

- 1 -

REMANUFACTURED CARBON FIBER AND RELATED SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application claims the benefit of: US Provisional Patent Application No. 63/612532 filed on December 20, 2023; US Provisional Patent Application No. 63/612534 filed on December 20, 2023; and UK Patent Application No. 2400850.0 filed on January 23, 2024, each of which is incorporated herein by reference in its entirety.

10

BACKGROUND

 A carbon fiber is an elongate strand, having a diameter of about 3 micrometers to about 10 micrometers (especially, about 6 to about 7 micrometers) and containing at least about 90 % w/w carbon atoms, more typically about 93% by weight (w/w) carbon atoms. The length of a carbon fiber may vary. Carbon fibers may comprise 15 graphene and/or nanotubes. Carbon fibers may have a density in a range of, for example, about 1.5 to about 2.5 g/cm³, such as about 1.8 g/cm³. Carbon fibers may typically be produced from a polymer, such as (but not limited to) polyacrylonitrile (PAN). PAN may first be spun into a fiber, which is then heated to drive off non- 20 carbon atoms (carbonization), producing a carbon fiber which may optionally be further treated, for example for improved handling. Besides PAN, other carbon fiber precursors include, for example, rayon and pitch.

 Carbon fibers may give rise to several advantages when added to composite materials. These include providing stiffness and tensile strength while keeping the 25 material lightweight; and resistance to chemical or thermal degradation. Thus, carbon fibers and composite materials comprising carbon fibers have many applications, for example in the automotive, aviation, marine, infrastructure and sports/recreation industries.

 However, despite their popularity, composite materials containing carbon 30 fibers may be difficult to recycle. There is a need for mechanisms of recycling such materials. There is also a need for improved methods for processing virgin (not recycled) carbon fibers.

- 2 -

Recycled or virgin carbon fibers may typically be supplied in the form of a continuous “tow” wound onto a bobbin or reel; or in the form of a bale of fibers. A tow may be defined as a bundle comprising a number of individual carbon fibers of about 1000 to about 60000, which may be held together (and thus protected) by a binding material. However, there may be difficulties in separating carbon fibers held together in, for example, a tow, for use in further processing.

There is also a need for carbon fiber-containing materials having improved properties.

10 SUMMARY

The present disclosure provides for methods of separating attached carbon fibers, carbon fiber separation devices, carbon fiber cutting and separation apparatus, methods of blending carbon fibers, fiber blending devices, forming nonwoven fabrics, nonwoven fabrics, carbon fiber separation and blending apparatus, materials made using these methods and devices, and the like.

In an aspect, the present disclosure provides for methods of separating attached carbon fibers, comprising: directing the attached carbon fibers to the moving surface of a conveyance, separating, at least partially, the carbon fibers on the moving surface of the conveyance, and directing a turbulent fluid flow to further separate the carbon fibers.

In an aspect, the present disclosure provides for methods of forming a nonwoven fabric, comprising: blending carbon fibers with further fibers, wherein a turbulent fluid flow blends the carbon fibers with the further fibers, thereby forming a homogeneous fiber blend; and aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer.

In an aspect, the present disclosure provides an apparatus for forming a nonwoven fabric, comprising: a fiber blending device configured to receive carbon fibers and further fibers, and to form a homogeneous fiber blend, using turbulent fluid flow; a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by aligning carbon fibers in the received homogeneous fiber blend; a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned

- 3 -

fiber layer; and a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.

In an aspect, the present disclosure provides nonwoven fabrics, comprising: a
5 plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters to about 12 centimeters, and a plurality of further fibers; wherein the carbon fibers are dispersed and aligned amongst the further fibers.

In an aspect, the present disclosure provides for carbon fiber separation devices comprising: a conveyance having a moveable surface, with a plurality of
10 protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers.

In an aspect, the present disclosure provides for methods of forming a
15 nonwoven fabric, comprising: blending carbon fibers by directing the carbon fibers onto a moving surface, wherein the carbon fibers are blended on the moving surface, and wherein a turbulent fluid flow further blends the carbon fibers, thereby forming a homogeneous fiber blend; and aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer.

20

BRIEF DESCRIPTION OF DRAWINGS

Further aspects of the present disclosure will be more readily appreciated upon review of the detailed description of its various embodiments, described below, when taken in conjunction with the accompanying drawings.

25 Figure 1 shows a carbon fiber separation device in accordance with the disclosure.

Figure 2 shows an expanded view of the conveyor of the carbon fiber separation device of Figure 1.

Figure 3 is a schematic representation of apparatus for forming a nonwoven
30 fabric in accordance with the disclosure.

Figures 4a and 4b shows differences between a homogeneous fiber blend (Fig 4b) in accordance with the disclosure, and an inhomogeneous fiber blend (Fig 4a).

Figures 5a to 5d show a nonwoven fabric in accordance with the disclosure.

- 4 -

Figures 6a and 6b respectively illustrate forming materials according to the eighth and ninth aspects of the disclosure.

Figures 7a and 7b show articles made from thermoplastic or thermoset material.

5 Figures 8a and 8b show a pipe liner for repair of an existing pipe, made from thermoplastic or thermoset material.

Figure 9 is an SEM image after destructive lab testing of a thermoplastic material (part) according to the eighth aspect of the disclosure.

10 Figure 10 shows graphs of the tensile strength, density and specific tensile strength of the material (part) according to the eighth aspect of the disclosure, in comparison to an analogous aluminum part.

Figures 11-13 are SEM images after destructive lab testing of a thermoplastic material (part) according to the eighth aspect of the disclosure.

15 Figure 14 shows graphs of the tensile strength, density and specific tensile strength of the material (part) according to the eighth aspect of the disclosure, in comparison to an analogous aluminum part.

Figure 15 is a flow chart describing a system for manufacturing a nonwoven fabric for forming a hardened finished part.

Figure 16 is a flow chart describing a thermoset forming system.

20 Figure 17 is a flow chart describing a thermoplastic forming system.

Figure 18 is a flow chart describing a method for manufacturing a nonwoven fabric and forming hardened finished parts.

Figure 19 is a flow chart describing a method of thermoset forming.

Figure 20 is a flow chart describing a method of thermoplastic forming.

25 Figure 21 illustrates a nonwoven needle punched fabric comprising carbon and filler fibers for thermoset forming.

Figure 22 illustrates a nonwoven needle punched fabric comprising carbon and thermoplastic fibers for thermoforming.

30 Figure 23 is a perspective view of a pipe liner that is a tubular fabric placed within a damaged host pipe.

Figure 24 illustrates the fabric of Fig. 23 thermoset into a hardened pipe liner.

Figure 25 is a perspective view of a pipe liner that is a tubular fabric placed within a damaged host pipe.

Figure 26 illustrates the fabric of Fig. 25 thermoformed into a hardened pipe liner.

Figure 27 is a cross-section of one or more pipe liners thermoformed within a host pipe.

5 Figure 28 illustrates comparable cross-sections of various types of pipe liners.

Figure 29 is a graph that illustrates prep and cure time of pipe liner forming systems.

Figure 30 illustrates a pull-in-place process of intra-pipe delivery for forming a pipe liner.

10 Figure 31 illustrates a pig utilized to form a pipe liner inside a host pipe.

Figure 32 illustrates an inversion process of intra-pipe delivery for forming a pipe liner.

Figure 33 is a perspective view of a pipe liner fully inverted into a host pipe.

Figure 34 is a front view of a skid mounted heater assembly.

15 Figure 35 illustrates various components of pipe liner forming subsystems in cross-section.

Figure 36 illustrates systems and processes of curing a pipe liner with heat.

Figure 37 illustrates a hardened finished pipe liner as a pipe repair.

20 DETAILED DESCRIPTION

This disclosure is not limited to particular embodiments described, and as such may, of course, vary. The terminology used herein serves the purpose of describing particular embodiments only, and is not intended to be limiting, since the scope of the present disclosure will be limited only by the appended claims.

Where a range of values is provided, each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between the upper and lower limit of that range and any other stated or intervening value in that stated range, is encompassed within the disclosure. The upper and lower limits of these smaller ranges may independently be included in the smaller ranges and are also encompassed within the disclosure, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included in the disclosure.

- 6 -

Embodiments of the present disclosure will employ, unless otherwise indicated, techniques of textiles, mechanical engineering, and the like, which are within the skill of the art. Such techniques are explained fully in the literature.

The following examples are put forth so as to provide those of ordinary skill in the art with a complete disclosure and description of how to perform the methods and use the compositions and compounds disclosed and claimed herein. Efforts have been made to ensure accuracy with respect to numbers (*e.g.*, amounts, temperature, *etc.*), but some errors and deviations should be accounted for. Unless indicated otherwise, parts are parts by weight, temperature is in °C, and pressure is at or near atmospheric. Standard temperature and pressure are defined as 20 °C and 1 atmosphere.

Before the embodiments of the present disclosure are described in detail, it is to be understood that, unless otherwise indicated, the present disclosure is not limited to particular materials, reagents, reaction materials, manufacturing processes, dimensions, frequency ranges, applications, or the like, as such can vary. It is also to be understood that the terminology used herein is for purposes of describing particular embodiments only, and is not intended to be limiting. It is also possible in the present disclosure that steps can be executed in different sequence, where this is logically possible. It is also possible that the embodiments of the present disclosure can be applied to additional embodiments involving measurements beyond the examples described herein, which are not intended to be limiting. It is furthermore possible that the embodiments of the present disclosure can be combined or integrated with other measurement techniques beyond the examples described herein, which are not intended to be limiting.

It should be noted that, as used in the specification and the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a support” includes a plurality of supports. In this specification and in the claims that follow, reference will be made to a number of terms that shall be defined to have the following meanings unless a contrary intention is apparent.

Each of the applications and patents cited in this text, as well as each document or reference cited in each of the applications and patents (including during the prosecution of each issued patent; “application cited documents”), and each of the PCT and foreign applications or patents corresponding to and/or claiming priority

- 7 -

from any of these applications and patents, and each of the documents cited or referenced in each of the application cited documents, are hereby expressly incorporated herein by reference. Further, documents or references cited in this text, in a Reference List before the claims, or in the text itself, and each of these documents or references (“herein cited references”), as well as each document or reference cited in each of the herein-cited references (including any manufacturer’s specifications, instructions, etc.) are hereby expressly incorporated herein by reference.

Prior to describing the various embodiments, the following definitions are provided and should be used unless otherwise indicated.

10

Discussion

The present disclosure provides for methods of separating attached carbon fibers, carbon fiber separation devices, carbon fiber cutting and separation apparatus, methods of blending carbon fibers, fiber blending devices, forming nonwoven fabrics, carbon fiber separation and blending apparatus, materials made using these methods and devices, and the like.

The following discussion will describe various embodiments generally and then a more detailed description of various aspects will be provided.

In an aspect, the present disclosure provides for methods of separating attached carbon fibers. The method can include directing the attached carbon fibers onto the moving surface of a conveyance (e.g., a conveyor, fluid flow (e.g., air) in a housing) and separating, at least partially (e.g., about 50% or more, about 60% or more, about 70% or more, about 80% or more, about 90% or more, or about 95% or more), the carbon fibers on the moving surface of the conveyance. In an aspect, the conveyance, such as a conveyor, includes a plurality of protrusions on the moving surface of the conveyor that pass between and separate carbon fibers on the moving surface of the conveyor. Then a turbulent fluid flow (e.g., air, water, steam) further separates (e.g., about 70% or more, about 80% or more, about 90% or more, or about 95% or more, about 97% or more) the carbon fibers. In an aspect, the attached carbon fibers (or those that are not separated or separated enough) can be placed on the conveyance again and subjected to the turbulent fluid flow until the attached carbon fibers are separated to a desired amount.

- 8 -

In an aspect, the present disclosure provides for a carbon fiber separation device. The carbon fiber separation device can include a conveyor having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers. The carbon fiber separation device also includes one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers. Methods of the present disclosure can be implemented using the carbon separation device.

In an aspect, the present disclosure provides for methods of forming a nonwoven fabric. The method includes directing the attached carbon fibers onto the moving surface of a conveyance, separating, and directing a turbulent fluid flow as described above and herein. Next the separated carbon fibers can be blended with further fibers by directing the carbon fibers and the further fibers onto a moving surface, where the carbon fibers and the further fibers are blended on the moving surface. In an aspect, the further fibers can be non-carbon fibers. In another aspect, the further fibers can be second amount of carbon fibers, where the second amount of carbon fibers are subsequently added to the initial carbon fibers. In another aspect, the blending may be of only carbon fibers without any further fibers added, where each of the method steps can be performed in the absence of the further fibers. The moving surface can be a conveyance such as that described above and herein that include protrusions. Then a turbulent fluid flow can be used to further blend the carbon fibers with the further fibers, thereby forming a homogeneous fiber blend. The method can also include aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer. In addition, the method can include cross-lapping the aligned fiber layer to form a cross-lapped fiber layer. Further, the method can include mechanically entangling the aligned fiber layer or the cross-lapped fiber layer, thereby forming the nonwoven fabric.

In an aspect, the present disclosure provides for an apparatus for forming a nonwoven fabric, comprising: a carbon fiber separation device configured to separate carbon fibers from attached carbon fibers using turbulent fluid flow; a fiber blending device configured to receive carbon fibers and optionally further fibers, and to form a homogeneous fiber blend, using turbulent fluid flow; a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and

- 9 -

further configured to form an aligned fiber layer by aligning fibers in the received homogeneous fiber blend; a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer. Methods of forming nonwoven fabric can be implemented using the apparatus for forming nonwoven fabric. In an aspect, blending only the carbon fibers may be desired or blending the carbon fibers with a second amount of carbon fibers may be desired. In an aspect, prior to mechanical entanglement, the blend of fibers that contain carbon fiber (and optionally further fibers and/or resin) can be lightly tacked. In an aspect, entangling or physically attaching the fibers to each other can be accomplished by the application of a controlled and limited heat source and temperature sufficient to create a tack or adhesion between the further fibers and the carbon fibers and/or using a minimal amount of needling, which can be used prior to the mechanical entanglement or to replace the mechanical entanglement. In an aspect, the light tack can include heating the nonwoven fabric in or using an oven, an infrared, a microwave or other appropriate heat source for nonwoven fabrics.

In an aspect, the present disclosure provides for nonwoven fabric. In an aspect, the nonwoven fabric includes a plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters to about 12 centimeters and a plurality of further fibers. The carbon fibers can optionally be dispersed amongst the further fibers. In an aspect, the nonwoven fabric includes the separated carbon fibers obtained from the methods and devices described herein (or other sources of carbon fibers) or the blended carbon fibers and further fibers obtained from the methods and devices described herein.

Now having described aspects of the present disclosure, various aspects will now be provided.

According to a first aspect of the present disclosure, there is provided a method of separating attached carbon fibers (e.g., having a mean length of about 5 centimeters to 12 centimeters), that includes:

- 10 -

- directing the attached carbon fibers onto the moving surface of conveyance (e.g., a conveyor) such that a plurality of protrusions on the moving surface of the conveyor pass between and separate carbon fibers on the moving surface of the conveyance (e.g., a conveyor), and
- 5 - directing a turbulent fluid flow to further separate the carbon fibers.

According to a second aspect, the present disclosure provides a carbon fiber separation device comprising:

- a conveyance (e.g., a conveyor) having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and
- 10 - one or more generators of a turbulent fluid flow, configured to direct a turbulent fluid flow to further separate the carbon fibers.

