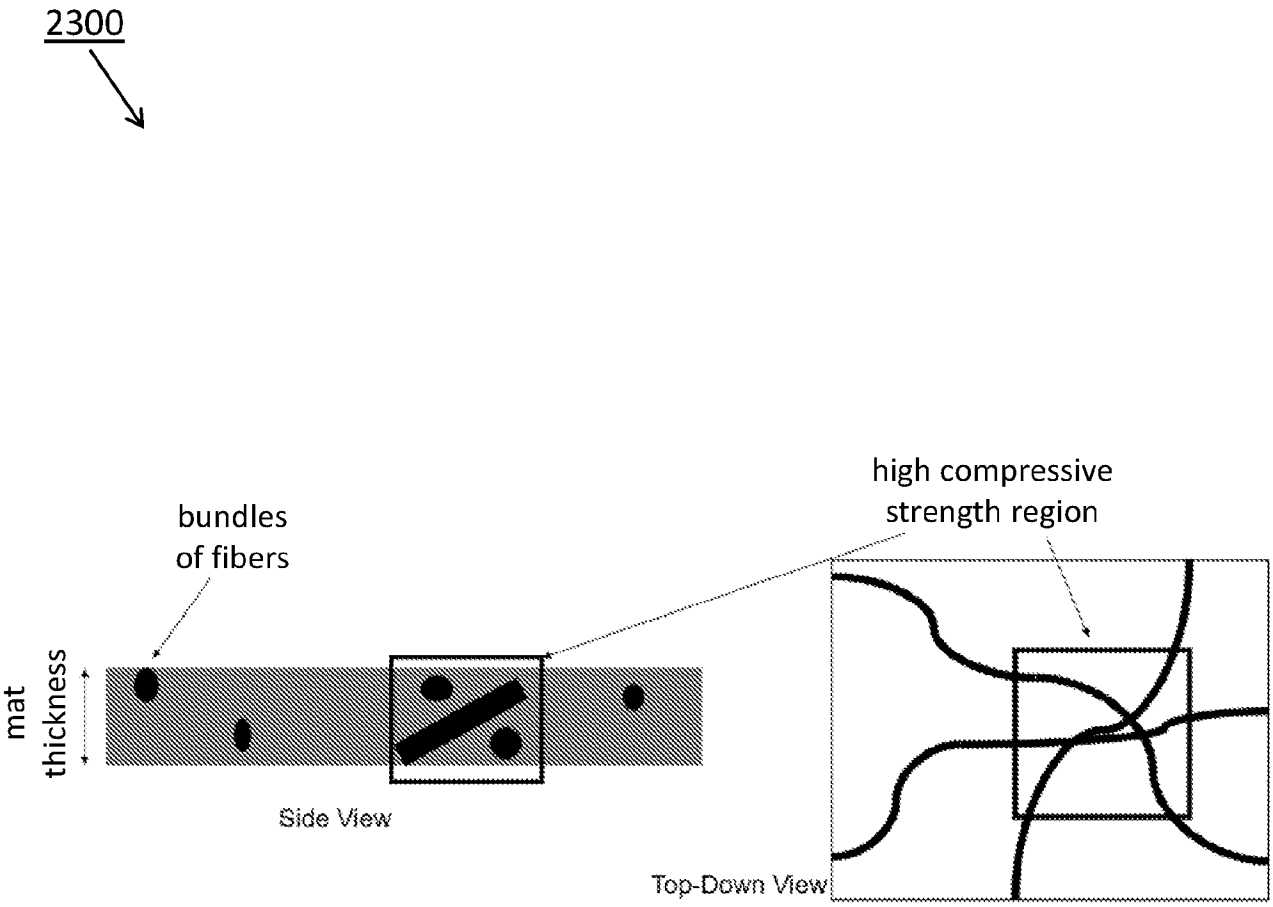

2300
bundles of fibers
high compressive strength region
mat thickness
Side View
Top-Down View

