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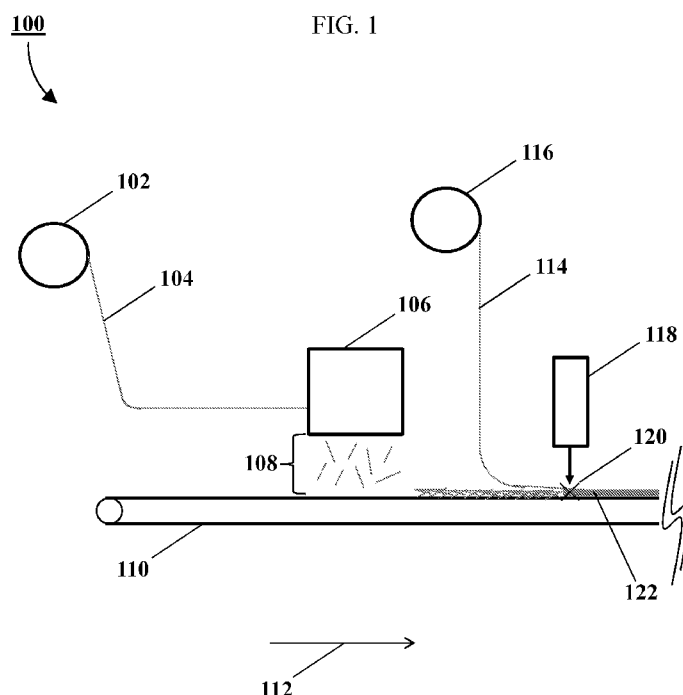
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(54) Title: STITCHED CHOPPED STRAND MAT



(57) Abstract: A carbon stitched chopped strand mat has properties that make it a suitable reinforcement in many composite materials, including in sheet molding compounds. The mat is made by spreading a carbon fiber tow to form a carbon ribbon, applying a coating to the ribbon, splitting the ribbon into carbon fiber bundles, drying the bundles, winding the bundles to form a multi-end roving, simultaneously chopping the ends of the roving to form chopped carbon fibers, randomly depositing the fibers within a defined space, applying a carrier to the space and stitching the carrier and fibers together.



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STITCHED CHOPPED STRAND MAT

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional patent application serial nos. 62/771,336, filed on November 26, 2018, titled STITCHED CHOPPED STRAND MAT, and 62/799,205, filed on January 31, 2019, titled STITCHED CHOPPED STRAND MAT, both of which are incorporated herein by reference in their entirety.

FIELD

[0002] The invention generally relates to reinforcement materials and, more particularly, to an improved non-woven reinforcing mat.

BACKGROUND

[0003] It is known to produce a chopped strand mat from chopped glass fibers. While some chopped strand mats use a resinous binder to hold the chopped fibers together, other chopped strand mats use stitching to hold the fibers together (and to a carrier). The stitched chopped strand mat made up of the chopped glass fibers has certain physical properties (e.g., thickness) and mechanical properties (e.g., modulus) that make the mat suitable as a reinforcement material for many downstream applications. However, the production of a similar mat using carbon fibers has proven difficult because of various processability challenges presented by carbon fibers (e.g., fuzz generation, fiber breakage, poor wettability). Thus, there is an unmet need for a stitched chopped strand mat made of carbon fibers.

SUMMARY

[0004] In view of the above, the general inventive concepts contemplate and encompass stitched chopped strand mats made from carbon fibers, as well as systems for and methods of producing said mats. The chopped strand mats made from chopped carbon fibers are expected to have improved (or otherwise differentiated) physical and/or mechanical properties, as compared to conventional glass stitched chopped strand mats. Accordingly, the carbon stitched chopped strand mats may provide improved performance in applications currently using glass stitched chopped strand mats, such as various molding applications. Additionally, the carbon stitched chopped strand mats may support new applications where the use of conventional glass stitched chopped strand mats would prove deficient, such as EMI shielding.

[0005] In one exemplary embodiment, a method of forming a reinforcement product is provided. The method comprises inputting a carbon fiber tow; spreading the carbon fiber tow to form a carbon ribbon; applying a coating to the carbon ribbon; splitting the carbon ribbon into a plurality of carbon fiber bundles, and drying the carbon fiber bundles.

[0006] In some exemplary embodiments, the method further comprises winding the carbon fiber bundles on a reel to form a multi-end roving.

[0007] In some exemplary embodiments, the method further comprises winding each of the carbon fiber bundles on a corresponding reel to form a plurality of single-end rovings.

[0008] In some exemplary embodiments, the method further comprises chopping the carbon fiber bundles into chopped carbon fibers; randomly depositing the chopped carbon fibers within a defined space; applying a carrier to the defined space; and stitching the carrier and the chopped fibers together to form a mat.

[0009] In some exemplary embodiments, the carrier is a glass veil. In some exemplary embodiments, the carrier is a sheet of polypropylene. In some exemplary embodiments, the carrier is a mesh fabric.

[0010] In some exemplary embodiments, the chopped carbon fibers are sandwiched between a first carrier and a second carrier. In some exemplary embodiments, the first carrier and the second carrier are made of different materials.

[0011] In some exemplary embodiments, the carbon fiber tow comprises at least 10,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 20,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 30,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 40,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 50,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 100,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 200,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 300,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 400,000 carbon filaments. In some exemplary embodiments, the carbon fiber tow comprises at least 500,000 carbon filaments.

[0012] In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 12,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 10,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 8,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 6,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 5,000 carbon filaments. In some exemplary embodiments,

each of the carbon fiber bundles comprises no more than 4,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 3,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 2,000 carbon filaments. In some exemplary embodiments, each of the carbon fiber bundles comprises no more than 1,000 carbon filaments.

[0013] In some exemplary embodiments, the carbon ribbon has a width within the range of 20 mm to 50 mm.

[0014] In some exemplary embodiments, the coating is an aqueous coating that imparts a water content in excess of 90 wt.% to the carbon ribbon. In some exemplary embodiments, the method further comprises drying the carbon ribbon to reduce the water content to within the range of 0.2 wt.% to 7.0 wt.%. In some exemplary embodiments, the method further comprises drying the carbon ribbon to reduce the water content to within the range of 1.5 wt.% +/- 0.5 wt.%.

[0015] In one exemplary embodiment, a method of forming a carbon stitched chopped strand mat is provided. The method comprises inputting a carbon fiber tow; spreading the carbon fiber tow to form a carbon ribbon; applying a coating to the carbon ribbon; splitting the carbon ribbon into a plurality of carbon fiber bundles; drying the carbon fiber bundles; winding the carbon fiber bundles to form a carbon multi-end roving; simultaneously chopping the ends of the carbon multi-end roving to form chopped carbon fibers; randomly depositing the chopped carbon fibers within a defined space; applying a carrier to the defined space; and stitching the carrier and the chopped fibers together to form the mat.

[0016] In some exemplary embodiments, the mat has an areal weight in the range of 400 g/m² to 1,200 g/m².

[0017] In some exemplary embodiments, the mat has an increase in thickness of 30% to 100% as compared to an identical mat made with glass fibers instead of carbon fibers. In some exemplary embodiments, the mat has an infused thickness in the range of 0.51 mm to 1.02 mm.

[0018] In some exemplary embodiments, the mat has a decrease in density of 14% to 18% as compared to an identical mat made with glass fibers instead of carbon fibers. In some exemplary embodiments, the mat has a density in the range of 1.40 g/cc to 1.54 g/cc.

[0019] In some exemplary embodiments, the mat has an increase in modulus of 125% to 200% as compared to an identical mat made with glass fibers instead of carbon fibers. In some exemplary embodiments, the mat has a modulus in the range of 25 GPa to 65 GPa.

[0020] In some exemplary embodiments, a resin is applied to the mat to form a sheet molding compound.

[0021] In one exemplary embodiment, a carbon stitched chopped strand mat is provided. The carbon stitched chopped strand mat has an areal weight in the range of 400 g/m² to 1,200 g/m². In some exemplary embodiments, the carbon stitched chopped strand mat has a thickness in the range of 0.51 mm to 1.02 mm; a density in the range of 1.40 g/cm³ to 1.54 g/cm³; and/or a modulus in the range of 25 GPa to 65 GPa.