According to a third aspect of the present disclosure, there is provided a carbon fiber cutting and separation apparatus, the carbon fiber cutting and separation apparatus comprising a carbon fiber separation device according to the second aspect of the disclosure and a cutting device upstream of the carbon fiber separation device.

According to a fourth aspect, the present disclosure provides a plurality of separated carbon fibers obtained or obtainable by a method in accordance with the first aspect.

According to a fifth aspect, the present disclosure provides a method of blending carbon fibers (preferably, separated carbon fibers, most suitably obtainable by a method in accordance with the first aspect of the disclosure; preferably, having a length of about 5 centimeters to about 12 centimeters) optionally with a plurality of further fibers, the method comprising:

- directing the carbon fibers and the optional further fibers onto the moving surface of a conveyance (e.g., a conveyor) such that the carbon fibers and the optional further fibers are blended by a plurality of protrusions on the moving surface, and
- 25 - directing a turbulent fluid flow to further blend the carbon fibers with the optional further fibers,
- 30 thereby forming a homogeneous fiber blend.

- 11 -

The method of blending separated carbon fibers may be incorporated in a method of forming a nonwoven fabric, which may further comprise one or more (preferably, all) of the following steps:

- 5 - aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer,
- cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and
- mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric.

Also provided is a method of separating carbon fibers (preferably, having a length of about 5 centimeters to about 12 centimeters) and blending the separated carbon fibers optionally with a plurality of further fibers, comprising performing a method in accordance with the first aspect of the disclosure then performing a method in accordance with the fifth aspect of the disclosure.

According to a sixth aspect, the present disclosure provides a fiber blending device configured to receive carbon fibers (preferably, separated carbon fibers, most suitably obtainable by a method in accordance with the first aspect of the disclosure; preferably having a length of about 5 centimeters to about 12 centimeters) and optional further fibers, and to form a homogeneous fiber blend, the device comprising:

- 20 - a conveyance (e.g., a conveyor) having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured for blending the carbon fibers with the optional further fibers, and
- 25 - one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further blend the carbon fibers with the optional further fibers.

Also provided is a carbon fiber separation and blending apparatus, comprising a carbon fiber separation device according to the second aspect of the disclosure and a fiber blending device according to the sixth aspect of the disclosure.

Also provided is a homogeneous fiber blend obtainable or obtained by a method according to the fifth aspect of the disclosure.

Also provided is an apparatus for forming a nonwoven fabric, which comprises the fiber blending device and one or more (preferably, all) of the following:

- 12 -

- (optional) a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by aligning fibers in the received homogeneous fiber blend,
- 5 - a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and
- a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a
- 10 nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.

In an aspect, the apparatus for forming a nonwoven fabric further comprises a carbon fiber separation device according to the second aspect of the disclosure or the carbon fiber cutting and separation device according to the third aspect of the

15 disclosure.

It has been found that bringing together all of: the carbon fiber separation device (or carbon fiber cutting and separation device); the fiber aligning device (such as a carding device); the cross-lapper; and the mechanical entanglement device (such as a needle punching device), in combination, may have a surprising synergistic effect

20 on the strength of the nonwoven fabric produced by the apparatus.

According to a seventh aspect of the present disclosure, there is provided a nonwoven fabric, comprising:

- a plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters (preferably, about 5 centimeters) to about
 - 25 12 centimeters, and
 - a plurality of further fibers;
- wherein the carbon fibers are dispersed amongst the further fibers.

In an eighth aspect, the present disclosure provides a material which is a thermoformed product of (or which is obtainable by thermoforming) a nonwoven

30 fabric according to the seventh aspect of the disclosure wherein the further fibers are non-carbon thermoplastic fibers.

- 13 -

In a ninth aspect, the present disclosure provides a material comprising a thermoset resin and a nonwoven fabric according to the seventh aspect of the disclosure, wherein the further fibers are non-carbon filler fibers.

It will be appreciated that features described in relation to one aspect of the present disclosure may be incorporated into other aspects of the present disclosure.

As described above and herein, the present disclosure provides for a method of separating attached carbon fibers. The carbon fibers can be attached to each other by binding material on the surface of the carbon fibers. The method includes directing the attached carbon fibers onto the moving surface of a conveyor such that protrusions pass between and separate carbon fibers on the moving surface of the conveyor. A turbulent fluid flow can be used to further separate the carbon fibers. Separation of the carbon fibers may include detaching binding material from the carbon fibers.

In addition, the present disclosure provides a carbon fiber separation device. The carbon fiber separation device can be implemented in the method described above and herein. The carbon fiber separation device can include a conveyance (e.g., a conveyor) and one or more generators of a turbulent fluid flow. The conveyor includes a moveable surface that includes a plurality of protrusions protruding therefrom. The protrusions are configured to pass between and separate the carbon fibers from the binding material. The generators of a turbulent fluid flow can direct a turbulent fluid flow to further separate the carbon fibers from the binding material. A description of an embodiment of the device is provided herein with reference to Figure 1; a description of the protrusions on the moveable surface is provided herein with reference to Figure 2.

The carbon fibers may have, or be cut to have, a mean length of about 5 centimeters to about 12 centimeters (especially, about 6 centimeters to about 11.5 centimeters, such as about 7.6 centimeters; 7.6 centimeters may be the optimal mean length; nevertheless, a few fibers (e.g., less than 2%, less than 5% or less than 10%) shorter than 5 centimeters may be present). Without wishing to be bound by theory, it has been found that carbon fibers having lengths in this range may improve the strength of a nonwoven fabric produced therefrom. Shorter fibers may be difficult to process, for example, because they may more easily be airborne; and may lead to weaker materials. Meanwhile, longer fibers may face difficulties in fiber aligning; for instance, when aligning comprises carding, they may become caught in carding wires

- 14 -

and cause one or more blockages. The mean length of the carbon fibers may suitably be measured by scanning electron microscopy (SEM).

The mean diameter of the carbon fibers may typically be about 3 micrometers to about 10 micrometers, especially about 6 micrometers to about 8 micrometers. The mean diameter of the carbon fibers may suitably be measured by scanning electron microscopy (SEM).

Thus, the ratio of the mean diameter of the carbon fibers to the mean length of the carbon fibers may be about 1:7,000 to about 1:26,000; such as about 1:6,000 to about 1:20,000, preferably about 1:10,000 to about 1:13,000.

The present disclosure also provides for a method of blending carbon fibers optionally with a plurality of further fibers. The carbon fibers can be separated by a method disclosed herein. Advantageously, separation of the carbon fibers is complete before blending begins. Some further fibers come with high tow/filament counts and must also be opened before blending; thus, the further fibers may also be separated from their tows via the carbon fiber separation device. The further fibers are preferably not carbon fibers (also referred to as "non-carbon fibers"). The blend produced is homogeneous.

In addition, the disclosure provides a fiber blending device. The fiber blending device can be implemented in the method described above and herein. The fiber blending device can include a conveyor and one or more generators of a turbulent fluid flow. The conveyor includes a moveable surface that includes a plurality of protrusions protruding therefrom. The protrusions are configured to blend the carbon fibers and the further fibers. The generators of a turbulent fluid flow can direct a turbulent fluid flow to further blend the carbon fibers with the further fibers. The blend produced by the device is homogeneous. A description is provided herein with reference to Figure 4b.

The blend of carbon fibers and further fibers can be used to form a nonwoven fabric. This can be accomplished by aligning (e.g., carding) carbon fibers in the blend to form an aligned fiber layer; cross-lapping the aligned fiber layer to form a cross-lapped fiber layer; and mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric. A description is provided herein with reference to Figures 5a to 5d.

- 15 -

Where the further fibers are thermoplastic fibers, the nonwoven fabric can be thermoformed. This has been found to result in an especially strong thermoformed material, for example with properties improved compared to corresponding aluminum material, as illustrated in Figure 6a and in Examples 3 and 4 with reference to Figures 9 to 14. It can be used to form articles as shown in Figures 7a to 8b.

Where the further fibers are filler fibers, the nonwoven fabric can be combined with a thermosetting resin, then be thermoset. This has been found to result in an especially strong thermoset material, for example with properties improved compared to corresponding aluminum material, as illustrated in Figure 6b and in Examples 1 and 2 hereinbelow. It can be used to form articles as shown in Figures 7a to 8b.

Thus, according to a first aspect of the present disclosure, there is provided a method of separating attached carbon fibers (preferably, having a mean length of about 5 centimeters to about 12 centimeters), comprising:

- directing the attached carbon fibers onto the moving surface of a conveyance (e.g., a conveyor) such that a plurality of protrusions on the moving surface of the conveyor pass between and separate carbon fibers on the moving surface of the conveyor, and
- directing a turbulent fluid flow to further separate the carbon fibers.

According to a second aspect, the present disclosure provides a carbon fiber separation device comprising:

- a conveyance (e.g., a conveyor) having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and
- one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers.

The present method of separating carbon fibers avoids striking the carbon fibers. It has been found that methods for separating carbon fibers wherein the carbon fibers are struck or otherwise subjected to force, especially concussive force, may lead to excessive breakage of the carbon fibers. Without wishing to be bound by theory, it is thought that this may significantly reduce the strength of a nonwoven fabric produced from the carbon fibers. It is thought that this may be particularly problematic when the carbon fibers are recycled carbon fibers.

- 16 -

As used herein, the term “recycled carbon fibers” refers to carbon fibers provided not by synthesis of carbon fibers from raw materials, but by the salvaging (i.e., reclaiming) of carbon fibers from prior applications, such as composite materials (for example, those used in automotive parts); especially from materials which are one or more of excess materials, materials having out-of-date certifications, off-spec materials, bobbins with short volumes remaining, fabric cutting selvage, production waste, and cured composite materials.

Thus, in an aspect, one or more of the methods described herein comprises or comprise preserving the length of carbon fibers while separating the carbon fibers. This is achieved through slow, gentle separation of the carbon fibers, described in the methods, apparatuses and devices described herein. Until now there has been a prejudice against slowing down the separation of fibers, as this may be perceived to increase manufacturing time and thus reduce efficiency and increase costs. There has been a drive towards fiber dwell times in separation devices of less than about 5 minutes. However, it has now surprisingly been found that specifically for carbon fibers, the benefits of slow and gentle separation outweigh the costs.

In an aspect, preserving the length of carbon fibers comprises preserving the length of at least about 75% (or at least about 65%, at least about 80%, at least about 85%, or at least about 90%) of the carbon fibers in the plurality of carbon fibers. Without wishing to be bound by theory, promoting preservation of the length of the carbon during separation (i.e., reducing breakage of the carbon fibers during separation) has been found to provide a stronger nonwoven fabric and stronger materials produced therefrom. The devices and apparatuses described herein may advantageously be configured accordingly.

In an aspect, the protrusions protruding from the surface of the conveyor are or comprise tapered fingers. Thus, the protrusions are preferably elongate (substantially longer than they are wide). The protrusions are dimensioned and configured to aid separation of the carbon fibers, especially in a gentle manner. Thus, the protrusions are dimensioned in accordance with the dimensions of carbon fibers (which have a diameter of about 3 micrometers to about 10 micrometers, as described herein). The protrusions may be rigid. The protrusions may be flexible and/or may be flexibly attached to the conveyor, the better to effect gentle separation. The height of the protrusions may be about 10 mm to about 50 mm, especially about 30 mm to about 50

- 17 -

mm. The protrusions may be angled relative to the surface of the conveyor, such as at an angle of about 30 to about 60 degrees, especially about 40 to about 50 degrees. The protrusions may suitably be made of metal, such as aluminum or steel; or they may be made of plastic, such as PVC. The protrusions may be spaced apart along the length
5 of the surface of the conveyor at regular intervals, such as at intervals of about 30 mm to about 100 mm, especially about 40 mm to about 80 mm. The protrusions may be spaced apart along the width of the surface of the conveyor at regular intervals, such as at intervals of about 10 mm to about 100 mm, especially about 20 mm to about 40 mm. There may be rows of protrusions on the surface of the conveyor, which may
10 preferably be staggered rows, the better to achieve separation of carbon fibers. Exemplary protrusions may be or comprise steel spikes on the surface of a conveyor which is a conveyor belt, especially a belt which is or comprises a lattice apron at an incline.

The protrusions can gently insert between carbon fibers brushing past them,
15 thereby separating the carbon fibers without undue breakage (e.g., about 25% or less, about 20% or less, about 15% or less) of the carbon fibers. This is in contrast to hammering or striking the carbon fibers to separate them, which has been found to cause breakage of the carbon fibers. Previously, little or no consideration was given to the breakage of carbon fibers during separation, but it has been surprisingly found that
20 by reducing breakage as described herein, a stronger carbon fiber-containing end product may be formed.

Thus, in an aspect, the length of at least about 75% of the carbon fibers is preserved (compared to unseparated but otherwise identical carbon fibers such as the starting material for the method according to the first aspect of the disclosure) during
25 the method according to the first aspect of the disclosure; and said method provides that at least about 80% (more preferably, at least about 90%) of the carbon fibers are unattached from each other.

Similarly, the apparatus according to the second and third aspects of the disclosure is preferably configured for use in a method of separating carbon fibers
30 wherein the length of at least about 75% of the carbon fibers is preserved and the method provides that at least about 80% (more preferably, at least about 90%) of the carbon fibers are unattached from each other.

- 18 -

In the plurality of separated carbon fibers according to the fourth aspect of the disclosure, preferably, the length of at least about 75% of the carbon fibers is preserved compared to an unseparated but otherwise identical plurality of carbon fibers (such as the starting material for the method according to the first aspect of the disclosure) and at least about 80% (more preferably, at least about 90%) of the carbon fibers are unattached from each other.

In an aspect, at least about 80% (more preferably, at least about 90%) of the carbon fibers used (as starting material) in the method according to the fifth aspect of the disclosure are unattached from each other; and the length of at least about 75% of the carbon fibers is preserved both prior to and during said method (compared to unseparated but otherwise identical carbon fibers such as the starting material for the method according to the first aspect of the disclosure).

The fiber blending device according to the sixth aspect of the disclosure is preferably configured for receiving separated carbon fibers wherein the length of at least about 75% of the carbon fibers is preserved (compared to unseparated but otherwise identical carbon fibers such as the starting material for the method according to the first aspect of the disclosure) and at least about 80% (more preferably, at least about 90%) of the carbon fibers are unattached from each other.

In an aspect, in the non-woven fabric according to the seventh aspect of the disclosure (and thus in the materials according to the eighth and ninth aspects of the disclosure) the length of at least about 75% of the carbon fibers is preserved (compared to unseparated but otherwise identical carbon fibers such as the starting material for the method according to the first aspect of the disclosure) and at least about 80% (more preferably, at least about 90%) of the carbon fibers are unattached from each other.

It will be understood that all references to the length of the carbon fibers being preserved can equally refer to the carbon fibers in question being unbroken, as can be ascertained by scanning electron microscopy. Thus, in all aspects of the disclosure, references to the length of at least about 75% of the carbon fibers being preserved means that at least about 75% of the carbon fibers are unbroken.