FIG. 23

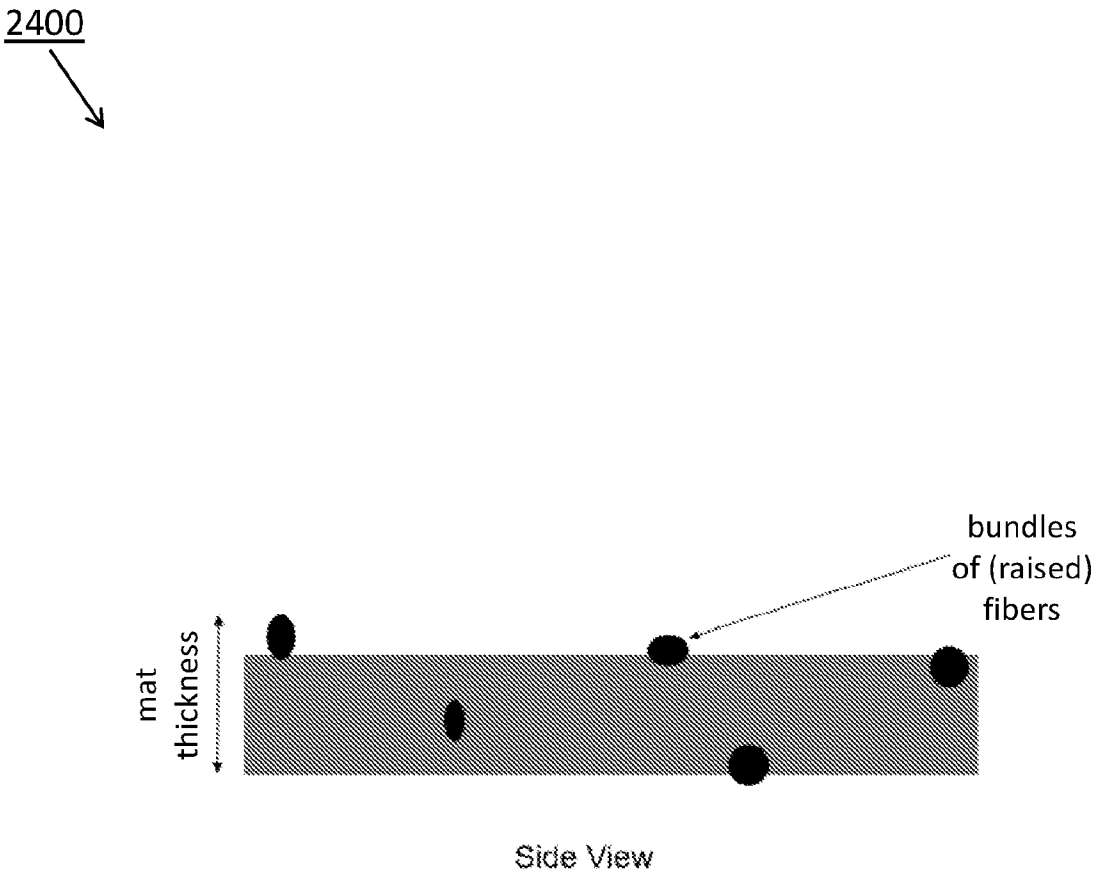


FIG. 24

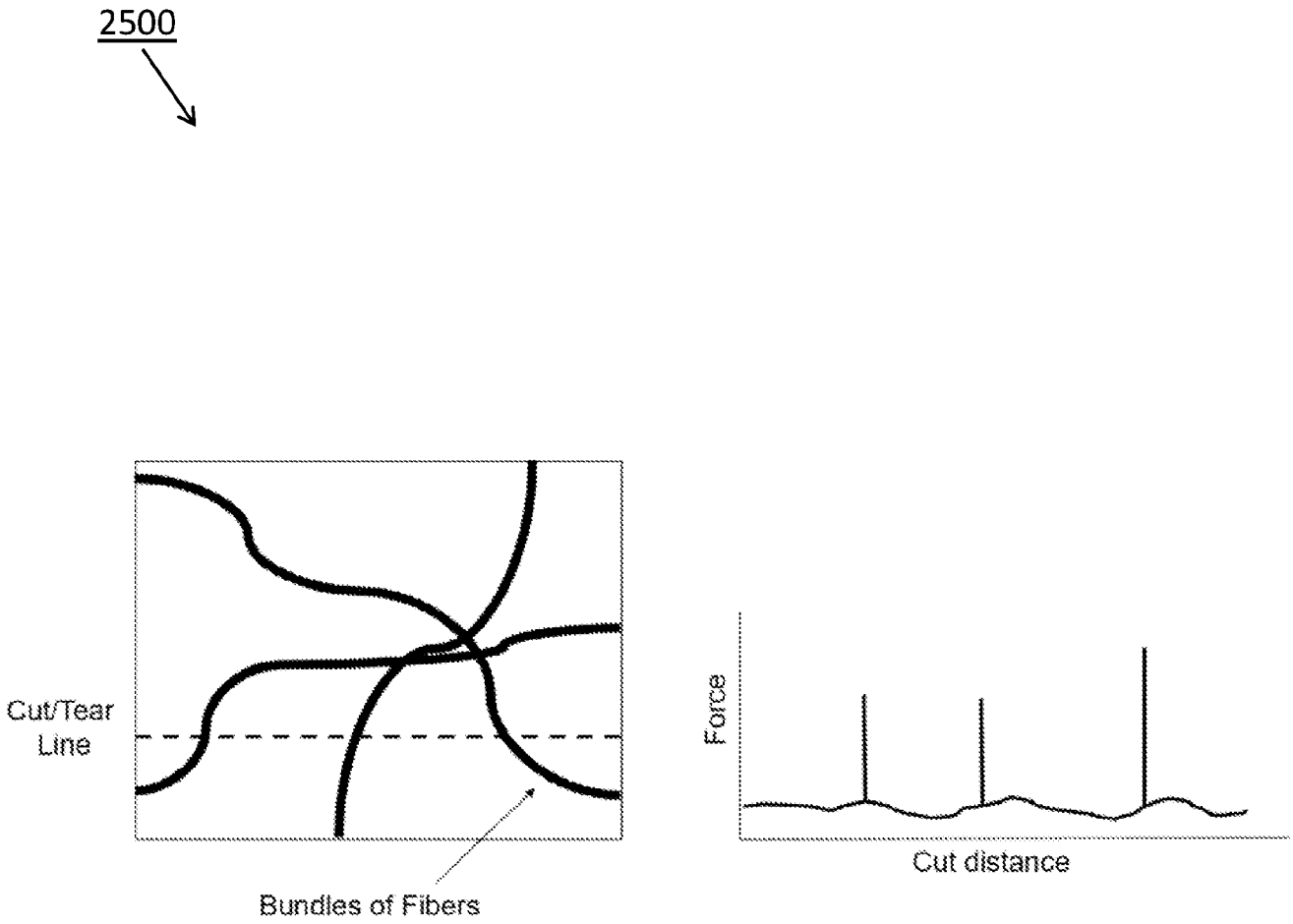


FIG. 25

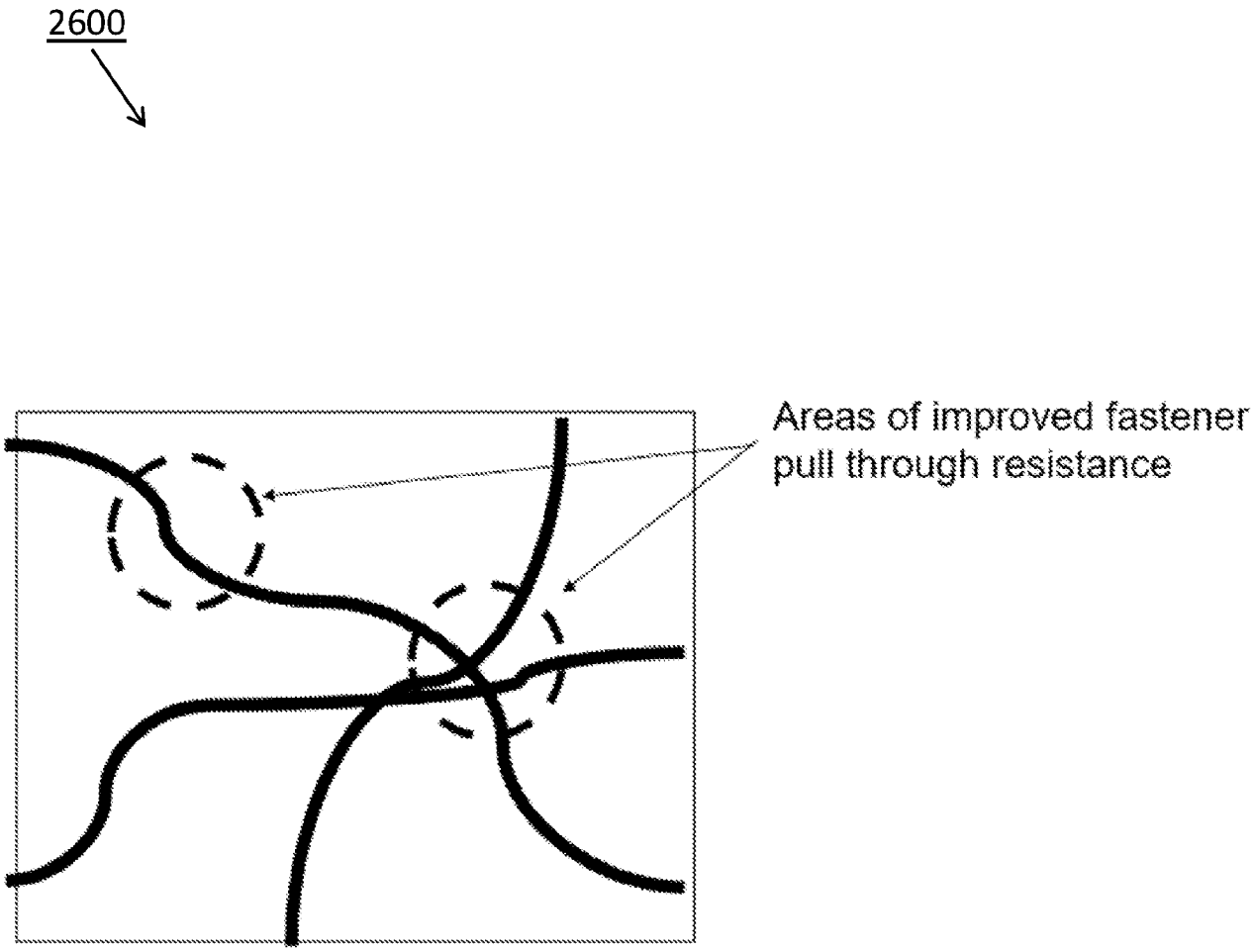


FIG. 26

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/060026

A. CLASSIFICATION OF SUBJECT MATTER

INV. C03B37/04 D04H1/4218 D04H1/4226 D21H13/40 D21H21/52
D21H27/10
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)

C03B D04H D21H

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 582 841 A (WATTON WILLIAM A [US] ET AL) 10 December 1996 (1996-12-10) cited in the application abstract; claims 1,11	1-18, 21-38, 41,44-48 19,49,50
X	US 7 856 853 B2 (OWENS CORNING INTELLECTUAL CAP [US]) 28 December 2010 (2010-12-28) cited in the application 25- 27	1
Y	US 8 087 265 B2 (GAVIN PATRICK M [US]; PELLEGRIN MICHAEL T [US] ET AL.) 3 January 2012 (2012-01-03) cited in the application claim 1	19

-/--

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 March 2025	08/04/2025

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gkerou, Elisavet

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/060026