[0022] Numerous other aspects, advantages, and/or features of the general inventive concepts will become more readily apparent from the following detailed description of exemplary embodiments, from the claims, and from the accompanying drawings being submitted herewith.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] Figure 1 is a diagram of a system for producing a carbon stitched chopped strand mat, according to an exemplary embodiment.

[0024] Figure 2 is a flowchart showing a method of producing a carbon stitched chopped strand mat, according to an exemplary embodiment.

[0025] Figure 3 is a flowchart showing a method of producing a carbon stitched chopped strand mat, according to another exemplary embodiment.

[0026] Figure 4 is a diagram of a carbon stitched chopped strand mat, according to an exemplary embodiment.

[0027] Figure 5 is a diagram of a carbon stitched chopped strand mat, according to an exemplary embodiment.

[0028] Figure 6 is a diagram of a carbon stitched chopped strand mat, according to an exemplary embodiment.

[0029] Figure 7 is a graph showing the tensile modulus (MPa) versus the fiber weight fraction (%) for three modeled mats.

[0030] Figure 8 is a graph showing the specific tensile modulus (MPa) versus the fiber weight fraction (%) for five modeled mats.

DETAILED DESCRIPTION

[0031] While the general inventive concepts are susceptible of embodiment in many different forms, there are shown in the drawings and will be described herein in detail specific embodiments thereof with the understanding that the present disclosure is to be considered merely as an exemplification of the general inventive concepts. Accordingly, the general inventive concepts are not intended to be limited to the specific embodiments illustrated herein.

[0032] A system 100 for producing a carbon-only chopped strand mat, according to one exemplary embodiment, is shown in FIG. 1. In the system 100, one or more tows 102 of continuous carbon fiber 104 are fed to a chopper 106. Any suitable carbon fibers can be used. The chopper 106 separates the continuous carbon fiber 104 into a series of discrete

chopped fibers 108, each of which have a predetermined length (e.g., within the range of 25 mm to 75 mm). The chopped fibers 108 are randomly deposited on a belt 110. The belt 110 moves in a production direction indicated by arrow 112. In some exemplary embodiments, the belt 110 is porous, such that a vacuum source (not shown) situated below the belt 110 can aid in holding the chopped fibers 108 in place. Then, a carrier 114 (e.g., a scrim) is fed from a supply 116 and laid on top of the chopped fibers 108 resting on the belt 110. The carrier 114 can be made of any suitable material. In some exemplary embodiments, the carrier 114 is a glass veil or continuous strand mat. In some exemplary embodiments, the carrier 114 is a sheet of polypropylene. In some exemplary embodiments, the carrier 114 is an open mesh fabric (e.g., a netting). A stitching machine 118 applies a stitching 120 to the carrier 114 and the chopped fibers 108 to hold them together, thereby forming a carbon stitched chopped strand mat 122. Any suitable stitching yarn, length, and pattern may be used. In some exemplary embodiments, the stitching yarn is a 5 gauge polyester stitching yarn. In some exemplary embodiments, there are approximately 1.97 stitches per cm in the mat 122.

[0033] While FIG. 1 shows one tow 102 of the continuous carbon fiber 104, it is contemplated that multiple tows 102 could be processed simultaneously. Furthermore, while the one or more tows 102 could be single-end rovings, it is more preferable from a processing standpoint that the tows 102 be multi-end rovings. In some exemplary embodiments, the tow 102 is a multi-end roving having 2 to 16 discrete ends. In some exemplary embodiments, the tow 102 is a multi-end roving having 8 or more discrete ends. In some exemplary embodiments, the tow 102 is a multi-end roving having at least 12 discrete ends. Each of the ends of the rovings 102 are fed to the chopper 106 for simultaneous processing thereof. In some exemplary embodiments, 48 ends are fed to the chopper 106 at once.

[0034] In some exemplary embodiments, the chopper 106 is a unitary device. In other exemplary embodiments, the chopper 106 is a system or collection of multiple

chopping devices working in parallel. Likewise, in some exemplary embodiments, the stitching machine 118 is a unitary device. In other exemplary embodiments, the stitching machine 118 is a system or collection of multiple stitching devices working in parallel.

[0035] Providing a typical carbon fiber tow (e.g., 24k or larger) as the input to the system 100 is not effective. In particular, carbon fibers are more difficult to process than many other types of reinforcement fibers (e.g., glass fibers), which can lead to slower production times and higher production costs. Carbon fibers are often brittle, which can lead to fiber breaks that cause frequent process disruptions. Additionally, carbon fibers often have low abrasion resistance and, thus, readily generate fuzz during processing thereof. This fuzz can also lead to frequent process disruptions. Additionally, due at least in part to their hydrophobic nature, carbon fibers are not as readily wettable as other types of reinforcement fibers, such as glass fibers, in traditional resins matrices. Wetting refers to the ability of the fibers to have appropriate surface wetting tension (i.e., to facilitate good impregnation of the resin into the spaces between filaments of each carbon fiber), homogenously disperse throughout a resin matrix, and achieve high compatibility between the fibers and the resin matrix. To form a composite material including carbon fibers, it is important to achieve excellent wetting of the carbon fibers to promote good adhesion between the carbon fibers and the resin.

[0036] When providing a typical carbon fiber tow (e.g., 24k or larger) as the input to the system 100, the resulting carbon stitched chopped strand mat will generally have poor infusion properties rendering it unsuitable as a composite reinforcement material. Instead, it is critical that the filament count in the carbon fiber tow be reduced to facilitate chopping and distribution of the carbon fibers so as to achieve acceptable infusion properties (e.g., infusion properties comparable to a glass-only stitched chopped strand mat). In some exemplary embodiments, each carbon fiber tow 102 input to the chopper has a filament count of 10,000

or less. In some exemplary embodiments, each carbon fiber tow 102 input to the chopper has a filament count of 3,000 or less. In some exemplary embodiments, each carbon fiber input to the chopper 106 has a filament count within the range of 1,000 to 10,000.

[0037] To obtain an acceptable carbon input, the filaments of a larger carbon tow (e.g., a 24k tow) are spread and split into a plurality of smaller filament bundles (e.g., 8 instances of 3,000 filaments), each of which are then formed into a discrete fiber or end of a multi-end roving. This decomposition of a larger carbon tow into multiple smaller carbon streams allows for a relatively homogenous distribution of the chopped carbon fibers throughout the mat. Consequently, the carbon stitched chopped strand mat has desirable properties, including an acceptable rate of infusion.

[0038] A method 200 of producing a carbon-only chopped strand mat, according to one exemplary embodiment, is shown in FIG. 2. The method 200 involves decomposing a large carbon fiber tow (e.g., one comprising 24,000 or more individual carbon filaments) into multiple smaller carbon fiber tows (e.g., ones comprising 10,000 or fewer individual carbon filaments).

[0039] As used herein, the terminology #k is used to describe the approximate number of individual filaments making up a tow, where #k is the product of # and 1,000 filaments. Thus, a 50k carbon fiber tow comprises 50,000 individual carbon fiber filaments.

[0040] In general, the method 200 involves decomposing a first carbon fiber tow into a plurality of second carbon fiber tows, wherein the first carbon fiber tow comprises at least x individual carbon fiber filaments and each of the second carbon fiber tows comprises substantially less than x individual carbon fiber filaments.

[0041] In some exemplary embodiments, the first carbon fiber tow comprises at least 10,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 20,000 carbon fiber filaments. In some exemplary embodiments, the first

carbon fiber tow comprises at least 30,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 40,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 50,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 100,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 200,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 300,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 400,000 carbon fiber filaments. In some exemplary embodiments, the first carbon fiber tow comprises at least 500,000 carbon fiber filaments.

[0042] In some exemplary embodiments, the first carbon fiber tow is a 24k tow. In some exemplary embodiments, the first carbon fiber tow is a 50k tow. In some exemplary embodiments, the first carbon fiber tow is a 475k tow.

[0043] In some exemplary embodiments, each second carbon fiber tow comprises no more than 12,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 10,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 8,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 6,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 5,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 4,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 3,000 carbon fiber filaments. In some exemplary embodiments, each second carbon fiber tow comprises no more than 2,000 carbon fiber filaments. In some exemplary

embodiments, each second carbon fiber tow comprises no more than 1,000 carbon fiber filaments.