Meanwhile, failure of carbon fiber-to-resin adhesion may be one of the primary modes of failure in composite materials containing carbon fibers, such as those comprising (e.g., formed from) nonwoven fabrics containing carbon fibers. It

- 19 -

has surprisingly been found that this mode of failure may be mitigated or prevented by the presently described thorough separation of carbon fibers which, importantly, happens prior to (and is finished before; it does not occur concurrently with) blending with the further fibers described herein. Without wishing to be bound by theory, it is
5 thought that the presently described separation of carbon fibers from each other (especially, while reducing or preventing breakage of carbon fibers) may enhance carbon fiber-to-resin adhesion in materials in accordance with the eighth and ninth aspects of the present disclosure. It may mitigate or prevent failure of resin to contact carbon fibers fully in “voids”, “dry spots” or “wet-out failures”. Properly separating
10 carbon fibers before blending them with the further fibers described herein may increase the surface area available for carbon fiber-to-resin contact and thus adhesion. Put another way, separation may act in synergy with blending to increase the performance (especially, strength) of the final product.

It will be appreciated that, as used herein, the terms “upstream” and
15 “downstream” are relative to the direction of motion of carbon fibers. Optionally, the carbon fiber separation device comprises a housing having an inlet upstream of the conveyor and the one or more generators of a turbulent fluid flow and an outlet downstream of the conveyor and the generator(s).

Optionally, the inlet comprises one or more feeder lines (for example, blower
20 ducts and/or conveyor belts) for feeding carbon fibers to the surface of the conveyor. This may have the advantage of ensuring the safety of operators while enabling continuous processing of carbon fibers.

In an aspect, the conveyor is upstream of a turbulent fluid flow zone in which a turbulent fluid flow, generated by the one or more generators of a turbulent fluid
25 flow, is directed to separate the carbon fibers. The conveyor may be connected to the turbulent fluid flow zone, which may be a container or compartment, by one or more ducts.

In an aspect, the conveyor is an apron having a surface (especially, a lattice apron; most especially a flexible lattice apron). Thus, directing the attached carbon
30 fibers onto the moving surface of the conveyor may be or comprise operating the lattice apron to carry carbon fibers along the surface of the lattice apron. Using a conveyor which is a lattice apron may help to reduce the net force on the carbon fibers, thereby further mitigating the risk of carbon fiber breakage.

- 20 -

In an aspect, the surface of the conveyor is disposed at an incline or configured to be disposed at an incline. Therefore, preferably, directing carbon fibers onto the moving surface of the conveyor is or comprises directing carbon fibers onto the inclined moving surface of the conveyor against gravity. As used herein, the term
5 incline has its normal meaning in the art, being used to mean an angle to the horizontal of more than 0 degrees and less than 90 degrees, such, for example, as an angle of about 10 degrees to about 80 degrees, especially about 20 degrees to about 70 degrees. Thus, carrying carbon fibers up the incline is against gravity. It will be appreciated that as used herein, the term "horizontal" is relative to the ground or floor.

10 In an aspect, the conveyor is a lattice apron having an inclined moveable surface. Thus, in an aspect, directing carbon fibers onto the moving surface of the conveyor is or comprises directing carbon fibers onto the inclined moving surface of the lattice apron.

Nevertheless, the movement of carbon fibers may additionally or alternatively
15 occur by other mechanisms, especially by upstream carbon fibers pushing downstream carbon fibers; and/or by pneumatic conveyance of the carbon fibers.

As used herein, the term "a turbulent fluid flow" refers to at least one jet of fluid (preferably, air) moving under unbalanced forces. Suitably, the jet has a Reynolds number of at least about 3500, such as at least about 4000. The one or more
20 generators of a turbulent fluid flow are not baffles or other obstruction simply configured to change the direction of an existing flow of fluid. Instead, they are the originators of a flow of fluid which is turbulent, preferably machines configured to force fluid into a turbulent jet. It will be appreciated that multiple generators may together be used to create a "single" area of turbulent fluid flow, or multiple areas of
25 turbulent fluid flow separated by areas of non-turbulent fluid.

The fluid can be air, water, or a combination of air and water (e.g., steam). In an aspect, the fluid is air. The fluid can be at ambient temperature or at a temperature of about 40 to about 90 °C.

The one or more generators may be or comprise one or more machines
30 (especially, one or more engines and/or one or more motors) configured to blow one or more jets of fluid, especially air. Suitably, the jets of fluid (especially, air) have a Reynolds number of at least about 3500, such as at least about 4000.

- 21 -

The turbulent fluid flow generator(s) may be or comprise one or more cyclones, such as, but not limited to, a cyclone obtainable from US Duct (of 4898 McCracken Rd., Kernersville, NC 27284, USA). Other ways for generating a turbulent fluid flow will be apparent to those of skill in the art.

5 Until now, it has not been appreciated that the combination of a turbulent fluid flow with the conveyor described herein can provide extremely gentle separation of carbon fibers. A turbulent fluid flow may advantageously provide for separation at particularly low impact.

10 For the avoidance of doubt, when a housing is present, the one or more generators of a turbulent fluid flow are downstream of the inlet of the housing and upstream of the outlet of the housing.

15 As described herein, in an aspect, the conveyor is upstream of a turbulent fluid flow zone in which a turbulent fluid flow, generated by the one or more generators of a turbulent fluid flow, is directed to separate the carbon fibers. The conveyor may be connected to the turbulent fluid flow zone, which may be a container or compartment, by one or more ducts.

Optionally, when a housing is provided, the inlet is upstream of the conveyor, the conveyor is upstream of the turbulent fluid flow zone and the turbulent fluid flow zone is upstream of the outlet.

20 The one or more generators of a turbulent fluid flow may be suitably positioned to direct a turbulent fluid flow into the turbulent fluid flow zone to separate the carbon fibers; but the one or more generators of a turbulent fluid flow need not themselves be disposed inside the turbulent fluid flow zone.

25 Optionally, carbon fibers may be circulated through the turbulent fluid flow zone more than once (before being discharged, for example before being discharged from the outlet of the housing described herein). In some embodiments, a number of about 20 to about 30% of the carbon fibers may be separated by the protrusions protruding from the surface of the conveyor; with the remainder of the separation occurring in the turbulent fluid flow zone (e.g., compartment).

30 Nevertheless, there may be a flow of fluid turbulence at or proximate the surface of the conveyor. Optionally, the one or more generators of a turbulent fluid flow may be so disposed as to provide one or more flows of fluid turbulences at or close to the surface of the conveyor.

- 22 -

In an aspect, the fluid is air, thus the turbulent fluid flow is a turbulent air flow.

In an aspect, also provided is a recirculation mechanism, for recirculating unseparated (remaining attached) carbon fibers to the conveyor (which preferably is an inclined lattice apron), especially for recirculating bundles of attached carbon fibers if present. Additionally or alternatively, there may be provided a recirculation mechanism for recirculating unseparated (remaining attached) carbon fibers to the conveyor or a further (preferably substantially identically functioning) carbon fiber separation device. Recirculation may lead to increased separation of the carbon fibers and thus to one or more advantages as described herein.

In an aspect, the carbon fiber separation device is configured to exclude bundles of attached carbon fibers from the carbon fibers discharged therefrom (e.g., from the outlet). Thus, the method of separating carbon fibers may comprise excluding bundles of attached carbon fibers from the carbon fibers discharged from the carbon fiber separation device (e.g., discharged from the outlet thereof).

In an aspect, the carbon fiber separation device comprises one or more controllers to control the dwell time of carbon fibers in the carbon fiber separation device. The dwell time in the carbon fiber separation device may suitably be about 5 minutes to about 3 hours, such as about 5 minutes to about 30 minutes. This has advantageously been found to promote gentle yet substantially complete separation of carbon fibers.

It has been found that using a series of carbon fiber separation devices and/or one or more controllers to control dwell time may increase throughput efficiency, for example enabling an operator to vary separation in dependence on the type(s) of carbon fiber starting material.

The attached carbon fibers may be bundles of attached carbon fibers. Each bundle may contain a number of attached carbon fibers of about 1000 to about 60000, especially about 3000 to about 60000. Such bundles may be known in the art as "tows". Suitably, separating the carbon fibers comprises separating carbon fibers from the bundles of attached carbon fibers. In an aspect, bundles are excluded from the carbon fibers that proceed to the step of blending separated carbon fibers with a plurality of further fibers.

- 23 -

The bundles of attached carbon fibers may be supplied as bundles of attached carbon fibers having a length of more than 12 centimeters. Thus, the cutting step described herein may be a step of cutting bundles of attached continuous carbon fibers to form bundles of attached carbon fibers having a mean length of from about 5
5 centimeters to about 12 centimeters.

Alternatively, the bundles of attached carbon fibers may be supplied as bundles of attached carbon fibers already having a mean length of about 5 centimeters to about 12 centimeters, so that no cutting step is required.

The attached carbon fibers may be attached to each other by binding material
10 on the surface of the carbon fibers. As used herein, the term binding material has its usual meaning in the art and refers to a substance for attaching carbon fibers to each other, such as an adhesive. Separating the carbon fibers may be or comprise detaching binding material, such as by forming cracks in binding material. Binding material, without limitation, may be or comprise epoxy, polyurethane, polyamide, polyethylene
15 oxide (PEO) and/or polyvinyl alcohol (PVA). As described herein, recycled or virgin carbon fibers may typically be supplied in the form of a continuous “tow” wound onto a reel, held together (and thus protected) by a binding material.

The carbon fiber separation device may further comprise one or more agitator rolls, which may be proximate the conveyor, each agitator roll being for brushing
20 carbon fibers (e.g., comprising protrusions on its surface, in the same manner as the conveyor). Thus, the method may further comprise a step of operating the agitator rolls to brush carbon fibers. The agitator rolls may be so disposed as to brush carbon fibers on or close to the surface of the conveyor. In an aspect, they are so disposed as to brush carbon fibers in a space downstream of the conveyor (and upstream of the
25 outlet if present). If the agitator rolls are so disposed as to brush carbon fibers in a space downstream of the conveyor (and, if present, upstream of the outlet), then the one or more generators of a turbulent fluid flow may be so configured as to provide a turbulent fluid flow in at least a further space, namely a turbulent fluid flow zone, downstream of the space in which the agitator rolls brush carbon fibers (and, if
30 present, upstream of the outlet). It has been found that using the conveyor, the one or more agitator rolls, and the turbulent fluid flow in that order (i.e., in sequence) may provide a convergent (increasingly gentle) thus especially gentle way of separating carbon fibers. The conveyor may suitably provide for “coarse” separation, the one or

- 24 -

more agitator rolls for “medium” separation, and the turbulent fluid flow (as provided by the one or more generators of a turbulent fluid flow) for “fine” separation. Thus, the device may comprise the conveyor (downstream of the inlet, if present), the one or more agitator rolls downstream of the conveyor, and a turbulent fluid flow zone
5 downstream of the one or more agitator rolls (and, if present, the outlet downstream of the turbulent fluid flow zone).

Also provided is a method of cutting and separating carbon fibers, comprising a step of cutting attached carbon fibers to have a mean length of about 5 centimeters to about 12 centimeters, prior to separating the cut (but still attached to each other,
10 e.g. in bundles) carbon fibers by a method in accordance with the first aspect of the disclosure.

Thus, according to a third aspect of the present disclosure, there is provided carbon fiber cutting and separation apparatus, the carbon fiber cutting and separation apparatus comprising a carbon fiber separation device according to the second aspect
15 of the disclosure and a cutting device upstream of the carbon fiber separation device.

The cutting device may comprise a precision cutting system configured to cut fibers to length with +/- 5 % accuracy. Suitable cutting systems are known in the art, but until now their application in precision cutting of carbon fibers to have a mean length of about 5 centimeters to about 12 centimeters, especially about 7.6
20 centimeters, in accordance with the present disclosure, had not been appreciated; nor the advantages of such lengths in mechanical entanglement, especially carding processes.

In an aspect, in accordance with all aspects of the disclosure, the term “separated” means that at least about 80% (more preferably, at least about 85%, at
25 least about 90%, at least about 95%) of the carbon fibers are unattached from each other after separation on the moving surface of the conveyor and/or the subjected to the turbulent fluid flow. As used herein, “unattached” means not chemically bonded (especially, not covalently bonded) to each other. It may especially mean not being attached by binding material; since, as described herein, separating the carbon fibers
30 may be or comprise detaching binding material. Nevertheless, it will be appreciated that a few carbon fibers may remain in physical contact with each other. Having at least about 80% (more preferably, at least about 85%, at least about 90%, at least about 95%) of the carbon fibers unattached from each other, while reserving a few

- 25 -

carbon fibers in physical contact, may optimize the strength of layers, fabrics and materials resulting therefrom.

When carbon fibers are separated from each other in accordance with all aspects of the disclosure (especially, in a material according to the eighth or ninth aspect of the disclosure), the mean distance between the closest points of adjacent carbon fibers may preferably be more than about 0.5 micrometers, especially more than about 5 micrometers, such as more than about 10 micrometers. Having a separation of at least about 0.5 micrometers means that the carbon fibers, themselves having a diameter of about 3 micrometers to about 10 micrometers (especially, about 6 to about 7 micrometers), are well separated. This may be measured by SEM imaging of a sample containing carbon fibers, the sample preferably comprising at least about 100 (preferably, at least about 200) carbon fibers. As used herein, “adjacent carbon fibers” means neighboring carbon fibers; carbon fibers are not adjacent if at least one other carbon fiber is disposed between them. Nevertheless, there may be other objects (especially, the non-carbon further fibers described herein) between adjacent carbon fibers, without affecting the adjacency of said carbon fibers.

Thus, according to a fourth aspect, the present disclosure provides a plurality of separated carbon fibers obtained or obtainable by a method in accordance with the first aspect, optionally wherein the mean distance between the closest points of adjacent carbon fibers is more than about 0.5 (especially, about 5) micrometers. The plurality of separated carbon fibers is suitably configured to produce a material according to the eighth or ninth aspect of the disclosure wherein, in the material, the mean distance between the closest points of adjacent carbon fibers is more than about 0.5 (especially, about 5) micrometers.

It has been surprisingly found that the same way by which carbon fibers can be separated gently without breakage can also serve to induce extremely homogeneous blending of the separated carbon fibers with other fibers, without inducing much breakage of the carbon fibers. Therefore, the fiber blending device preferably has some or all of the features of the carbon fiber separation device.

Also, as described herein, it has surprisingly been found that carbon fiber-to-resin adhesion may be improved by the presently described thorough blending of carbon fibers with further fibers to form a homogeneous blend, as opposed to a non-

- 26 -

homogeneous blend. Thorough mixing mitigates against “clumps” of carbon fibers; clumps may prevent resin fully contacting (“wetting out”) carbon fiber.

Thus, according to the fifth aspect of the disclosure there is provided a method of blending carbon fibers (preferably, separated carbon fibers, most suitably obtainable by a method in accordance with the first aspect of the disclosure; and preferably having a length of about 5 centimeters to about 12 centimeters) the method comprising:

- directing the carbon fibers and the further fibers onto the moving surface of a conveyance (e.g., a conveyor) such that the carbon fibers and the further fibers are blended by a plurality of protrusions on the moving surface, and/or
 - directing a turbulent fluid flow to further blend the carbon fibers with the further fibers,
- thereby forming a homogeneous fiber blend.

The step of directing the carbon fibers and the further fibers onto the moving surface of a conveyance (e.g., a conveyor) (such that the carbon fibers and the further fibers are blended by a plurality of protrusions on the moving surface) may be optional. That step may be omitted. Alternatively, that step may be replaced, for example replaced by a step of directing the carbon fibers and the further fibers into a duct or chamber, within which the carbon fibers and the further fibers are subjected to the step of directing a turbulent fluid flow to further blend the carbon fibers with the further fibers. Suitably, the duct or chamber contains a turbulent fluid flow zone described herein in which a turbulent fluid flow, generated by the generator(s) of a turbulent fluid flow, is directed to blend the carbon fibers with the further fibers.