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8 250 884 B2 (GAVIN PATRICK M [US]; LAWSON RICHARD D [US] ET AL.) 28 August 2012 (2012-08-28) cited in the application column 6, lines 51-61	1,20
Y	US 3 653 860 A (SMITH ROY E ET AL) 4 April 1972 (1972-04-04) cited in the application paragraph [0070]	49
Y	US 3 972 702 A (MCCORMICK RONALD O ET AL) 3 August 1976 (1976-08-03) cited in the application paragraph [0041]	50
X	US 4 207 086 A (EISENBERG ARNOLD J [US] ET AL) 10 June 1980 (1980-06-10) cited in the application the whole document	1
X	WO 2023/150740 A2 (OWENS CORNING INTELLECTUAL CAPITAL LLC [US]) 10 August 2023 (2023-08-10) paragraphs [0039], [0026]; claim 1	39,40, 42,43

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2024/060026

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5582841 A	10-12-1996	CA 2219919 A1	07-11-1996
		DE 69620749 T2	29-08-2002
		EP 0823886 A1	18-02-1998
		JP H11504895 A	11-05-1999
		US 5582841 A	10-12-1996
		WO 9634834 A1	07-11-1996
US 7856853 B2	28-12-2010	CA 2635815 A1	09-08-2007
		US 2007175243 A1	02-08-2007
		WO 2007089710 A1	09-08-2007
US 8087265 B2	03-01-2012	AT E517067 T1	15-08-2011