[0044] In some exemplary embodiments, each second carbon fiber tow is a 3k tow.

In some exemplary embodiments, each second carbon fiber tow is a 2k tow. In some exemplary embodiments, each second carbon fiber tow is a 1k tow.

[0045] Notwithstanding these examples, the decomposition that occurs in the method 200 is not limited to any specific carbon tow input size nor any specific reduced carbon tow output size. Furthermore, it should be appreciated that actual filament counts may vary (e.g., +/- 5%) from the indicated values.

[0046] In some exemplary embodiments, the first carbon fiber tow is decomposed into n second carbon fiber tows, wherein the first carbon fiber tow comprises at least x individual carbon fiber filaments and each of the second carbon fiber tows comprises approximately x/n individual carbon fiber filaments. Thus, depending on processing parameters, a large carbon fiber tow could be decomposed into different numbers of smaller carbon fiber tows. For example, a 24k carbon fiber tow could be decomposed into six 4k carbon fiber tows, eight 3k carbon fiber tows, or twelve 2k carbon fiber tows.

[0047] In a first step 202, the method 200 involves introducing a first carbon fiber tow (e.g., a 24k carbon fiber tow) into the process. Any suitable carbon fiber can be used. Carbon fiber is frequently supplied in the form of a continuous tow wound onto a reel. Each carbon filament in the tow is a continuous cylinder having a diameter that on average is within the range of 5-10 μm . Thus, in step 202, the carbon fiber tow is fed from its reel and guided into the process to a location where the carbon fiber tow will undergo spreading.

[0048] To effectively decompose the carbon fiber tow into the smaller carbon fiber tows, the carbon fiber tow should first be spread into a thin ribbon of about 30-80 g/m^2 areal weight. This spreading will provide an increased alignment of the carbon fiber tow for easier

and more uniform splitting. Thus, in a second step 204, the carbon fiber tow is spread into such a ribbon.

[0049] It was found that application of a coating composition (to the already formed/packaged carbon fiber tow) is important to the decomposition of the carbon fiber tow. For example, the coating composition might improve the downstream split cohesion, improve the dispersion and solubility of the carbon fibers with respect to the desired matrix material, and improve the stiffness of the carbon fibers. Any suitable coating composition can be used. For example, exemplary coating compositions are described in the international patent application entitled *Post-Coating Composition for Reinforcement Fibers* that published as WO 2017/062734, the entire disclosure of which is incorporated herein by reference. The coating can be applied to the carbon fibers in any suitable manner, such as by drawing the carbon fibers through a coating bath.

[0050] Accordingly, in a third step 206, a coating composition is applied to the carbon fiber tow. The coating composition is an aqueous solution comprising about 4 wt.% solids and about 96 wt.% water. In other exemplary embodiments, the ratio of solids to water in the coating composition can differ, although a considerable majority of the coating composition will always be water. In some exemplary embodiments, the coating composition includes between 0.55 wt.% and 7.0 wt.% of solids. In some exemplary embodiments, the coating step 206 also includes processing (e.g., scraping) for removing excess coating composition from the carbon fiber tow.

[0051] Once the carbon fiber tow has been coated in step 206, the carbon fiber tow should be in the form of a flat ribbon approximately 20-50 mm wide and, in some exemplary embodiments, approximately 30 mm wide. In step 208, this ribbon is split so as to form multiple discrete collections of carbon fiber filaments. In some exemplary embodiments, the input carbon fiber tow is split into at least two distinct groups or “splits.” In some exemplary

embodiments, the input carbon fiber tow is split into at least five splits, or at least seven splits, or at least ten splits for a 24k carbon fiber tow, or at least fifteen or at least twenty splits for a 50k carbon fiber tow.

[0052] In some exemplary embodiments, the coating step 206 may come after the splitting step 208 instead of before the splitting step 208. In some exemplary embodiments, the coating step 206 may come both before and after the splitting step 208.

[0053] Next, the coated splits are dried in step 210. For example, the coated splits are pulled through a dryer or other heating means, such as an oven, to dry the coating composition on the separate carbon bundles.

[0054] In some exemplary embodiments, an optional winding operation, noted as step 212, can be carried out on the coated, split carbon fibers. In this manner, the split carbon fibers could be wound on separate reels, bobbins, or the like to form separate (smaller) carbon fibers tows as compared to the input carbon fiber tow. Alternatively, the split carbon fibers could be wound on the same reel, bobbin, or the like to form a multi-end carbon fiber roving. In other exemplary embodiments, the winding of step 212 could be skipped and the coated, split carbon fibers simply conveyed further downstream for other (in-line) processing.

[0055] By way of background, this winding operation can also refer to the act of pulling the input carbon fiber tow (and its various subsequent forms) through some or all of the processing associated with the method 200. It is generally important to manage the tension of the input carbon fiber tow (and its various subsequent forms) during the processing thereof. This tension can be imparted and controlled, in whole or in part, as part of this winding step 212.

[0056] In the method 200, the split carbon fibers are preferably conveyed onward or otherwise used to form a carbon multi-end roving that is then chopped in step 214 (e.g., using the chopper 106). The chopped carbon fibers are distributed (e.g., randomly) on a belt or

other surface where they are stitched to a carrier disposed thereon in step 216, thereby forming a carbon stitched chopped strand mat.

[0057] A corresponding exemplary system for forming a carbon stitched chopped strand mat can be understood from the above description of the system 100 and the method 200. In particular, it has been discovered that by combining a number of differently positioned and shaped rollers, spreaders, guide eyes, and other related structure, large bundles of carbon fibers (such as those having at least 24,000 individual carbon filaments) can be successfully split into any number of splits to produce separate sets of carbon fibers having as few as 1,000 individual carbon filaments, and that these smaller carbon fiber bundles can be maintained through the use of the post-coating composition for further processing downstream, such as formation of a carbon stitched chopped strand mat (see FIGS. 4-6).

[0058] A method 300 of producing a carbon-only chopped strand mat, according to another exemplary embodiment, is shown in FIG. 3. Like reference numbers are used to show similar processing across the methods 200, 300.

[0059] In the method 300, a moisture control step 220 takes place. In particular, after the coating step 206 and before the splitting step 208, a partial drying of the input carbon fiber tow takes place in step 220. As noted above, the coating step 206 results in a considerable amount (e.g., 93 wt.% or more of the coating) of water on the carbon fibers. The partial drying is intended to reduce the moisture content on the carbon fiber tow prior to splitting. Specifically, it has been found that careful control of the moisture content on the carbon fiber tow prior to splitting significantly impacts the overall splitting process. If too little water is on the carbon fiber tow, generation of fuzz occurs and/or breakage of the carbon fiber filaments results, both of which degrade the overall efficiency of the splitting process. If too much water is on the carbon fiber tow, the separate carbon fiber splits may coalesce and rejoin downstream and/or the splitting equipment may become plugged with

coating residue or carbon fibers. Both of these situations can lead to wasted time and resources.

[0060] It was determined that the input carbon fiber tow should have a moisture content within the range of 0.2 wt.% and 7.0 wt.%, more preferably, between 0.3 wt.% to 3 wt.%, for effective splitting of the coated carbon fiber tow, and most preferably between 0.7 wt.% to 2 wt.%. This is a considerable reduction of the original moisture content of 90 wt.% or more (measured relative to the coating weight). From trials, it was discovered that maintaining a moisture content of approximately 1.5 wt.% +/- 0.5 wt.% on the carbon fiber tow was ideal for splitting the carbon fiber tow into multiple splits. Recognizing that the target moisture level on the carbon fiber tow may vary based on one or more parameters of the method 300, such as the line speed, type of splitting device employed, etc., the particular moisture content to be achieved can be selected (still within the range of 0.2 wt.% and 7.0 wt.%) based on said parameter(s).