Optionally, the method of blending separated carbon fibers is incorporated in a method of forming a nonwoven fabric, which further comprises one or more (preferably, all) of the following steps:

- aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer,
- cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and
- mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric.

Especially preferred is a method of forming a nonwoven fabric, comprising:

- 27 -

- separating carbon fibers having a length of about 5 centimeters to about 12 centimeters (such as by a method in accordance with the first aspect of the disclosure);
 - 5 - blending the separated carbon fibers with further fibers (such as by a method in accordance with the fifth aspect of the disclosure), thereby forming a homogeneous fiber blend;
 - aligning (especially, carding) the fibers in the homogeneous fiber blend to form an aligned fiber layer;
 - cross-lapping the aligned fiber layer to form a cross-lapped fiber layer; and
 - 10 - mechanically entangling (especially, needle punching) the cross-lapped fiber layer,
- thereby forming the nonwoven fabric.

It has been found that bringing all these steps together, in combination, may have a surprising synergistic effect on the strength of the resultant nonwoven fabric.

15 Also provided is a method of separating carbon fibers (preferably, having a length of about 5 centimeters to about 12 centimeters) and blending the separated carbon fibers with a plurality of further fibers, comprising performing a method in accordance with the first aspect of the disclosure and a method in accordance with the fifth aspect of the disclosure.

20 According to a sixth aspect, the present disclosure provides a fiber blending device configured to receive carbon fibers (preferably, separated carbon fibers, most suitably obtainable by a method in accordance with the first aspect of the disclosure) and further configured to form a homogeneous fiber blend by blending the received carbon fibers with a plurality of further fibers. The carbon fibers, being preferably

25 separated, may suitably be separated carbon fibers received from a carbon fiber separation device according to the second aspect of the disclosure or a carbon fiber cutting and separation apparatus according to the third aspect of the disclosure.

Thus, according to a sixth aspect, the present disclosure provides a fiber blending device configured to receive carbon fibers (preferably, separated carbon

30 fibers, most suitably obtainable by a method in accordance with the first aspect of the disclosure) having a length of from about 5 centimeters to about 12 centimeters and to form a homogeneous fiber blend, the device comprising:

- 28 -

- a conveyance (e.g., a conveyor) having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured for blending the carbon fibers with the further fibers, and
- 5 - one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further blend the carbon fibers with the further fibers.

The conveyor of the fiber blending device may be optional. The conveyor may be omitted. Alternatively, the conveyor may be replaced, for example replaced by a
10 duct or chamber, within which the carbon fibers and the further fibers are subjectable to a step of directing a turbulent fluid flow to further blend the carbon fibers with the further fibers. Suitably, the duct or chamber is configured to contain, or contains, a turbulent fluid flow zone described herein in which a turbulent fluid flow, generated by the generator(s) of a turbulent fluid flow, is directed to blend the carbon fibers with
15 the further fibers.

Also provided is a carbon fiber separation and blending apparatus, comprising a carbon fiber separation device according to the second aspect of the disclosure and a fiber blending device according to the sixth aspect of the disclosure.

Also provided is a homogeneous fiber blend obtainable or obtained by a
20 method according to the fifth aspect of the disclosure. As used herein, the term homogeneous may mean that the fiber blend is a substantially uniform mixture, without irregularities. This may be quantified in that the ratio of carbon fibers to further fibers per cubic millimeter of material has a coefficient of variation (standard deviation divided by mean) of about 0.001 to about 0.3.

25 Also provided is an apparatus for forming a nonwoven fabric, which comprises the fiber blending device and one or more (preferably, all) of the following:

- a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by aligning fibers in the received homogeneous fiber blend;
- 30 - a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and

- 29 -

- a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.

5 In an aspect, the apparatus for forming a nonwoven fabric further comprises a carbon fiber separation device according to the second aspect of the disclosure or a carbon fiber cutting and separation device according to the third aspect of the disclosure.

10 The fiber blending device may suitably have one or more of the features of the carbon fiber separation device. Thus, the configuration of the fiber blending device may be one of the configurations described herein with reference to the carbon fiber separation device. It will be appreciated that features of the two devices may be interchangeable.

15 The conveyor of the fiber blending device may suitably have one or more of the features of the conveyor of the carbon fiber separation device. For conciseness, these are not repeated in full here. Particularly, the protrusions of the fiber blending device may suitably have one or more of the features of the protrusions of the carbon fiber separation device. For conciseness, these are not repeated here.

20 Moreover, the one or more generators of a turbulent fluid flow of the fiber blending device may suitably have one or more of the features of the generators of a turbulent fluid flow of the carbon fiber separation device. For conciseness, these are not repeated here, although it is to be noted that preferably, the conveyor is upstream of a turbulent fluid flow zone in which a turbulent fluid flow, generated by the generator(s) of a turbulent fluid flow, is directed to separate the carbon fibers. The

25 conveyor may be connected to the turbulent fluid flow zone, which may be a container or compartment, by one or more ducts. Preferably, the one or more generators are or comprise one or more machines (especially, one or more engines and/or one or more motors) configured to blow one or more jets of air. Preferably, the jets of air have a Reynolds number of at least about 3500, such as at least about 4000.

30 In an aspect, also provided is a recirculation mechanism, for recirculating fibers to the conveyor (which preferably is an inclined lattice apron). Alternatively, there may be provided a recirculation mechanism for recirculating fibers to the conveyor of a further (preferably substantially identically functioning) fiber blending

- 30 -

device. Recirculation may lead to increased homogeneity of blending and thus to one or more advantages as described herein.

One or more controllers may be provided, to control the dwell time of fibers in the fiber blender.

5 In some embodiments, several fiber blending devices may be connected in series. Thus, in some embodiments, blending the separated carbon fibers is or comprises feeding the separated carbon fibers together with the plurality of further fibers through a series of fiber blenders; and optionally using one or more controllers to control their dwell time in the fiber blenders.

10 It has been found that using a series of fiber blenders and/or one or more controllers to control dwell time may increase throughput efficiency, for example enabling an operator to vary blending in dependence on the type(s) of further fibers used.

The further fibers may be non-carbon thermoplastic fibers or non-carbon filler
15 fibers. The further fibers may typically have a diameter of about 10 micrometers to about 70 micrometers. The further fibers may have a length of about 5 centimeters to about 12 centimeters, especially about 7.6 centimeters.

Optionally, the further fibers are crimped. Crimping of the further fibers may be advantageous in the step of aligning the fibers in the homogeneous fiber blend. For
20 example, where aligning is or comprises carding, crimped further fibers may assist with pulling the carbon fibers through carding wires, thereby reducing processing time.

Optionally, the further fibers are (non-carbon) filler fibers. As used herein, the term "filler fiber" may mean any non-thermoplastic, non-carbon polymeric fiber.
25 Filler fiber may be provided as bulking component and/or provide additional structural support. The filler fibers may preferably be polymer fibers. The filler fibers may be selected from fibers of aramids, para-aramids, polyester, polyethylene terephthalate (PET), flax, oxidized polyacrylonitrile (OPAN), other non-thermoplastic fibers, polyvinyl alcohol (PVOH/PVA) and combinations thereof; especially a
30 combination of para-aramid and OPAN.

Optionally, the further fibers are (non-carbon) thermoplastic fibers. The thermoplastic fibers may preferably be thermoplastic polymer fibers. The thermoplastic fibers may be selected from fibers of polypropylene (PP), maleic

- 31 -

anhydride grafted polypropylene (MAgPP), polyamide PA6, polyamide PA66, polyamide PA12, polyphenylene sulfide (PPS), polycarbonate (PC), polyetherimide (PEI), polyetheretherketone (PEEK), and combinations thereof; especially one or both of polypropylene and maleic anhydride grafted polypropylene.

5 When the further fibers are (non-carbon) filler fibers, the % w/w of carbon fibers in the homogeneous fiber blend may suitably be about 1 % w/w to about 100 % w/w, preferably about 10% to about 70%. The greater the % w/w of carbon fibers present, the stronger the resultant material may be. Preferably, no thermoplastic fibers are present when the further fibers are filler fibers.

10 When the further fibers are (non-carbon) thermoplastic fibers, the % w/w of carbon fibers in the homogeneous fiber blend may suitably be about 1% w/w to about 80% w/w, preferably about 10% w/w to about 60% w/w. The greater the % w/w of carbon fibers present, the stronger the resultant material may be.

 The further fibers may be chemically treated, for example, to improve bonding
15 with the carbon fibers.

 In preferred embodiments, the further fibers are or comprise one or more thermoplastic polyolefin fibers (which may be selected from one or more of: polyethylene, for example low-density, high-density, and linear low-density polyethylene; polypropylene; maleic anhydride grafted polypropylene and
20 polybutene; especially, one or both of polypropylene and maleic anhydride grafted polypropylene). In an aspect, the thermoplastic polyolefin is treated (especially, reacted, such as during a pre-treatment step of reacting liquid polyolefin before it is spun into fiber) with one or more acid anhydrides (which may be selected from one or more of: acetic anhydride; naphthalenetetracarboxylic dianhydride; adenosine
25 triphosphate; and maleic anhydride; especially, maleic anhydride).

 It has been found, for example, that where the further fibers are or comprise polypropylene (PP), pre-treatment (especially, reaction) of liquid PP before it is spun into fiber, with maleic anhydride (MAPP), may serve to aid bonding with the carbon fibers. The reaction of liquid PP with MAPP may occur in the presence of an initiator.
30 Thus, preferably, the further fibers are or comprise polypropylene (PP) treated with maleic anhydride (MAPP). In the art, the product of the reaction between PP and MAPP may be known as maleic anhydride grafted polypropylene (MAgPP). Thus,

- 32 -

preferably, the further fibers are or comprise one or both of PP and MAgPP, most especially MAgPP.

Suitably, where the further fibers are or comprise one or both of polypropylene (PP) and maleic anhydride grafted polypropylene (MAgPP), the carbon fibers may themselves be treated with MAPP. Such treatment may serve to aid bonding between the further fibers and the carbon fibers.

Other additives may include, but are not limited to, UV protectants and fire retardants.

In an aspect, the method of forming a nonwoven fabric comprises performing the method of separating carbon fibers according to the first aspect, prior to the blending step.

The step of aligning the fibers in the homogeneous fiber blend may be or comprise receiving the homogeneous fiber blend from the fiber blender or the fiber blenders and feeding the homogeneous fiber blend to a fiber aligning device.

Optionally, the step of aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer is or comprises carding the carbon fibers in the homogeneous fiber blend to form a carded fiber layer. Thus, optionally, the apparatus comprises a carding machine having carding wires. As used herein, the term carding has its normal meaning in the art. Thus, a carding machine typically comprises an inner cylinder and an outer belt, both set with hundreds of fine carding wires. The intermeshing wires separate the fibers and pull them into somewhat parallel form within a fibrous web.

Aligning has been found to provide control over the percentage of fibers that point in any given direction.

It will be appreciated that the homogeneous fiber blend is formed prior to being fed to the fiber aligning device. It has been found that trying to form a homogeneous fiber blend (i.e., blending) simultaneously with aligning fibers does not achieve the level of homogeneity required to optimize the properties (such, for example, as the strength) of the nonwoven fabric. For example, it may be possible to blend fibers during carding, but that is not preferred here.

It will also be appreciated that the aligned fiber layer may be defined as a web of fibers in which the fibers are arranged somewhat parallel, essentially parallel, or parallel to each other.

- 33 -

The aligned fiber layer is formed before it is cross-lapped to form a cross-lapped fiber layer. The relevant apparatus may be configured accordingly.

Cross-lapping may have its normal meaning in the art, thus may comprise laying the aligned fiber layer onto a conveyance (e.g., a conveyor). The direction in
5 which the fibers are laid down may be defined as the machine direction (also known as warp or as 0°); perpendicular to the machine direction may be the cross direction (also known as weft or 90°). In cross-lapping, sections of the aligned fiber layer may be laid over each other thereby forming a layered, i.e., cross-lapped, fiber layer. Thus, cross-lapping may increase the areal weight (in gsm) of the fiber layer.

10 When an aligned carbon fiber layer is cross-lapped, the interfaces between laps may become a point of weakness or even a point of material failure (evaluated by measuring the interlaminar shear strength of a finished molded part). Introducing fibers in the z direction by mechanical entanglement (preferably, needle punching), especially while also only having a single mechanically entangled ply, prevents or
15 mitigates against this problem. Further and surprisingly, by using carbon fibers having a length of about 5 centimeters to about 12 centimeters (preferably, about 7.6 centimeters), i.e. short fibers, for the z-direction reinforcement, the resultant materials may be kept pliable prior to finishing (especially, molding) steps, making them easier to work with in subsequent manufacturing.

20 Optionally, the step of mechanically entangling the cross-lapped fiber layer is or comprises needle punching the cross-lapped fiber layer to form the nonwoven fabric. Thus, optionally, the apparatus comprises a needle punching machine. Needle punching may be or comprise feeding the cross-lapped fiber layer onto a bed of
25 barbed needles. The needles may move in and out of the layer, thereby entangling the fibers. Needles may contact the layer from below and/or from above; thus, there may be one or two beds of needles present in the needle punching machine. Entangling the fibers, especially by needle punching, re-orientates a number of fibers in the z direction (wherein the x-y plane is the plane of the cross-lapped fiber layer; and the z direction is perpendicular to the cross-lapped fiber layer). Forming a single ply with a number
30 of carbon fibers in the z direction has been found to increase the strength of the material eventually formed (especially, compared to a multi-ply arrangement, wherein inter-ply separation may occur).

- 34 -

Thus, in an aspect, some (such about 1% to about 10% by number) carbon fibers in the nonwoven fabric obtainable by or made by the disclosed methods, comprising mechanical entanglement (especially, needle punching), are in the z direction. In an aspect some (such about 1 % to about 10 % by number) carbon fibers
5 in the nonwoven fabric according to the seventh aspect of the disclosure, and in the materials according to the eighth and ninth aspects of the disclosure, are in the z direction. In this context, the z direction is the z axis through the thickness of the fabric (or material), substantially perpendicular to the surface of the fabric (or material); the x-y plane is substantially parallel to the surface of the fabric (or
10 material). It will be appreciated that where the material according to the eighth and ninth aspects of the disclosure is formed into a shape having surface curvature, the z axis remains substantially perpendicular to the surface of the fabric at any given point on its surface.

Modifications to fiber alignment (e.g., carding) and/or cross-lapping may
15 allow for a variety of fiber orientations to be fed into mechanical entanglement (e.g., needle punching), thereby modulating the percentage of fibers in a given orientation.

It has been found that when mechanical entanglement is needle punching, it is advantageous to needle punch only once, through the entire depth of the layer. This results in a layer of a single ply. Surprisingly, this has been found not only to avoid
20 inter-ply delamination, but to increase strength (to a greater than expected degree) in the vertical direction. The steps prior to mechanical entanglement, when it is needle punching, may advantageously be enabling of needle punching only once. i.e., it has been found that the preceding steps, especially when they involve blending, aligning which is carding, and cross-lapping, result in a cross-lapped fiber layer that is suitable
25 for needle punching only once. Thus, in an aspect, the step of mechanically entangling the cross-lapped fiber layer is a step of needle punching the layer once to form a nonwoven fabric of a single ply.