		CA 2669783 A1	17-07-2008
		CN 101663247 A	03-03-2010
		EP 2125647 A1	02-12-2009
		ES 2373142 T3	31-01-2012
		JP 2010514656 A	06-05-2010
		KR 20090099061 A	21-09-2009
		RU 2009128753 A	10-02-2011
		US 2008156042 A1	03-07-2008
		WO 2008085460 A1	17-07-2008
US 8250884 B2	28-08-2012	CA 2680014 A1	25-09-2008
		CN 101641300 A	03-02-2010
		EP 2125646 A1	02-12-2009
		JP 2010522132 A	01-07-2010
		KR 20100014424 A	10-02-2010
		RU 2009135090 A	27-04-2011
		US 2008229786 A1	25-09-2008
		WO 2008116176 A1	25-09-2008
US 3653860 A	04-04-1972	NONE	
US 3972702 A	03-08-1976	NONE	
US 4207086 A	10-06-1980	AU 517853 B2	27-08-1981
		BE 872327 A	16-03-1979
		BR 7807751 A	31-07-1979
		CA 1109676 A	29-09-1981
		FI 783442 A	24-06-1979
		FR 2412507 A1	20-07-1979
		GB 2010800 A	04-07-1979
		JP S5488323 A	13-07-1979
		JP S6033774 B2	05-08-1985
		MX 147745 A	10-01-1983
		NL 7811272 A	26-06-1979
		NO 147067 B	18-10-1982
		SE 437823 B	18-03-1985
		US 4207086 A	10-06-1980
		ZA 786266 B	31-10-1979
		ZA 786736 B	30-01-1980
WO 2023150740 A2	10-08-2023	CN 118829616 A	22-10-2024
		EP 4476188 A2	18-12-2024
		WO 2023150740 A2	10-08-2023