[0061] The partial drying that takes place in step 220 can be implemented in any suitable manner, such as by conduction, convection, or radiation. For example, the input carbon fiber tow may contact one or more heated rollers that act to partially dry the carbon fibers. In some exemplary embodiments, the heated rollers are heated to a temperature in the range of 350 °F to 450 °F. Variables such as the number of heated rollers, the contact surface/angle between the heated rollers and the carbon fibers, the line speed, etc. can be adjusted to control the partial drying of the carbon fibers. Once the input carbon fiber tow has had its moisture content reduced to a desired level, splitting of the input carbon fiber tow occurs in step 208 as described above. Further processing of the carbon fibers takes place in steps 210, 212, 214, and 216, as described above, to form a carbon stitched chopped strand mat.

[0062] A corresponding exemplary system for forming a carbon stitched chopped strand mat can be understood from the above description of the system 100 and the method 300. In particular, it has been discovered that by combining a number of differently positioned and shaped rollers, spreaders, guide eyes, and other related structure, large bundles of carbon fibers (such as those having at least 24,000 individual carbon filaments) can be successfully split into any number of splits to produce separate sets of carbon fibers having as few as 1,000 individual carbon filaments, and that these smaller carbon fiber bundles can be maintained through the use of the post-coating composition for further processing downstream, such as formation of a carbon stitched chopped strand mat (see FIGS. 4-6). Furthermore, the system would include one or more means for carrying out the partial drying of step 220, such as one or more heated godet rollers.

[0063] The methods and systems described herein or otherwise encompassed by the general inventive concepts support the continuous processing of carbon fibers at speeds in excess of 25 m/min, for example, speeds in the range of 30 m/min to 45 m/min.

[0064] A carbon stitched chopped strand mat 400, according to one exemplary embodiment, is shown in FIG. 4. The carbon stitched chopped strand mat 400 includes a carrier 402 attached to a random distribution 404 of chopped carbon fibers by a stitching yarn 406. In some exemplary embodiments, an areal weight of the carbon stitched chopped strand mat 400 is within the range of 400 g/m² to 1,200 g/m².

[0065] The carbon stitched chopped strand mat 400 exhibits a gain in bulk (e.g., thickness) as compared to a conventional glass-only stitched chopped strand mat. In some exemplary embodiments, the carbon stitched chopped strand mat 400 is expected to realize an increase in thickness of 30% to 100% versus a comparable glass-only stitched chopped strand mat.

[0066] The carbon stitched chopped strand mat 400 exhibits a reduction in density as compared to a conventional glass-only stitched chopped strand mat. In some exemplary embodiments, the carbon stitched chopped strand mat 400 is expected to realize a decrease in density of 14% to 18% versus a comparable glass-only stitched chopped strand mat.

[0067] The carbon stitched chopped strand mat 400 exhibits a gain in elastic modulus as compared to a conventional glass-only stitched chopped strand mat. In some exemplary embodiments, the carbon stitched chopped strand mat 400 is expected to realize an increase in modulus of 125% to 200% versus a comparable glass-only stitched chopped strand mat.

[0068] A carbon stitched chopped strand mat 500, according to another exemplary embodiment, is shown in FIG. 5. The carbon stitched chopped strand mat 500 includes a carrier 502. A first random distribution 504 of carbon fibers is attached to one side of the carrier 502 by a stitching yarn 506. A second random distribution 508 of carbon fibers is attached to the opposite side of the carrier 502 by the stitching yarn 506. In some exemplary embodiments, two separate applications of the stitching yarn 506 are used, i.e., one for each of the distributions 504, 508.

[0069] A carbon stitched chopped strand mat 600, according to another exemplary embodiment, is shown in FIG. 6. The carbon stitched chopped strand mat 600 includes a first carrier 602 attached to one side of a random distribution 604 of carbon fibers by a stitching yarn 606. A second carrier 608 is attached to the opposite side of the distribution 604 by the stitching yarn 606. In some exemplary embodiments, two separate applications of the stitching yarn 606 are used, i.e., one for each of the carriers 602, 608. In some exemplary embodiments, the carriers 602, 608 are the same material. In some exemplary embodiments, the carriers 602, 608 are different materials.

[0070] The improved stitched chopped strand mats disclosed or otherwise suggested herein (e.g., the mats 400, 500, 600) have certain improved physical properties (e.g.,

thickness) and/or mechanical properties (e.g., modulus), as compared to conventional glass-only stitched chopped strand mats. The improved stitched chopped strand mats are suitable as reinforcement materials for many downstream applications. For example, the mats can be rolled up for storage and transport, where they can eventually be unwound and used as a reinforcement (e.g., as a prepreg or preform) in various processes such as light resin transfer molding, high-pressure resin transfer molding, vacuum-assisted resin transfer molding, etc. In some exemplary embodiments, the mats are used to form sheet molding compound (SMC).

[0071] The graph 700 of FIG. 7 shows a plot of the tensile modulus (MPa) versus the fiber weight fraction (%) for three modeled mats, with the upper curve being a carbon chopped strand mat formed only from carbon fibers, the middle curve being a hybrid chopped strand mat formed from both carbon fibers and glass fibers, and the lower curve being a glass chopped strand mat formed only from glass fibers.

[0072] The graph 800 of FIG. 8 shows a plot of the specific tensile modulus (MPa) versus the fiber weight fraction (%) for five modeled mats, with the upper curve being a carbon chopped strand mat formed only from carbon fibers, the three middle curves being hybrid chopped strand mats formed from both carbon fibers and glass fibers, and the lower curve being a glass chopped strand mat formed only from glass fibers.

[0073] Additionally, the properties of two carbon chopped strand mats, to be formed from the processing described herein, were modeled/estimated as shown in Table 1.

#	Areal Weight (g/m ²)	Infused Density	Dry Thickness (mm)	Infused Thickness (mm)	Average Tensile Modulus (GPa)
CMER: Estimate 1	450	1.47	0.75	0.56	45
CMER: Estimate 2	600	1.47	1.45	0.99	45

Table 1

[0074] It will be appreciated that the scope of the general inventive concepts is 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 to the methods and systems disclosed. 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 claimed herein, and any equivalents thereof. For example, while the exemplary embodiments shown and described herein involve the use of carbon fibers, the general inventive concepts are not so limited and instead may be applicable to the use of other types of fibers as well, such as graphite fibers and polymer fibers.

CLAIMS

1. A method of forming a reinforcement product, the method comprising:
inputting a carbon fiber tow;
spreading the carbon fiber tow to form a carbon ribbon;
applying a coating to the carbon ribbon;
splitting the carbon ribbon into a plurality of carbon fiber bundles; and
drying the carbon fiber bundles.
2. The method of claim 1, further comprising winding the carbon fiber bundles on a reel to form a multi-end roving.
3. The method of claim 1, further comprising winding each of the carbon fiber bundles on a corresponding reel to form a plurality of single-end rovings.
4. The method of claim 1, further comprising chopping the carbon fiber bundles into chopped carbon fibers;
randomly depositing the chopped carbon fibers within a defined space;
applying a carrier to the defined space; and
stitching the carrier and the chopped fibers together to form a mat.
5. The method of claim 4, wherein the carrier is a glass veil.
6. The method of claim 4, wherein the carrier is a sheet of polypropylene.

7. The method of claim 4, wherein the carrier is a mesh fabric.
8. The method of claim 4, wherein the chopped carbon fibers are sandwiched between a first carrier and a second carrier.
9. The method of claim 8, wherein the first carrier and the second carrier are made of different materials.
10. The method of claim 1, wherein the carbon fiber tow comprises at least 10,000 carbon filaments.
11. The method of claim 1, wherein the carbon fiber tow comprises at least 20,000 carbon filaments.
12. The method of claim 1, wherein the carbon fiber tow comprises at least 30,000 carbon filaments.
13. The method of claim 1, wherein the carbon fiber tow comprises at least 40,000 carbon filaments.
14. The method of claim 1, wherein the carbon fiber tow comprises at least 50,000 carbon filaments.
15. The method of claim 1, wherein the carbon fiber tow comprises at least 100,000 carbon filaments.

16. The method of claim 1, wherein the carbon fiber tow comprises at least 200,000 carbon filaments.
17. The method of claim 1, wherein the carbon fiber tow comprises at least 300,000 carbon filaments.
18. The method of claim 1, wherein the carbon fiber tow comprises at least 400,000 carbon filaments.
19. The method of claim 1, wherein the carbon fiber tow comprises at least 500,000 carbon filaments.
20. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 12,000 carbon filaments.
21. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 10,000 carbon filaments.
22. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 8,000 carbon filaments.
23. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 6,000 carbon filaments.

24. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 5,000 carbon filaments.
25. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 4,000 carbon filaments.
26. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 3,000 carbon filaments.
27. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 2,000 carbon filaments.
28. The method of claim 1, wherein each of the carbon fiber bundles comprises no more than 1,000 carbon filaments.
29. The method of claim 1, wherein the carbon ribbon has a width within the range of 20 mm to 50 mm.
30. The method of claim 1, wherein the coating is an aqueous coating that imparts a water content in excess of 90 wt.% to the carbon ribbon.
31. The method of claim 30, further comprising drying the carbon ribbon to reduce the water content to within the range of 0.2 wt.% to 7.0 wt.%.

32. The method of claim 30, further comprising drying the carbon ribbon to reduce the water content to within the range of 1.5 wt.% +/- 0.5 wt.%.
33. A method of forming a carbon stitched chopped strand mat, the method comprising:
- forming a carbon multi-end roving using the method of claim 1,
 - simultaneously chopping the ends of the carbon multi-end roving to form chopped carbon fibers;
 - randomly depositing the chopped carbon fibers within a defined space;
 - applying a carrier to the defined space; and
 - stitching the carrier and the chopped fibers together to form the mat.
34. The method of claim 33, wherein the mat has an areal weight in the range of 400 g/m² to 1,200 g/m².
35. The method of claim 33, wherein the mat has an increase in thickness of 30% to 100% as compared to an identical mat made with glass fibers instead of carbon fibers.
36. The method of claim 33, wherein the mat has a thickness in the range of 0.51 mm to 1.02 mm.
37. The method of claim 33, wherein the mat has a decrease in density of 14% to 18% as compared to an identical mat made with glass fibers instead of carbon fibers.
38. The method of claim 33, wherein the mat has a density in the range of 1.40 g/cm³ to 1.54 g/cm³.

39. The method of claim 33, wherein the mat has an increase in modulus of 125% to 200% as compared to an identical mat made with glass fibers instead of carbon fibers.
40. The method of claim 33, wherein the mat has a modulus in the range of 25 GPa to 65 GPa.
41. A method of forming a sheet molding compound, the method comprising:
forming a carbon stitched chopped strand mat using the method of claim 33;
and
applying a resin to the mat.
42. A carbon stitched chopped strand mat having an areal weight in the range of 400 g/m² to 1,200 g/m²; a thickness in the range of 0.51 mm to 1.02 mm; a density in the range of 1.40 g/cm³ to 1.54 g/cm³; and a modulus in the range of 25 GPa to 65 GPa.