Advantageously, each of the methods described herein further comprises collecting airborne carbon fibers and removing the collected carbon fibers from the
30 vicinity in which the method is being performed.

Carbon fibers may typically be conductive, having a resistivity of about $2 \mu\Omega$ m to about $30 \mu\Omega$ m ($2 \times 10^{-4} \Omega$ cm to $3 \times 10^{-3} \Omega$ cm). For example, T700S standard modulus carbon fiber obtainable from Toray Industries, Inc. (of Nihonbashi Mitsui

- 35 -

Tower, 1-1, Nihonbashi-Muromachi 2-chome, Chuo-ku, Tokyo 103-8666, Japan) has a resistivity of $16 \mu\Omega \text{ m}$ ($1.6 \times 10^{-3} \Omega \text{ cm}$). Without wishing to be bound by theory, it is thought that conductive carbon fibers may increase the risk of spark formation and thus of shorting out motors, drives, circuit boards, control boards, computers, fluorescent lighting, and infrastructure wall wiring fixtures. There has therefore been a prejudice against processing carbon fibers using apparatus typically intended for manufacturing nonwoven fabrics, particularly against separating fibers; aligning fibers, especially by carding using carding wires; and/or mechanically entangling fibers, especially using needle punch machines. In an aspect, therefore, each of the devices and apparatuses described herein further comprises one or more appliances (especially, ductwork under negative pressure; preferably, equipped with one or more filters, such as one or more high-efficiency particulate absorbing, or "HEPA", filters) for collecting and removing airborne carbon fibers.

Advantageously, each of the methods described herein is performed on apparatus with entirely insulated electronics. In an aspect, therefore, each of the devices and apparatuses described herein has entirely insulated electronics. The electronics may be insulated by suitable enclosures, such, for example, as enclosures obtainable from NEMA Enclosures (of 1118 Pleasantville Drive, Houston, TX 77029, USA) or OKW Enclosures Ltd (of 15 Brunel Way, Segensworth East, Fareham, PO15 5TX, UK). The enclosures may be or comprise insulating materials, especially plastic.

According to a seventh aspect of the present disclosure, there is provided a nonwoven fabric, comprising:

- a plurality of carbon fibers separated from each other and having a mean length of about 2.5 (preferably, about 5) centimeters to about 12 centimeters, and
 - a plurality of further fibers;
- wherein the carbon fibers are dispersed amongst the further fibers.

In an aspect, the nonwoven fabric is a product of or is obtainable by the method of forming a nonwoven fabric described herein. In an aspect, a plurality (such as a number of about 1 % to about 10 %) of the carbon fibers in the fabric are substantially oriented in the z direction as it is defined herein.

The method of separating carbon fibers in accordance with the first aspect of the disclosure may be a method of separating attached carbon fibers having a mean

- 36 -

length of about 5 centimeters to about 12 centimeters. Processing of the carbon fibers in the methods described herein is carried out while minimizing breakage of the carbon fibers, thereby providing a strong product, such as a material according to the eighth or ninth aspects of the disclosure. Nevertheless, a small amount of breakage may occur. For example, up to about 25 % (by number) of the carbon fibers may undergo some level of breakage during processing. Therefore, when starting with carbon fibers having a mean length of about 5 centimeters, the resultant non-woven fabric may contain carbon fibers having a mean length of below (such as just below) 5 centimeters.

10 The nonwoven fabric may suitably have an areal weight of about 100 gsm to about 12,000 gsm; such as about 3000 gsm.

 In preferred embodiments, a plurality (such as a number of about 1 % to about 10 %) of the total carbon fibers in the non-woven fabric are substantially parallel to the z direction (i.e., the direction parallel to the thickness of the fabric; i.e., the direction perpendicular to the major plane of the fabric). This deliberate orientation of carbon fibers has been found to impart strength to the non-woven fabric and to materials resulting therefrom. It may be facilitated by the mechanical entanglement described herein.

 In all aspects of the disclosure (including and especially the nonwoven fabric according to the seventh aspect of the disclosure), carbon fibers in the x-y plane (which, in the nonwoven fabric, is the major plane of the fabric, perpendicular to its z direction as described herein) may be oriented in a manner giving rise to properties (especially, tensile strength measured in accordance with ASTM D638-08 and/or tensile modulus measured in accordance with ASTM D638) which are unidirectional, quasi-unidirectional, isotropic, quasi-isotropic, orthotropic, quasi-anisotropic or anisotropic. As used herein, those terms have their usual meaning in the art. It has been found that aligning, cross-lapping and/or mechanically entangling (especially, a combination of all three) may enable modulation of the directionality of these properties. Thus, the directionality of the properties of the nonwoven fabric may be selected in dependence on the specification and requirements of particular products incorporating them; and the aligning, cross-lapping and/or mechanically entangling may be adjusted accordingly.

- 37 -

Thus, unidirectionality may be preferred when the fabric is used to form pressure vessels. Quasi-unidirectionality may be preferred when the fabric is used to form pipes or for pipe repair. Anisotropy may be preferred when the fabric is used for exterior automotive parts (e.g., for cars or trucks) and jet skis. Quasi-anisotropy may be preferred when the fabric is used for load-bearing automotive parts (such, for example, as a trailer bed). Isotropy or quasi-isotropy may be preferred for a wide array of products, in which no single area, plane or axis is required to bear an excessive load; such, for example, as garden decking, trailer floors, or the walls and/or roof of a trailer or truck.

10 In a material according to the eighth aspect of the disclosure, in contrast to the orientation of the carbon fibers, which may specifically be configured to impart certain properties to the fabric, the orientation of the (non-carbon) thermoplastic further fibers in the fabric may be immaterial. For example, (non-carbon) thermoplastic fibers may be thermoformed, thus melted to form a resin; while the
15 carbon fibers suitably retain a deliberate orientation within the resin matrix, the thermoplastic fibers cannot be said to have retained an orientation.

When the further fibers are (non-carbon) thermoplastic fibers, the nonwoven fabric may, especially, be for forming or repairing a pipe, such as a water or sewage pipe.

20 The nonwoven fabric may be cut to shape. It may be seamed. It may be surface treated. Where the further fibers are thermoplastic fibers, it may undergo surface melting of the thermoplastic fibers to form a surface layer of thermoplastic resin (having embedded carbon fibers).

The nonwoven fabric may be thermoformed using one or both (especially,
25 both) of heat and pressure, thereby forming a thermoformed thermoplastic material. Optionally, thermoforming occurs in a mold, optionally a hand lay-up open mold, resin transfer mold (RTM), vacuum assisted resin transfer mold (VARTM), vacuum bag, autoclave, pultrusion mold, compression mold, a pipe, or a combination thereof; preferably, a pipe such as is used for utilities (e.g., for potable water); sewage; flood
30 control; and fuel (e.g., oil or gas) distribution lines.

When the thermoforming occurs in a pipe, the nonwoven fabric may be formed into a pipe liner inside the pipe. The pipe liner may have a seamed, tubular shape, with an outer surface facing the host pipe and an inner surface. This may be

- 38 -

especially suitable for forming a pipe liner for the repair of a host pipe. This may be known as cured-in-place-pipe, or a thermoformed-in-place-pipe. A sleeve may be provided between the host pipe and the outer surface of the pipe liner. An inner coating may be provided on the inner surface of the pipe liner. The inner coating may
5 itself be or comprise a further pipe liner made from thermoplastic or thermoset material.

When the further fibers are (non-carbon) thermoplastic fibers that are or comprise polypropylene (PP) treated with maleic anhydride (MAPP), i.e., maleic anhydride grafted polypropylene (MAGPP), it has been found that an especially strong
10 material is formed when thermoforming is carried out in dry conditions and under heat.

Thus, in an eighth aspect, the present disclosure provides a material which is a thermoformed product of (or which is obtainable by thermoforming) a nonwoven fabric according to the seventh aspect of the disclosure wherein the further fibers are
15 non-carbon thermoplastic fibers. Thus, in the material according to the eighth aspect of the disclosure, there is provided thermoformed resin formed from the thermoplastic fibers. As described herein, the material according to the eighth aspect of the disclosure may be or comprise a pipe liner.

When the further fibers are (non-carbon) filler fibers, the nonwoven fabric
20 may be infused with a thermosetting resin or a thermoplastic resin, thereby forming a resin-impregnated nonwoven fabric. The resin-impregnated nonwoven fabric may, especially, be for forming or repairing a pipe, such as a water or sewage pipe. Optionally, the resin is a thermosetting resin, which is selected from epoxy, polyester, phenolic resin, vinyl ester, or a combination thereof. The thermosetting resin-
25 impregnated nonwoven fabric may further be cured using heat (optionally, provided by steam) and/or UV light, thereby forming a thermoset material. Optionally, curing occurs in a mold, optionally a hand lay-up open mold, resin transfer mold (RTM), vacuum assisted resin transfer mold (VARTM), vacuum bag, autoclave, pultrusion mold, compression mold, a pipe, or a combination thereof; preferably, a pipe such as
30 is used for utilities (e.g., for potable water); sewage; flood control; and fuel (e.g., oil or gas) distribution lines.

When the curing occurs in a pipe, the nonwoven fabric, infused with a thermosetting resin, may be formed into a pipe liner inside the pipe. The pipe liner

- 39 -

may have a seamed, tubular shape, with an outer surface facing the host pipe and an inner surface. This may be especially suitable for forming a pipe liner for the repair of a host pipe. This may be known as cured-in-place-pipe. A sleeve may be provided between the host pipe and the outer surface of the pipe liner. An inner coating may be
5 provided on the inner surface of the pipe liner. The inner coating may itself be or comprise a further pipe liner made from thermoplastic or thermoset material.

Thus, in a ninth aspect, the present disclosure provides a material comprising a thermoset resin and a nonwoven fabric according to the seventh aspect of the disclosure, wherein the further fibers are non-carbon filler fibers. As described herein,
10 the material according to the ninth aspect of the disclosure may be or comprise a pipe liner.

Also provided herein is a method of forming a material according to the ninth aspect of the disclosure (especially wherein the material is a pipe liner) comprising infusing with a thermosetting resin a nonwoven fabric according to the seventh aspect
15 of the disclosure wherein the further fibers are (non-carbon) filler fibers; and curing the infused nonwoven fabric, thereby forming a material according to the ninth aspect of the disclosure. Optionally, the method comprises forming the nonwoven fabric into a shape, especially the shape of a pipe liner, before the curing step.

Infusion of the thermosetting resin may preferably occur in situ, for example at
20 or close to the site of a pipe repair (such as a sewage or water pipe repair) to be carried out. Alternatively, infusion of the thermosetting resin may occur offsite; the nonwoven fabric infused with a thermosetting resin may then be shipped as a wet prepreg to the site of use. During shipping, it may be stored at temperatures of below about 0 °C, such as below about - 10°C, to mitigate against undesirable curing, en
25 route, of the thermosetting resin. Moreover, workers may need to work quickly and/or at low temperatures to form the nonwoven fabric infused with a thermosetting resin into place, such as during pipe repair, without undesirable curing occurring before the nonwoven fabric infused with a thermosetting resin is in place.

In contrast, when the further fibers are (non-carbon) thermoplastic fibers, not
30 being infused with thermosetting resin, the nonwoven fabric may be shipped at ambient temperature (for example, a temperature in the range of from about 0 to about 40 °C) from its site of manufacture to a site of use. This may enable simpler shipping procedures. Moreover, there may be no need for workers to work quickly, nor at low

- 40 -

temperatures, to put the nonwoven fabric wherein the further fibers are (non-carbon) thermoplastic fibers, not being infused with thermosetting resin, into place, such as during pipe repair. Once in place, the nonwoven fabric may be thermoformed as desired and in a time frame selected at will. The removal of time constraints on
5 workers in this and other scenarios may be an especially important advantage of a nonwoven material wherein the further fibers are (non-carbon) thermoplastic fibers, for which infusion with thermosetting resin is not required.

Thus, provided herein is a method of forming a material according to the eighth aspect of the disclosure (especially wherein the material is a pipe liner),
10 comprising thermoforming a nonwoven fabric according to the seventh aspect of the disclosure wherein the further fibers are (non-carbon) thermoplastic fibers. For this, infusion with thermosetting resin is not required. Optionally, the method comprises forming the nonwoven fabric into a shape, especially the shape of a pipe liner, before the thermoforming step.

15 The material according to the eighth aspect of the disclosure may be in the form of a layer having a thickness of about 0.01 mm to about 50 mm.

The material according to the ninth aspect of the disclosure may be in the form of a layer having a thickness of about 0.01 mm to about 50 mm.

It has been found that in a nonwoven fabric according to the seventh aspect of
20 the disclosure, there may remain some contact between the carbon fibers. For example, a number of carbon fibers, such as about 10 to about 15% (by number), may be in contact. While such an arrangement still represents a high level of separation, it has been found that the level of separation of carbon fibers in a material according to the eighth or ninth aspect of the disclosure may be even higher, such as by having a
25 number of carbon fibers below about 5% in contact. Without wishing to be bound by theory, it is thought that liquid thermosetting resin, or liquid thermoplastic resin, may flow around carbon fibers thus aiding their further separation. This has been investigated by SEM imaging, such as described in Examples 3 and 4 hereinbelow.

Optionally, in all aspects of the disclosure, the plurality of carbon fibers is or
30 comprises a plurality of virgin carbon fibers. Optionally, the plurality of carbon fibers is or comprises a mixture of recycled carbon fibers and virgin carbon fibers. Optionally, in all aspects of the disclosure, the plurality of carbon fibers is or comprises a plurality of recycled carbon fibers.

- 41 -

In an aspect, all carbon fibers of the plurality of carbon fibers have the same or substantially the same modulus. Their modulus may be measured using ASTM C1557-20. Optionally, substantially all carbon fibers of the plurality of carbon fibers have a modulus of about 25 to about 50 msi. Optionally, substantially all carbon fibers of the plurality of carbon fibers are type SM (standard modulus), i.e., having a modulus of about 33 to about 34 msi. Optionally, substantially all carbon fibers of the plurality of carbon fibers are type IM (intermediate modulus), i.e., having a modulus of about 41 to about 43 msi. It will be appreciated that the type, and thus the modulus, of carbon fiber may vary from one production run to another; within a given production run, the modulus of the carbon fibers may preferably be the same or substantially the same.

A material according to the eighth aspect of the disclosure may have less than about 5%, preferably less than about 3% by volume of void space, measured in accordance with ASTM D2734. A material according to the eighth aspect of the disclosure may have a tensile strength of at least about 100 MPa, especially at least about 200 MPa, measured in accordance with ASTM D638. A material according to the eighth aspect of the disclosure may have a specific tensile strength of at least about 100 kN*m/kg, especially at least about 200 kN*m/kg. A material according to the eighth aspect of the disclosure may have a density or specific gravity of about 0.5 g/cm³ to about 2 g/cm³, especially about 0.9 g/cm³ to about 1.2 g/cm³, measured in accordance with ASTM D792. A material according to the eighth aspect of the disclosure may have a tensile modulus of at least about 15,000 MPa, measured in accordance with ASTM D638. A material according to the eighth aspect of the disclosure may have a flexural strength of at least about 200 MPa, measured in accordance with ASTM D790.

A material according to the ninth aspect of the disclosure may have less than about 5%, preferably less than about 2% by volume of void space, measured in accordance with ASTM D2734. A material according to the ninth aspect of the disclosure may have a tensile strength of at least about 50 MPa, especially at least about 200 MPa, measured in accordance with ASTM D638. A material according to the ninth aspect of the disclosure may have a density or specific gravity of about 0.9 g/cm³ to about 1.5 g/cm³, especially about 1.1 g/cm³ to about 1.5 g/cm³, measured in accordance with ASTM D792. A material according to the ninth aspect of the

- 42 -

disclosure may have a tensile modulus of at least about 5,000 MPa, especially at least about 15,000 MPa, measured in accordance with ASTM D638. A material according to the ninth aspect of the disclosure may have a flexural modulus of at least about 10,000 MPa, measured in accordance with ASTM D790.

5 A material according to the eighth or ninth aspect of the disclosure may be or may be comprised by one or more vehicle parts, especially automotive parts, such as (but not limited to) a hood (also known as a bonnet), bumper, cowling, decklid, fender, fascia, grille, pillar, hard trim, door body, door handle, body panel, sill, rim, hubcap, trunk (also known as a boot or hatch), or hinge. The vehicle (especially,
10 automotive) part may be or be comprised by an internal combustion vehicle, a hybrid vehicle, or an electric vehicle. The vehicle may be any automotive vehicle, such as a car, truck, bus, freight trailer, lorry; any marine vehicle, such as a boat, kayak, or jet ski; or any aircraft, such as an airplane, helicopter, or drone.

15 Now having described the features of the present disclosure, additional features are described below.

 In an aspect, the present disclosure provides for a method of separating attached carbon fibers, comprising: directing the attached carbon fibers to the moving surface of a conveyance, separating, at least partially, the carbon fibers on the moving
20 surface of the conveyance, and directing a turbulent fluid flow to further separate the carbon fibers.

 In an aspect, in the method, the conveyance is a conveyor, wherein the conveyor includes a plurality of protrusions on the moving surface of the conveyor which pass between and separate carbon fibers on the moving surface of the
25 conveyor. In an aspect, in the method, the attached carbon fibers have a mean length of about 5 centimeters to about 12 centimeters. In an aspect, in the method, the turbulent fluid flow is generated by one or more engines, one or more motors, or both one or more engines and one or more motors, where the one or more engines and the one or more motors are each configured to blow one or more jets of fluid at the carbon
30 fibers. In an aspect, in the method, the attached carbon fibers are attached to each other by binding material on the surface of the carbon fibers, wherein separating the carbon fibers is or comprises detaching binding material with carbon fiber breakage at about 25% or less. In an aspect, in the method, once separated, about 80% or more of

- 43 -

the carbon fibers are substantially unattached from each other. In an aspect, in the method, the surface of the conveyor is disposed at an incline; and directing the attached carbon fibers onto the moving surface of the conveyor includes directing the attached carbon fibers onto the inclined moving surface of the conveyor against
5 gravity. In an aspect, the method further comprises brushing the carbon fibers using one or more agitator rolls.

In an aspect, the present disclosure provides for a method of forming a nonwoven fabric, comprising: blending carbon fibers with further fibers, wherein a turbulent fluid flow blends the carbon fibers with the further fibers, thereby forming a
10 homogeneous fiber blend; and aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer.

In an aspect, the method further comprises directing the carbon fibers and the further fibers onto a moving surface of a conveyance such that the carbon fibers and the further fibers are blended by a plurality of protrusions on the moving surface. In
15 an aspect, the method further comprises directing the attached carbon fibers onto the moving surface of a conveyance; separating, at least partially, the carbon fibers on the moving surface of the conveyor; and directing a turbulent fluid flow to further separate the carbon fibers. In an aspect, in the method, the conveyor is a conveyance, wherein separating includes directing the carbon fibers onto the moving surface of the
20 conveyor such that the carbon fibers are separated by a plurality of protrusions on the moving surface. In an aspect, the method further comprises: cross-lapping the aligned fiber layer to form a cross-lapped fiber layer. In an aspect, the method further comprises: mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric. In an aspect, the method further comprises: mechanically
25 entangling the aligned fiber layer. In an aspect, in the method, the further fibers are a second amount of carbon fibers. In an aspect, in the method, the further fibers are selected from the group consisting of: a thermoplastic fiber, a thermoset fiber, a non-carbon filler fiber, and a combination thereof.

In an aspect, the present disclosure provides an apparatus for forming a
30 nonwoven fabric, comprising: a fiber blending device configured to receive carbon fibers and further fibers, and to form a homogeneous fiber blend, using turbulent fluid flow; a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by

- 44 -

aligning carbon fibers in the received homogeneous fiber blend; a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.

In an aspect, the apparatus further comprises: a carbon fiber separation device configured to separate carbon fibers from attached carbon fibers using turbulent fluid flow to form separated carbon fibers. In an aspect, in the apparatus, the carbon fiber separation device includes: a conveyance having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers. In an aspect, in the apparatus, the fiber blending device comprises: wherein the conveyance is a conveyor, wherein the conveyor has a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured for blending the carbon fibers with the further fibers, and one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further blend the carbon fibers with the further fibers.

In an aspect, the present disclosure provides a nonwoven fabric, comprising: a plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters to about 12 centimeters, and a plurality of further fibers; wherein the carbon fibers are dispersed and aligned amongst the further fibers.

In an aspect, in the nonwoven fabric, the further fibers are a second amount of carbon fibers. In an aspect, in the nonwoven fabric, the further fibers are selected from the group consisting of: a thermoplastic fiber, a thermoset fiber, a non-carbon filler fiber, and a combination thereof. In an aspect, in the nonwoven fabric is in the form of a single ply. In an aspect, in the nonwoven fabric, the carbon fibers are recycled carbon fibers.

In an aspect, the present disclosure provides a carbon fiber separation device comprising: a conveyance having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass

- 45 -

between and separate the carbon fibers, and one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers.

In an aspect, the present disclosure provides for a method of forming a
5 nonwoven fabric, comprising: blending carbon fibers by directing the carbon fibers onto a moving surface, wherein the carbon fibers are blended on the moving surface, and wherein a turbulent fluid flow further blends the carbon fibers, thereby forming a homogeneous fiber blend; and aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer.

10 In an aspect, in the method, blending includes directing the carbon fibers onto the moving surface of the conveyor such that the carbon fibers are blended by a plurality of protrusions on the moving surface. In an aspect, in the method, prior to blending further comprising: directing the attached carbon fibers onto the moving surface of a conveyor; separating, at least partially, the carbon fibers on the moving
15 surface of the conveyor; and directing a turbulent fluid flow to further separate the carbon fibers. In an aspect, in the method, separating includes directing the carbon fibers onto the moving surface of the conveyor such that the carbon fibers are separated by a plurality of protrusions on the moving surface.

In an aspect, the present disclosure provides for methods of manufacturing a
20 nonwoven fabric for forming a hardened finished part, where the method includes: (a) providing a volume of about 2" to 5" long substantially individual carbon fibers; (b) providing a volume of about 2" to 5" long non-carbon fibers; (c) blending the volume of substantially individual carbon fibers with the volume of non-carbon fibers to create a homogenous fiber blend; (d) aligning the fibers of the homogenous fiber
25 blend; (e) orienting layers and building the areal weight of the homogenous fiber blend; and (f) mechanically entangling the non-carbon and substantially individual carbon fibers into a nonwoven fabric; wherein the nonwoven fabric is structured to hold a resin proximate the substantially individual carbon fibers and to form a hardened finished part with application of a curing agent and pressure on the
30 nonwoven fabric.

In an aspect, the method can further comprise opening and separating carbon fiber tows into substantially individual carbon fibers, whereby carbon fiber tows are excluded from the provided volume of substantially individual carbon fibers.

- 46 -

In an aspect, in the method, opening and separating the carbon fiber tows separates the binding on the carbon fiber tows while breaking about 25% or less of the individual carbon fibers.

5 In an aspect, in the method, the volume of about 2" to 5" long substantially individual carbon fibers comprises pieces of substantially individual carbon fibers of about 2" or less long.

10 In an aspect, in the method, the carbon fibers of a carbon fiber tow entering a tow opener have given lengths. The method can further comprise monitoring the dwell time of the carbon fibers in the tow opener such that at least 90% or at least 84% of the carbon fibers exiting the tow opener are substantially individual carbon fibers and at least 75% of the carbon fibers exiting the tow opener have about the same given lengths or the same given lengths as the carbon fibers that entered the tow opener.

15 In an aspect, in the method, aligning comprises carding, and wherein creation of the homogenous blend is achieved prior to carding.

In an aspect, in the method, the nonwoven fabric has an areal weight of 100 gsm to 12,000 gsm and is structured to form a hardened finished part thickness of 1/10 mm to 12 mm.

20 In an aspect, in the method, the incremental areal weight of 1000 gsm adds about an incremental 1mm of thickness to the hardened finished part.

In an aspect, the method further comprises substantially individual carbon fibers needle punched through the thickness of the oriented layers to integrate the oriented layers into a single ply.

25 In an aspect, the method further comprises specifying the structure of the nonwoven fabric and producing a homogenous nonwoven fabric within 1% variance of the specification.

30 In an aspect, the method comprises specifying the hardened finished part thickness, tensile strength, resin, curing agent, pressure, and curing dwell time, and controlling the percent mix of the homogenous fiber blend; wherein the hardened finished part thickness and tensile strength are within 10% variance from specification.

In an aspect, the method further comprises a hardened finished part of uniform thickness formed with application of heat and pressure to the nonwoven fabric.

- 47 -

In an aspect, in the method, the uniform thickness and/or performance is within 10% variance of the specification.

In an aspect, in the method, the non-carbon fibers have a non-linear structure along the length of the fiber.

5 In an aspect, the method further comprises applying a curing agent and pressure to the nonwoven fabric to form a hardened finished part.

In an aspect, in the method, the finished hardened part is a pipe liner formed inside a host pipe.

10 In an aspect, in the method, the non-carbon fibers include at least one member selected from the group consisting of aramids, para-aramids, polyester, flax, PVOH, carbon fiber precursors (OPAN), and another non-thermoplastic filler, and wherein the nonwoven fabric is structured to be infused with a thermoset resin.

In an aspect, the method further comprises infusing the nonwoven fabric with a thermoset resin.

15 In an aspect, the method further comprising epoxy or vinyl ester, wherein a hardened finished part formed from an about 250 gsm, about 0.25" thick nonwoven fabric has a flexural modulus exceeding about 8,000 MPa per ASTM D790.

In an aspect, in the method, the hardened finished part has a Specific Tensile Strength greater than 120 kN*m/kg.

20 In an aspect, in the method, the non-carbon fibers are thermoplastic fibers that are a dry resin. The method includes storing or handling the nonwoven fabric at ambient temperature. The thermoplastic fibers include at least one member selected from the group consisting of PP, PA6, PA66, PA12, PPS, PC, PEI, PEEK, and other thermoplastics.

25 In an aspect, in the method, the hardened finished part has a specific gravity of about 1.02 g/cm³ per ASTM D792 and a tensile strength of at least 100 MPa per ASTM D638-08.

In an aspect, the method further comprises polypropylene fibers chemically modified with maleic anhydride and heating the woven fabric to at least 400° F.

30 In an aspect, in the method, the hardened finished part has a specific gravity of about 1.04 g/cm³ per ASTM D792 and a tensile strength of at least 200 MPa per ASTM D638-08.

- 48 -

In an aspect, the method further comprises orienting the layers from 60° to 85° angles and seaming the nonwoven fabric into a tube-shaped pipe liner fabric, wherein the substantially individual carbon and non-carbon fibers are oriented in the circumferential direction of the pipe liner fabric.

5 In an aspect, in the method, the pipe liner fabric is sufficiently fluid-tight to inflate with air (e.g., when the ends of the pipe liner fabric are closed or plugged).

In an aspect, the method further comprises partially melting the outer surface of the pipe liner fabric.

10 In an aspect, the method further comprises forming the nonwoven fabric into a hardened finished part (e.g., about 1 mm to 12 mm thick) using dry heat of about 400° to 475° F and an inflation pressure of about 3-125 psi, wherein the hardened finished part is a pipe liner.

In an aspect, the method includes a second pipe liner about 2-3 mm thick thermoformed within the first pipe liner at about 100-120 PSI in about 10-20 minutes.

15 In an aspect, the method further comprises using dry heat of about 400° to 405° F.

In an aspect, the present disclosure provides for methods of manufacturing a nonwoven fabric for forming a hardened finished part, where the method includes:

- 20 (a) providing a volume of about 2" to 5" long substantially individual carbon fibers; (b) providing a volume of about 2" to 5" long non-carbon fibers; (c) blending the volume of substantially individual carbon fibers with the volume of non-carbon fibers to create a homogenous fiber blend; (d) carding the fibers of the homogenous fiber blend, wherein creation of the homogenous blend is achieved prior to carding; (e) orienting layers and building the areal weight of the homogenous fiber blend; and
- 25 (f) mechanically entangling the non-carbon and substantially individual carbon fibers into a nonwoven fabric; wherein the nonwoven fabric is structured to hold a resin proximate the substantially individual carbon fibers and to form a hardened finished part with application of a curing agent and pressure on the nonwoven fabric.

30 In an aspect, the present disclosure provides for systems for manufacturing a nonwoven fabric for forming a hardened finished part, where the system includes: (a) a controller; (b) a fiber blender that blends a volume of 2" to 5" long substantially individual carbon fibers with a volume of 2" to 5" long non-carbon fibers to create a homogenous fiber blend, wherein tows are excluded from the volume of substantially

- 49 -

individual carbon fibers; (c) a system that receives the homogenous fiber blend and then aligns the carbon and non-carbon fibers of the homogenous fiber blend; (d) a cross-lapper that layers and builds the areal weight of the homogenous fiber blend; and (e) a needle loom that entangles the cross-lapped carbon and non-carbon fibers
5 into a nonwoven fabric; wherein the nonwoven fabric is structured to hold a resin proximate each of the carbon fibers and to form a hardened finished part with application of a resin, curing agent, and pressure on the nonwoven fabric.

In an aspect, in the system, the controller receives a specification for the structure of the nonwoven fabric and/or a finished part thickness, wherein the
10 homogenous fiber blend is calibrated to produce the homogenous nonwoven fabric having structural properties within 1% variance of the specification.

In an aspect, the system further comprises specification of the hardened finished part thickness, tensile strength, resin, curing agent, pressure, and curing dwell time, and controlling the percent mix of the homogenous fiber blend; wherein the
15 hardened finished part thickness and tensile strength are within 10% variance from specification.

In an aspect, the system further comprises a hardened finished part of uniform thickness formed with application of heat and pressure to the nonwoven fabric.

In an aspect, in the system, the uniform thickness and/or performance is within
20 10% variance of the specification.

In an aspect, the system further comprises a system for preventing electrical shorting or interference caused by electrical conductance of the carbon fibers.

In an aspect, the system further comprises a tow opener that opens and separates carbon fiber tows into about 2" to 5" long substantially individual carbon
25 fibers.

In an aspect, in the system, the tow opener separates the binding on the carbon fiber tows while breaking less than 25% of the substantially individual carbon fibers, and wherein the volume of substantially individual carbon fibers exiting the tow opener comprises pieces of substantially individual carbon fibers less than 2" long.

30 In an aspect, in the system, the controller monitors the dwell time of the carbon fibers in the tow opener, and wherein at least 90% of the carbon fibers exiting the tow opener are substantially individual carbon fibers, with at least 75% of those

- 50 -

substantially individual carbon fibers having about the same or the same given lengths as the carbon fibers that entered the tow opener.