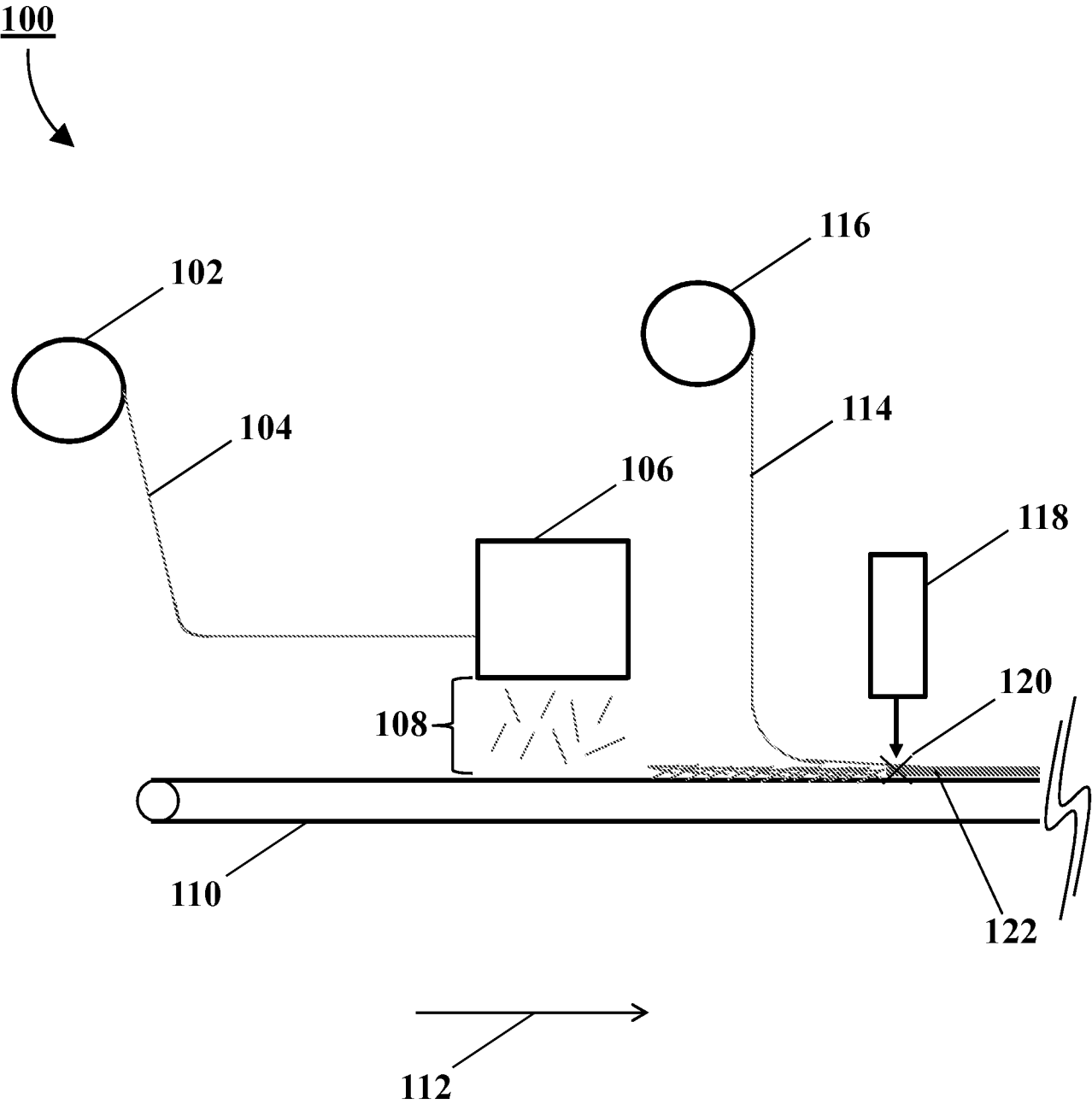


FIG. 1

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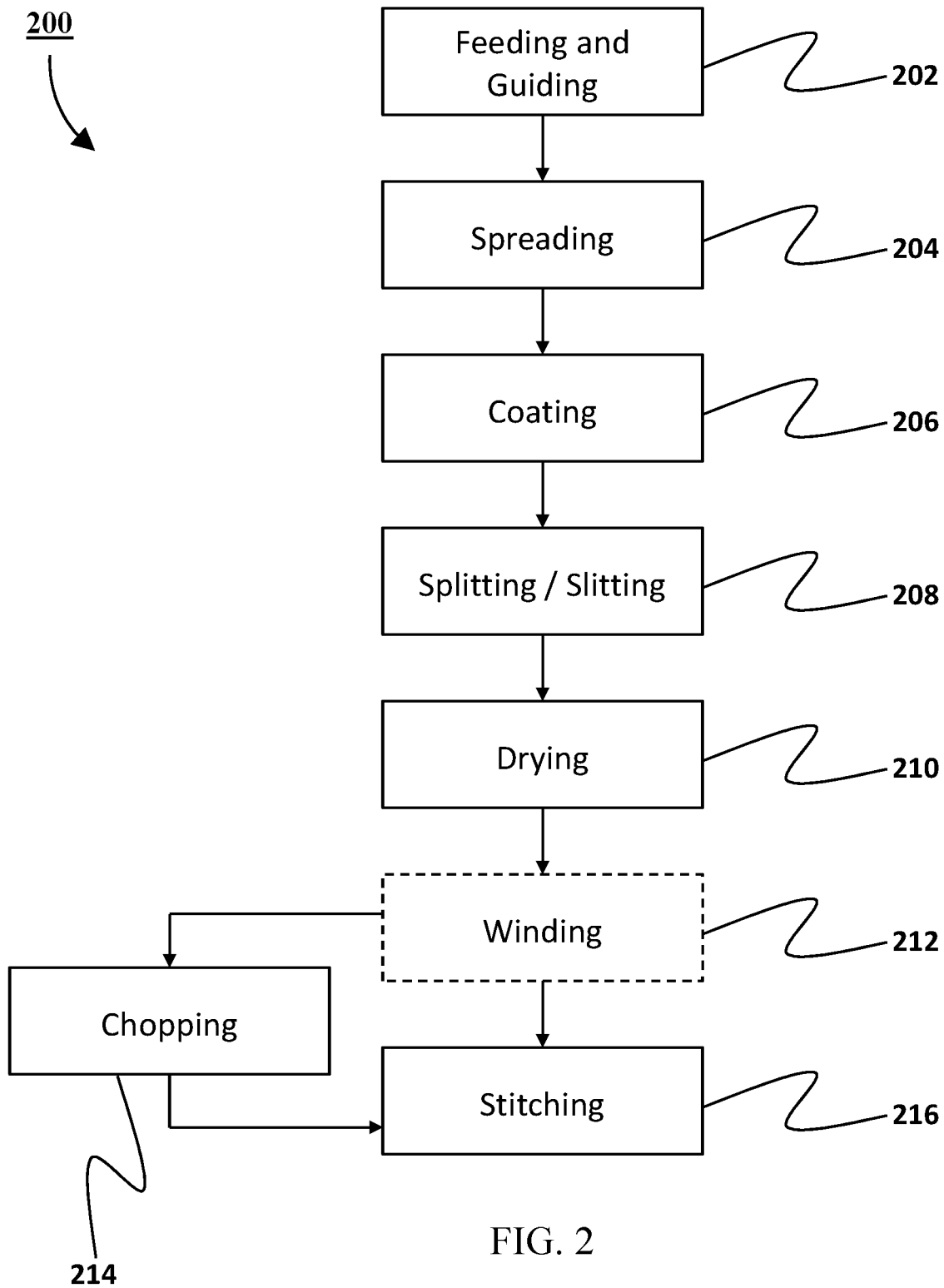
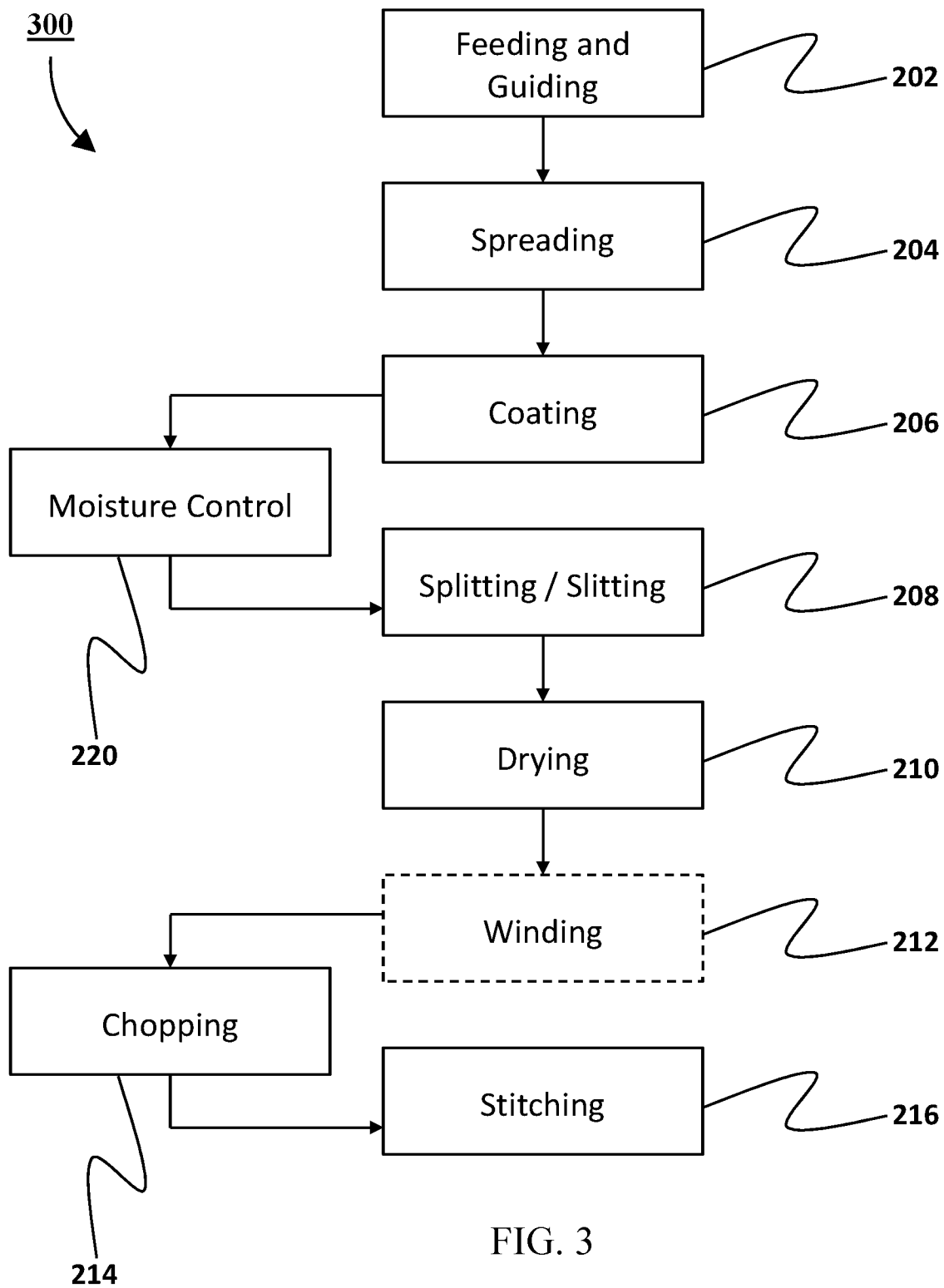


FIG. 2

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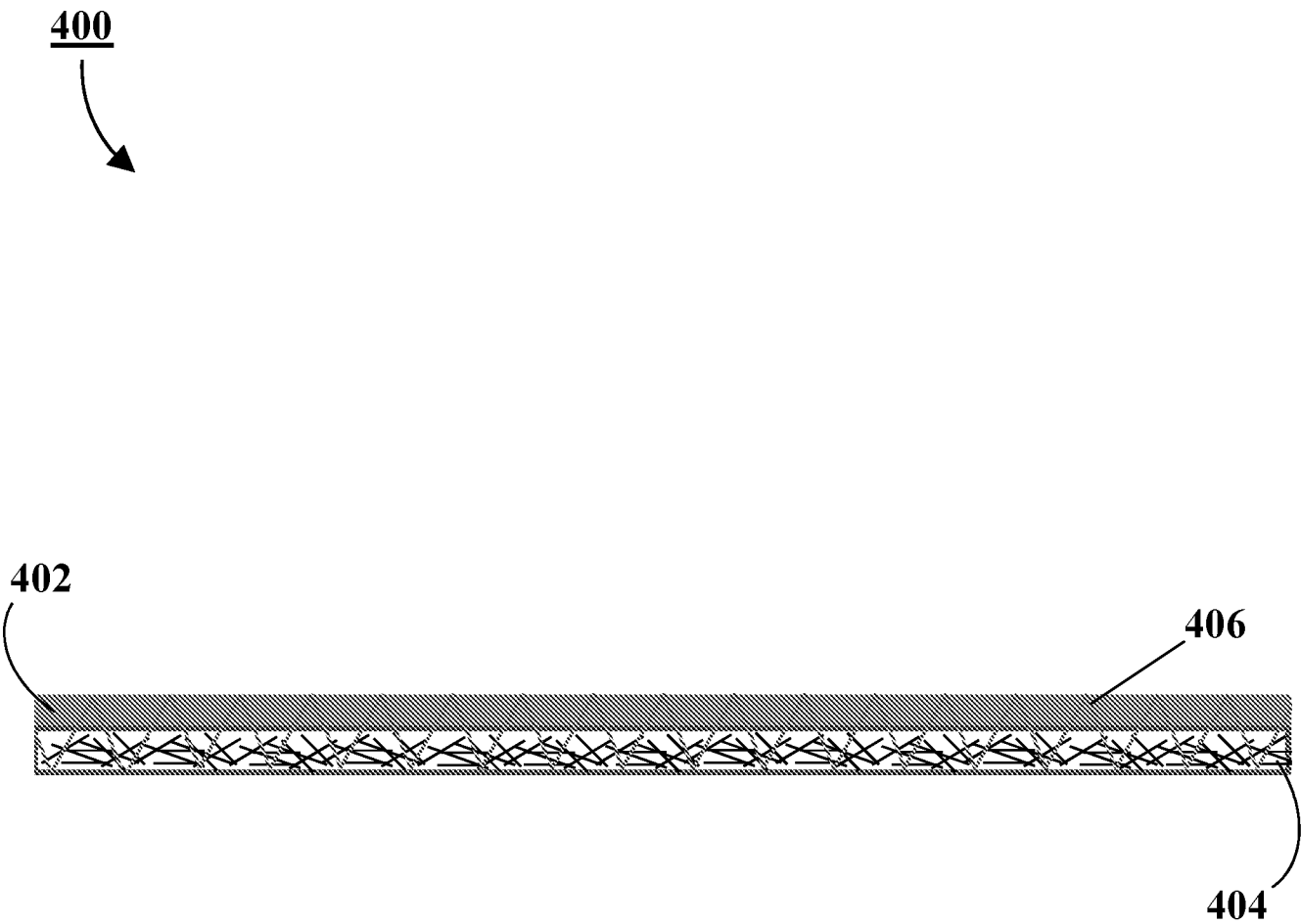


FIG. 4

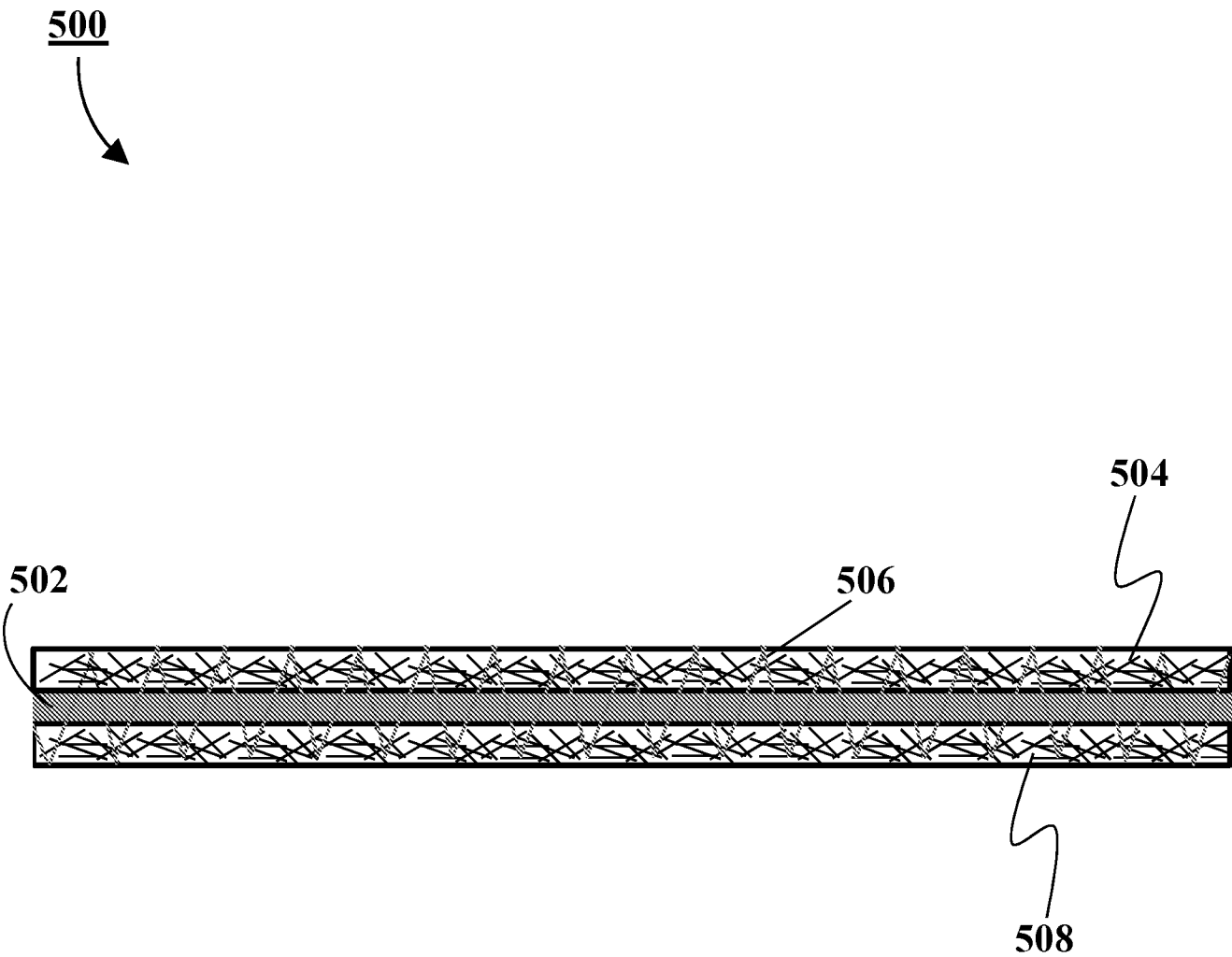


FIG. 5

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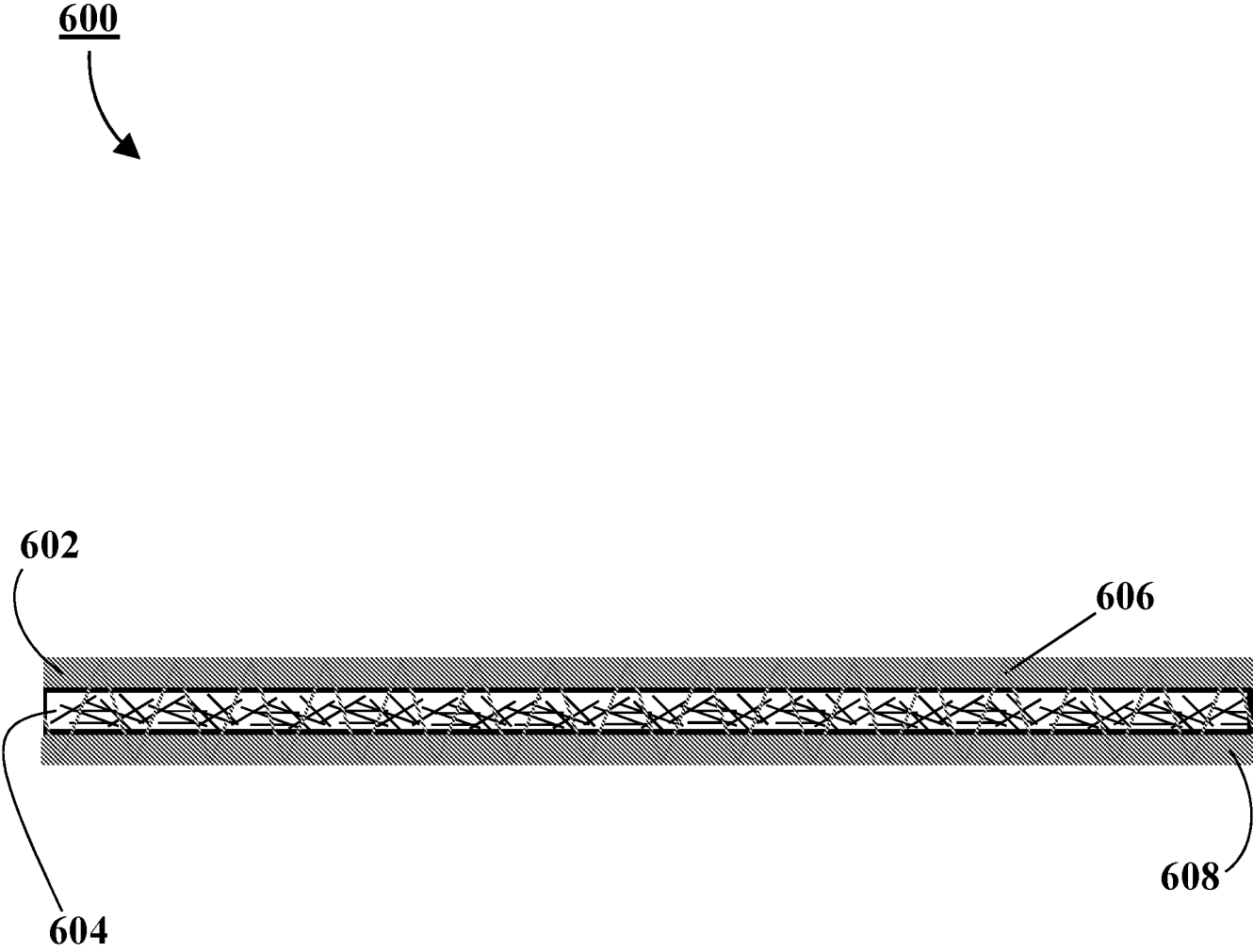