In an aspect, in the system, the system that aligns the carbon and non-carbon fibers of the homogenous fiber blend is a carding system.

5 In an aspect, in the system, the nonwoven fabric has an areal weight of about 100 gsm to 12,000 gsm and is structured to form a hardened finished part thickness of about 1/10 mm to 12 mm.

In an aspect, in the system, the incremental areal weight of about 1000 gsm adds an incremental thickness of about 1 mm to the hardened finished part.

10 In an aspect, the system further comprises substantially individual carbon fibers needle punched through the thickness of the oriented layers to integrate the oriented layers into a single ply.

In an aspect, the system further comprises a thermoset or thermoplastic resin.

15 In an aspect, the system further comprises a thermoset or thermoplastic forming system that applies a curing agent and pressure to the resin on the nonwoven fabric to form a hardened finished part.

In an aspect, in the system, the non-carbon fibers include at least one member selected from the group consisting of aramids, para-aramids, polyester, flax, PVOH, carbon fiber precursors (OPAN), and another non-thermoplastic filler, and wherein
20 the nonwoven fabric is structured to be infused with a thermoset resin.

In an aspect, the system further comprises a thermoset resin infusing the nonwoven fabric.

In an aspect, the system further comprises epoxy or vinyl ester, wherein a hardened finished part formed from an about 250 gsm, 0.25" thick nonwoven fabric
25 has a flexural modulus exceeding about 8,000 MPa per ASTM D790.

In an aspect, in the system, the non-carbon fibers are thermoplastic fibers that are a dry resin, and further comprising storing or handling the nonwoven fabric at ambient temperature, the thermoplastic fibers including at least one member selected from the group consisting of PP, PA6, PA66, PA12, PPS, PC, PEI, PEEK, and
30 another thermoplastic.

In an aspect, the system further comprises chemically modified polypropylene fibers with maleic anhydride and heating the woven fabric to at least 400° F.

- 51 -

In an aspect, in the system, a hardened finished part has a specific gravity of about 1.04 g/cm³ per ASTM D792 and a tensile strength of at least 200 MPa per ASTM D638-08.

5 In an aspect, in the system, a hardened finished part has a specific gravity of about 1.02 g/cm³ per ASTM D792 and a tensile strength of at least 100 MPa per ASTM D638-08.

In an aspect, the system further comprises a pipe liner forming system, wherein the hardened finished part is a pipe liner formed inside a host pipe.

10 In an aspect, in the system, the curing agent has dry heat of 400° to 475 °F and the inflation pressure is about 3-125 PSI, and wherein the hardened finished part is a pipe liner (e.g., 1 mm to 12 mm thick).

In an aspect, in the system, a first pipe liner about 2-3 mm thick is thermoformed at about 5-30 PSI in about 20 to 90 minutes.

15 In an aspect, in the system, a second pipe liner about 2-3 mm thick is thermoformed within the first pipe liner at about 100-120 PSI in about 10-20 minutes.

In an aspect, in the system, the curing agent has dry heat of about 400° to 405° F.

20 In an aspect, in the system, the nonwoven fabric has cross-lapped layers oriented from about 60° to 85° angles, and wherein when the nonwoven fabric is seamed to form a tube-shaped pipe liner fabric the substantially individual carbon and non-carbon fibers are oriented in the circumferential direction of the pipe liner fabric.

In an aspect, in the system, the pipe liner fabric is sufficiently fluid-tight to inflate with air when the ends of the tubular nonwoven fabric are closed or plugged.

25 In an aspect, the system further comprises a surface treatment that partially melts the outer surface of the pipe liner fabric.

30 In an aspect, the present disclosure provides for systems for manufacturing a nonwoven fabric for forming a hardened finished part, where the system includes: (a) a controller that receives a specification for the structure of the nonwoven fabric; (b) a fiber blender that blends a volume of about 2" to 5" long substantially individual carbon fibers with a volume of about 2" to 5" long non-carbon fibers to create a homogenous fiber blend, wherein tows are excluded from the volume of substantially individual carbon fibers, and wherein the controller optimizes the homogenous fiber blend; (c) a system that receives the homogenous fiber blend and then aligns the

- 52 -

carbon and non-carbon fibers of the homogenous fiber blend; (d) a cross-lapper that layers and builds the areal weight of the homogenous fiber blend; and (e) a needle loom that entangles the cross-lapped carbon and non-carbon fibers into a nonwoven fabric having structural properties within about 1% or about 10% variance from the specification; wherein the nonwoven fabric is structured to hold a resin proximate
5 each of the carbon fibers and to form a hardened finished part with application of a resin, curing agent, and pressure on the nonwoven fabric; and wherein the structural properties of the homogenous nonwoven fabric are within about 1% or about 10% variance of the specification.

10 In an aspect, the present disclosure provides for nonwoven fabrics structured to be formed into a hardened finished part, where the nonwoven fabric comprises: (a) a homogenous fiber blend of a volume of about 2" to 5" long substantially individual carbon fibers and a volume of about 2" to 5" long non-carbon fibers; (b) an areal weight built of cross-lapped layers of the homogenous fiber blend, wherein the
15 substantially individual carbon fibers are aligned prior to being cross-lapped; and (c) entanglement of the cross-lapped layers of the homogenous fiber blend into a nonwoven fabric structured to hold a resin proximate each of the carbon fibers and to form a hardened finished part with application of a resin, curing agent, and pressure on the nonwoven fabric.

20 In an aspect, in the nonwoven fabric, the volume of substantially individual carbon fibers comprises pieces of substantially individual carbon fibers less than 2" long.

In an aspect, in the nonwoven fabric, the nonwoven fabric has an areal weight of 100 gsm to 12,000 gsm and is structured to form a hardened finished part thickness
25 of about 1/10 mm to 12 mm.

In an aspect, the nonwoven fabric further comprises substantially individual carbon fibers needle punched through the thickness of the oriented layers to integrate the oriented layers into a single ply.

30 In an aspect, the nonwoven fabric further comprises a hardened finished part of uniform thickness formed with application of heat and pressure to the nonwoven fabric.

In an aspect, in the nonwoven fabric, the non-carbon fibers have a non-linear structure along their length.

- 53 -

In an aspect, the nonwoven fabric further comprises a thermoset or thermoplastic resin on the nonwoven fabric.

In an aspect, in the nonwoven fabric, the nonwoven fabric having a resin is stored or handled at ambient temperature.

5 In an aspect, in the nonwoven fabric, the non-carbon fibers include at least one member selected from the group consisting of aramids, para-aramids, polyester, PET, flax, PVOH, carbon fiber precursors (OPAN), and another non-thermoplastic filler, and wherein the nonwoven fabric is structured to be infused with a thermoset resin.

10 In an aspect, the nonwoven fabric further comprises a thermoset resin infusing the nonwoven fabric.

In an aspect, the nonwoven fabric further comprises epoxy or vinyl ester, wherein a hardened finished part formed from a about 250 gsm, about 0.25" thick nonwoven fabric has a flexural modulus exceeding about 8,000 MPa per ASTM D790.

15 In an aspect, in the nonwoven fabric, the hardened finished part having a Specific Tensile Strength greater than 120 kN*m/kg.

In an aspect, in the nonwoven fabric, the non-carbon fibers are thermoplastic fibers that are a dry resin, and further comprising storing or handling the nonwoven fabric at ambient temperature, the thermoplastic fibers including at least one member
20 selected from the group consisting of PP, PA6, PA66, PA12, PPS, PC, PEI, PEEK, and another thermoplastic.

In an aspect, the nonwoven fabric further comprises polypropylene fibers chemically modified with maleic anhydride and heating the woven fabric to at least 400° F.

25 In an aspect, in the nonwoven fabric, a hardened finished part has a specific gravity of about 1.04 g/cm³ per ASTM D792 and a tensile strength of at least 200 MPa per ASTM D638-08.

In an aspect, in the nonwoven fabric, a hardened finished part has a specific gravity of about 1.02 g/cm³ per ASTM D792 and a tensile strength of at least 100
30 MPa per ASTM D638-08.

In an aspect, in the nonwoven fabric, the nonwoven fabric has cross-lapped layers oriented from 60° to 85° angles, and wherein when the nonwoven fabric is seamed to form a tube-shaped pipe liner fabric, wherein the substantially individual

- 54 -

carbon and non-carbon fibers are oriented in the circumferential direction of the pipe liner fabric.

In an aspect, in the nonwoven fabric, the pipe liner fabric is sufficiently fluid-tight to inflate with air when the ends of the tubular nonwoven fabric are closed or
5 plugged.

In an aspect, the nonwoven fabric further comprises a surface treatment that is a film or sprayed-on coating or a partial melt of the inner or outer surface of the pipe liner fabric.

In an aspect, the nonwoven fabric further comprises a hardened finished part
10 (e.g., about 1 mm to 12 mm thick) using dry heat of about 400° to 475° F and inflation pressure of about 3-125 psi, wherein the hardened finished part is a pipe liner.

In an aspect, in the nonwoven fabric, a first pipe liner about 2-3 mm thick is thermoformed at 5-30 PSI in 20 to 90 minutes.

15 In an aspect, in the nonwoven fabric, a second pipe liner about 2-3 mm thick is thermoformed within the first pipe liner at about 100-120 PSI in about 10-20 minutes.

In an aspect, in the nonwoven fabric, the curing agent has dry heat of 400° to 405° F.

In an aspect, the present disclosure provides for a hardened finished part
20 formed from a nonwoven fabric, the finished part includes: (a) a nonwoven fabric comprising: (1) a homogenous fiber blend of a volume of about 2" to 5" long substantially individual carbon fibers and a volume of about 2" to 5" long non-carbon fibers; (2) an areal weight built of cross-lapped layers of the homogenous fiber blend, wherein the substantially individual carbon fibers are aligned prior to being cross-
25 lapped; and (3) entanglement of the cross-lapped layers of the homogenous fiber blend into a nonwoven fabric; and (b) a thermoset or thermoplastic resin on the nonwoven fabric proximate each of the substantially individual carbon fibers and cured under pressure; wherein the nonwoven fabric with cured resin is a hardened finished part.

30 In an aspect, in the hardened finished part, the volume of substantially individual carbon fibers comprises pieces of substantially individual carbon fibers less than 2" long.

- 55 -

In an aspect, in the hardened finished part, the nonwoven fabric has an areal weight of about 100 gsm to 12,000 gsm and is structured to form a hardened finished part thickness of about 1/10 mm to 12 mm.

5 In an aspect, the hardened finished part further comprises substantially individual carbon fibers needle punched through the thickness of the oriented layers to integrate the oriented layers into a single ply.

In an aspect, the hardened finished part further comprises a hardened finished part of uniform thickness formed with application of heat and pressure to the nonwoven fabric.

10 In an aspect, in the hardened finished part, the non-carbon fibers have a non-linear structure along their length.

In an aspect, in the hardened finished part, the non-carbon fibers include at least one member selected from the group consisting of aramids, para-aramids, polyester, PET, flax, PVOH, and carbon fiber precursors (OPAN).

15 In an aspect, the hardened finished part further comprises a thermoset resin infusing the nonwoven fabric.

In an aspect, the hardened finished part further comprises epoxy or vinyl ester, wherein a hardened finished part formed from a about 250 gsm, 0.25" thick nonwoven fabric has a flexural modulus exceeding about 8,000 MPa per ASTM D790.

20 In an aspect, in the hardened finished part has a Specific Tensile Strength greater than 120 kN*m/kg.

In an aspect, in the hardened finished part the resin is thermoplastic including at least one member selected from the group consisting of PP, PA6, PA66, PA12, PPS, PC, PEI, and PEEK.

25 In an aspect, the hardened finished part further comprising polypropylene chemically modified with maleic anhydride heated to at least 400° F.

In an aspect, in the hardened finished part has a specific gravity of about 1.04 g/cm³ per ASTM D792 and a tensile strength of at least 200 MPa per ASTM D638-08.

30 In an aspect, in the hardened finished part has a specific gravity of about 1.02 g/cm³ per ASTM D792 and a tensile strength of at least 100 MPa per ASTM D638-08.

- 56 -

In an aspect, in the hardened finished part the hardened finished part is a pipe liner, and wherein the cross-lapped layers are oriented from about 60° to 85° angles in the nonwoven fabric, and the substantially individual carbon fibers are oriented in the circumferential direction of the pipe liner.

5 In an aspect, in the hardened finished part the hardened finished part is a pipe liner thermoformed using dry heat of about 400° to 475° F and inflation pressure of about 3-125 psi.

In an aspect, the hardened finished part has a first pipe liner about 2-3 mm thick is thermoformed at about 5-30 PSI in about 20 to 90 minutes.

10 In an aspect, the hardened finished part has a second pipe liner about 2-3 mm thick is thermoformed within the first pipe liner at about 100-120 PSI in about 10-20 minutes.

In an aspect, in the hardened finished part the curing agent is dry heat of 400° to 405° F.

15 Now having described the features of the present disclosure, additional features are described in reference to the following figures.

Figure 1 shows a tow opener or carbon fiber separation device (100). Carbon fibers (101) bound by binding material (thus, attached) enter the device (100) via inlet (102) and are received by feeder belts (103). (Arrows show the direction of movement of carbon fibers through device (100); it will be appreciated that the direction of the arrows is from upstream to downstream, as the movement of the carbon fibers is from upstream to downstream). The attached carbon fibers are directed onto the moving surface of conveyor (104), which in Figure 1 is a conveyor belt at an incline and thus against gravity. There are protrusions protruding from the surface of the conveyor (protrusions not shown in Figure 1) which pass between and separate carbon fibers on the moving surface of the conveyor. The mass of carbon fibers flowing from upstream to downstream may itself facilitate carbon fibers being carried along. The protrusions pull the carbon fibers from each other (and from binding material, if present) in a slow and gentle action, minimizing impact and thereby mitigating or avoiding breakage of the carbon fibers. Meanwhile, a turbulent air flow in the device, generated by one or more generators of a turbulent air flow (suitably, cyclones; not shown) aids gentle separation. Also present are agitator rolls (105) having a surface for brushing carbon fibers, thus further aiding separation. Separated carbon fibers are discharged from

20
25
30

- 57 -

outlet (106), to which they have been directed by guides (107). Also provided is a recirculation mechanism (108), having ductwork for recirculating unseparated (remaining attached) carbon fibers (109) to the conveyor (104), especially for recirculating bundles of attached carbon fibers (109). Although not shown in Figure 1, 5 recirculation mechanism (108) may alternatively send unseparated (remaining attached) carbon fibers to another carbon fiber separation device, which is analogous and substantially identically functioning to carbon fiber separation device (100). Controller (110) monitors and controls the dwell time in carbon fiber separation device (100), which can be adjusted by an operator if desired, for example by 10 adjusting the flow rate of attached carbon fibers into the device (100). Typically, after a time period of about 5 to about 30 minutes, separated carbon fibers (111) are ready to pass on to blending (not shown).

Figure 2 shows an expanded view of the conveyor (conveyor belt) (104) of Figure 1. Gears (112) enable operation of the conveyor (104) as a conveyor belt. 15 Protrusions (113) protrude from the surface (114) of the conveyor belt (104). As described herein, protrusions (113) are dimensioned and configured to aid separation of the carbon fibers in an especially gentle manner. The protrusions shown in Figure 2 are elongate, having the form of mechanical fingers, while also comprising an attachment for joining to surface (114) of the conveyor belt (104). The protrusions 20 may suitably be made of metal, such as aluminum, steel or PVC. During use, protrusions (113) gently insert between carbon fibers (not shown) brushing past, thereby separating the carbon fibers without undue breakage thereof.