FIG. 6

700

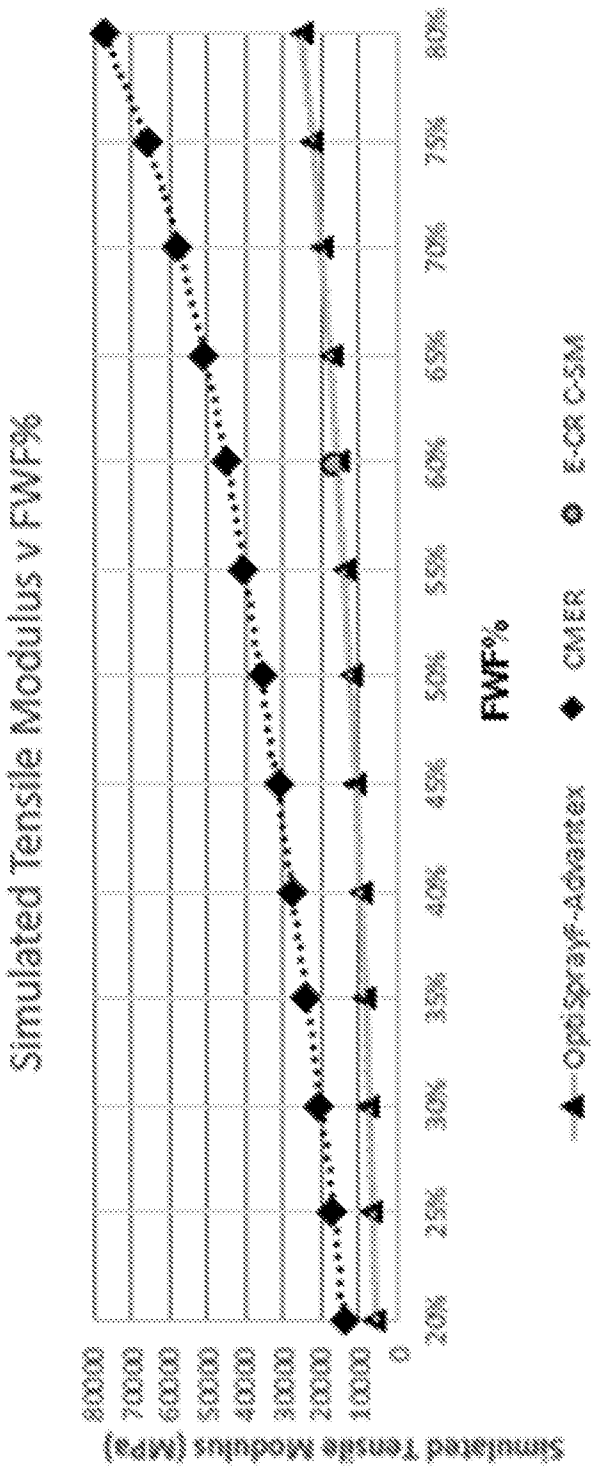


FIG. 7

800

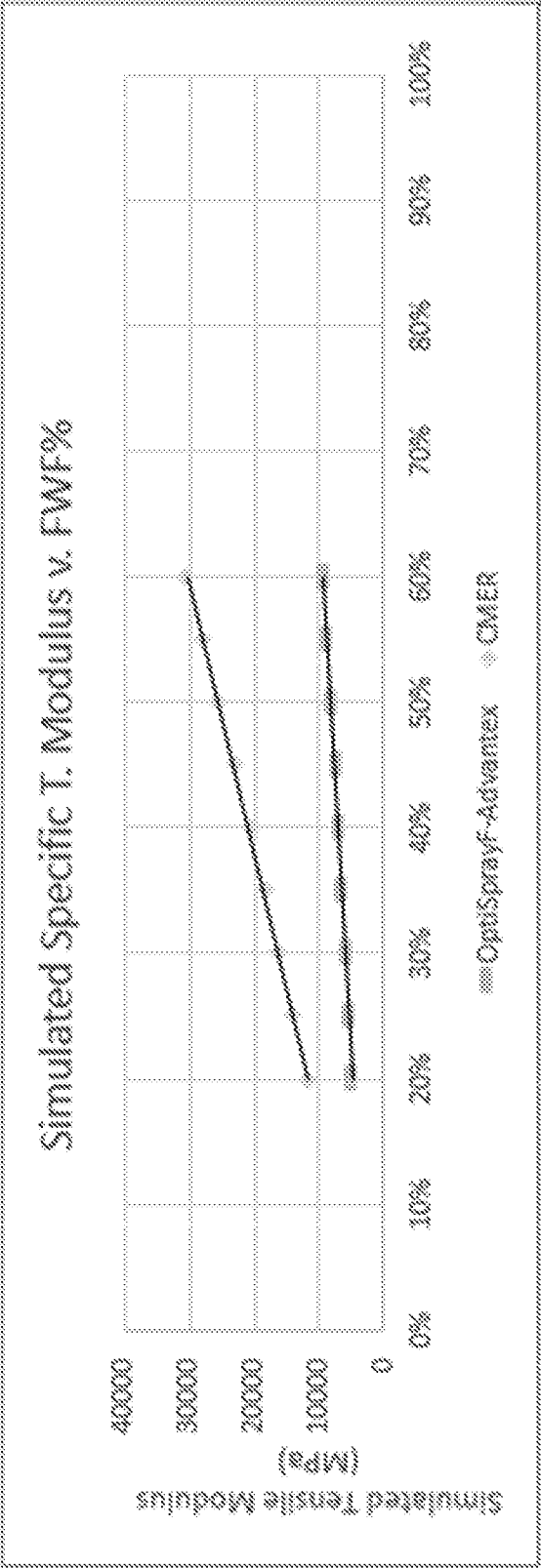


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/062087

A. CLASSIFICATION OF SUBJECT MATTER

INV. D04H1/4242 D04H1/52 D04H1/64 D04H3/002 D04H3/115
D04H3/12 B32B5/06 B32B5/26 B32B5/28 B29C70/18

ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

D04H B32B B29C H05K

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	W0 2018/167076 A1 (GURIT UK LTD [GB]) 20 September 2018 (2018-09-20) pages 26-27 -----	1, 10-32 2-9, 33-42
X A	W0 2017/198568 A1 (HEXCEL REINFORCEMENTS UK LTD [GB]) 23 November 2017 (2017-11-23) figure 1; examples -----	42 1-41
A	W0 2017/062734 A1 (OCV INTELLECTUAL CAPITAL LLC [US]) 13 April 2017 (2017-04-13) cited in the application claims 1, 5 -----	1, 20-28, 30, 32
A	US 2003/107148 A1 (DAVIS TROY A [US] ET AL) 12 June 2003 (2003-06-12) examples -----	42



Further documents are listed in the continuation of Box C.



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

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"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

6 February 2020

Date of mailing of the international search report

17/02/2020

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Authorized officer

Saunders, Thomas

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2019/062087

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