It will be appreciated that a fiber blending device as described herein may have one or more, preferably all, of the features of the carbon fiber separation device 25 (100) of Figure 1. Thus, a conveyor in a fiber blending device as described herein may have one or more, preferably all, of the features of the conveyor (104) of Figures 1 and 2.

Figure 3 is a schematic representation of apparatus (300) for forming a nonwoven fabric. Cutting device (301) receives attached carbon fibers, for example in 30 tows, and cuts the carbon fibers (still attached to each other) to have a mean length of about 5 centimeters to about 12 centimeters. From cutting device (301), the attached cut carbon fibers pass to carbon fiber separation device (100) as described with reference to Figure 1. Optionally, cutting device (301) and carbon fiber separation

- 58 -

device (100) together form part of carbon fiber cutting and separation apparatus (302). Carbon fibers are optionally recirculated to carbon fiber separation device (100); and/or carbon fibers optionally pass to one or more further carbon fiber separation devices (not shown). Separated carbon fibers then pass to fiber blending device (303).

5 Also received by fiber blending device (303) are further fibers, which are non-carbon fibers and may be thermoplastic fibers or filler fibers as described herein. The fiber blending device (303) forms a homogeneous fiber blend by blending the received carbon fibers with a plurality of further fibers. The fibers are optionally recirculated to fiber blending device (303); and/or the fibers optionally pass to one or more further

10 fiber blending devices (not shown). Controllers (304a, 304b) monitor and control dwell time in the carbon fiber separation device (100) (or devices) and in the fiber blending device (303) (or devices). Optionally, carbon fiber separation device (100) and carbon fiber blending device (303) together form part of carbon fiber separation and blending apparatus (305). Optionally, cutting device (301) is also part of carbon

15 fiber separation and blending apparatus (305). Although in Figure 3, one controller (304a) is shown in the fiber separation device (100) and one (304b) is shown in the carbon fiber blending device (303), it will be appreciated that only one or more than one controller may be provided in the fiber separation device (100); similarly, only one or more than one controller may be provided in the carbon fiber blending device

20 (303). One, or more than one controller may be provided in other devices, especially in blending device (303). From blending device (303), the homogeneous fiber blend proceeds to fiber aligning device (306), for example a carding machine, in which an aligned fiber layer is formed by aligning (e.g., carding with carding wires) fibers in the homogeneous fiber blend (particularly, aligning the carbon fibers). The aligned

25 fiber layer passes to cross-lapper (307), which forms a cross-lapped fiber layer by cross-lapping the received aligned fiber layer. The cross-lapped fiber layer is mechanically entangled by mechanical entanglement device (308), for example a needle punch machine, which forms a nonwoven fabric by mechanically entangling (e.g., needle punching) the received cross-lapped fiber layer. It will be appreciated

30 that needle punching may occur on the same conveyor belt on which cross-lapping occurs. Optional further processing steps (309) may then be performed. For example, the fabric may be cut to shape. It may be surface treated. It may be seamed. A backing sheet may be added. As shown in Figure 3, all components of apparatus (300) have

- 59 -

entirely insulated electronics, provided by suitable enclosures and represented schematically by bold outline (310). Also provided is appliance (311) for collecting and removing airborne carbon fibers.

Figures 4a and 4b shows differences between a homogeneous fiber blend (Fig 4b) in accordance with the disclosure, and an inhomogeneous fiber blend (Fig 4a). In Figure 4a, carbon fibers (400a-c) are attached to each other and are not homogeneously blended with further (non-carbon) fibers such as further fibers (401a-c). Although not shown, the carbon fibers (400a-c) of Figure 4a may also be of varying lengths and not have a mean length of about 5 centimeters to about 12 centimeters. In contrast, in Figure 4b, carbon fibers are separated and are homogeneously blended with further (non-carbon) fibers such as further fibers (401a-c). Although not shown, the carbon fibers (400a-c) of Figure 4a are also of similar lengths and have a mean length of about 5 centimeters to about 12 centimeters. Thus, composite materials formed using a homogeneous fiber blend as depicted in Figure 4b may be stronger than composite materials formed using an inhomogeneous fiber blend as depicted in Figure 4a.

Figure 5a shows a sample (504) of a nonwoven fabric in accordance with the disclosure. The nonwoven fabric has a surface (503) having a suitable length and a suitable width; and a side (501) having a thickness (502). The thickness may be selected in accordance with a preferred areal weight in gsm. The thickness may depend on the cross-lapping and mechanical entanglement undergone by the nonwoven fabric; and may be selected in accordance with product specifications and formulation requirements. Meanwhile, Figure 5b shows the sample (504) of the nonwoven fabric schematically. Illustrated on the sample (504) are the x, y and z axes. Mechanical entanglement which is needle punching has resulted in some of the carbon fibers in the sample, labeled as carbon fibers (505), being substantially parallel to the z axis of the fabric, which is in a single ply (506); while most carbon fibers (not shown) remain substantially parallel to the x-y plane. It will be understood that a few carbon fibers punched substantially parallel to the z axis may be bent or broken; however, they do not protrude from the sides of the nonwoven fabric, which has uniform edges. Figure 5c shows an x-y plane (507) through the ply (506) of the sample (504) of the nonwoven fabric (schematically), now with the carbon fibers (508) in that x-y plane shown (aligned into the x-y plane by a carding operation (e.g.,

- 60 -

one layer of carbon fibers, about 70% to 90% or about 80% to 90% of the fibers are oriented within about 30 to 40 degrees of each other)); carbon fibers substantially parallel to the z axis are not shown. Figure 5d shows, schematically, a roll of the fabric (509), ready for shipping to a location of interest. A layer (510) of the fabric
5 may be protected by a backing sheet (not shown) or surface treated before being formed into roll (509).

In Figure 6a, nonwoven fabric (600a) is provided comprising carbon fibers and non-carbon thermoplastic fibers, having a thickness (601a). The nonwoven fabric (600a) is thermoformed to produce thermoformed material (600b) under pressure,
10 optionally in a mold (not shown). The change in thickness (compaction) from nonwoven fabric thickness (601a) to material thickness (601b) is illustrated by dotted lines adjacent material (600b). In general, a single ply carbon/TP fabric 3204 having an areal weight of 100 gsm to 12,000 gsm is structured to form a finished part having a consolidated ply thickness 601b of 1/10 mm to 12 mm, respectively. Each
15 incremental 1,000 gsm of areal weight adds about 1 mm of incremental thickness to the hardened finished part. Carbon/TP fabric structure, thickness, and performance can be specified within 1% variance, and the resultant hardened finished part 2275 can likewise be specified to have uniform thickness 601b within 1% variance, given the parameters of the molding process. However, specification is not limited to 1%
20 variance, but remains novel at a 10% variance, for example, for the purposes of this Application. In general, final part thickness 601b is calculated accounting for at least areal weight, fiber weight fraction, fiber densities and lengths, resin type and chemistry, curing agent, and pressure.

In Figure 6b, nonwoven fabric (600c) contains filler fibers. In this
25 embodiment, a thermosetting resin (not shown) is applied to the fabric (600c), followed by curing to form a thermoset material (600d). The process shown in Figure 6b further involves compaction, for example in a mold, to produce a final thermoset material (600d) having a compacted thickness (601d); but a smaller change in thickness occurs, from thickness (601c) to thickness (601d) in Figure 6b, than the
30 change shown in Figure 6a from thickness (601a) to (601b). This may be due to the application of the additional thermosetting resin in Figure 6b. Specification of carbon/filler fiber, the Fiber Weight Fraction, fabric thickness, and areal weight can be made and controlled within 1% variance. However, specification of final part

- 61 -

thickness and performance depends greatly upon the resin selected, the ability of the fabric to take in the infused resin, and the uniformity of manufacturing, including wet out, storage, and handling at the jobsite, as well as resin type and chemistry, curing agent, and pressure.

5 Figures 7a and 7b show articles made from thermoplastic or thermoset material (600a or 600c). Figure 7a shows (in perspective view) a truck cab roof (700a), having a surface (701) with contours (702). Besides contours (702), the roof (700a) may have various other structural features, including but not limited to gussets, ribs, boss features, draft angles, and sharp corners. Figure 7b shows a perspective
10 view of a fan (700b) having blades (703a-c) adjoining a hub (704) and reinforced by spokes (705a-c). Figures 7a and 7b demonstrate several advantages of the present disclosure, including the possibility of forming sharp, well-defined edges and intersections, such as for the production of geometrically complex shapes. The present nonwoven fabric having carbon fibers of a mean length of about 2.5 (especially, about
15 5) centimeters to about 12 centimeters allows the formation of sharp, well-defined edges and intersections, more easily than would be possible with a woven fabric (having much longer, continuous carbon fibers) which cannot bend into complex or deep mold shapes. However, until now carbon fibers in nonwoven fabrics, typically produced in wet laid processes, have tended to have a length of much less than 2.5
20 centimeters. It has surprisingly been found that the lengths employed herein improve the strength of the material compared to shorter lengths. While there may be a little breakage of the fibers during the methods disclosed herein, advantageously breakage is minimized.

 Figure 8a shows (in perspective view) a pipe liner (800) made from
25 thermoplastic or thermoset material (600a or 600c). In Figure 8a, carbon fibers are aligned (in this case, carded) in material (803) to provide quasi-unidirectional properties (achieved during carding by orienting more carbon fibers in the weft orientation, perpendicular to the direction that would become the length of the pipe). This imparts strength to the pipe liner (800), which may be especially advantageous in
30 view of overburden (also known in the art as vertical stress) which may, for example, be a factor if the pipe liner (800) is located underground. The pipe liner (800) has an inner cavity (805) defined by an inner surface (806). The pipe liner (800) also has an outer surface (807) and a thickness (808) between the inner surface (806) and the

- 62 -

outer surface (807). In use, a sleeve (not shown) may be provided between a host pipe (not shown in Figure 8a) and the outer surface (807) of the pipe liner (800). An inner coating (not shown) may be provided on the inner surface (806) of the pipe liner (800). The inner coating may itself be or comprise a further pipe liner made from thermoplastic or thermoset material. Having an additional pipe liner, in this way, may further increase the strength and durability of the mended pipe. Figure 8b shows (in perspective view) the pipe liner (800) inside a damaged host pipe (809) having breaches (810a, 810b) in its surface. It will be appreciated that there may be only one breach, or there may be more than two breaches; and the breaches may be of varying size.

The flow charts of Figures 15-17 outline a system for manufacturing a nonwoven needle punched fabric for forming a hardened finished part 2100. This system generally comprises a controller 2101, a fiber preparation and blending system 2108, a carding and needle punch system 2180, a resultant needle punched broadgood or fabric 2200, either a thermoset forming system 2210 or a thermoplastic forming system 2260, and a carbon fiber filtration and isolation system 2105 for airborne fibers because they are electrically conductive. Contrary to almost all manufacturers of nonwoven needle punched fabrics, carbon fibers 2130 are the focus of the present system 2100, and without adequate isolation 2105 of electronics (using, for example, NEMA 4- and IP65-rated enclosures), the carbon fibers 2130 will short out, interfere with, or otherwise damage the manufacturing controllers and equipment, such as motors, drives, wiring, lighting, and so on. Due in part to this difficulty, and in part to the general lack of a developed market and required processes for carbon fiber recycling, the employed machinery was modified and improved. Beyond my contracted manufacturers, no other manufacturer possesses the combination of systems or methods designed to produce the material disclosed in this specification. The system 2100 may include destructive lab testing 2106 to confirm target performance properties.

In Figure 15, the first stage of the fiber preparation and blending system 2108 is carbon fiber preparation 2110. Carbon fibers 2130 may be recycled (rCF) or virgin (vCF) material, or a mix of the two, and they may be sourced as discontinuous fibers or as long or continuous filaments in tows (carbon fibers bound by binding material) 101, which are fiber bundles of typically 3,000 to 60,000 filament counts, or greater.

- 63 -

“Carbon” refers primarily to carbon fibers, but also comprises carbon nanotubes, graphene fibers, graphite, and other materials similarly related to carbon. It is understood that “fiber” and “filament” are often used synonymously in common discussion; however, in this specification the term “fiber” is employed to denote a staple fiber that is a shorter, discontinuous fiber. If required, a chopper 2112, precision cutter 2114, or similar device cuts filaments or tows 101 to the desired carbon fiber length, which is 2” to 4” (25 mm to 125 mm) long, with a preferred length of about 3” (76 mm). A length up to 5” is possible, but carbon fibers 2130 longer than 4” tend to become caught and compacted in the wires of the card line 2182 and fail to flow through to the cross lapper 2184. Carbon fibers 2130 in tows 101 often arrive on bobbins and are fed into a precision cutting system 2114 to be cut to length with +/- 5% accuracy. Carbon fibers 2130 that arrive in bales are opened and processed by fiber chopping equipment 2112 that controls the fiber length within a less precise range. A timer 2121 controls a tow opener 2122 (which is the same as the carbon fiber separation device 100) that separates the carbon fibers 2130 from one another, breaking or separating the binder or sizing on the tow 101 without excessive breakage of the carbon fibers 2130, until substantially individual carbon fibers 2130 exit the tow opener 2122. In other words, tows 101 are excluded from the exiting volume of carbon fibers 2130.

Carbon fibers 2130 with sizing 2133 present is preferred, as testing has proven that sizing 2133 aids carding 2382, makes the carbon fibers 2130 more easily processed without breakage, and results in a stronger carbon-to-resin bond 1104. rCF 2130 that has been recycled through pyrolysis or solvents results in the fiber sizing being removed and will typically need to be re-sized 2133 before use. A chemical modifier 2145 may be added, though carbon fibers 2130 are typically used as sourced. Whereas carbon fibers 2130 may range from 5-10 microns in diameter, preferably carbon fibers 2130 are 6-7 microns in diameter and are type SM having standard modulus of 33-36 msi or type IM having intermediate modulus of 43-47 msi (generally 29-51 msi, though not limited to this range), and a particular production run is preferably limited to a particular type or class. Uniformity increases predictable performance, whereas mixing carbon fibers 2130 across types leads to less predictable performance.

- 64 -

Non-carbon fibers 2140 are also sourced and further prepared, which may include opening tows of non-carbon fibers 2140 (which may be achieved via carbon fiber separation device 100). Filler fibers 2141 include, but are not limited to, aramids, para-aramids, polyester, PET, flax, PVOH or PVA, carbon fiber precursors (i.e., OPAN), or a combination of filler fibers 2141. Thermoplastic fibers 2144 include, but are not limited to PP, PA6, PA66, PA12, PPS, PC, PEI, PEEK, or a combination of thermoplastic fibers 2144. A chemical modifier 2145 may be applied to fibers 2141, 2144, 2130 to aid bonding. Preferably, maleic anhydride is the chemical modifier 2145 applied to PP to produce polypropylene fibers (thermoplastic fibers 2144), though the chemical modifier 2145 is not limited to maleic anhydride (MAPP). Other additives may include UV protectants, fire retardants, etc. Non-carbon fibers 2140 are preferably 3-10 denier (15-67 microns) and crimped (non-linear structure) 3147 to grab and pull the carbon fibers 2130 through the carding line 2182, thus reducing processing time.

The second stage of the fiber preparation and blending system 2108 is the fiber blender 2150, where a fiber weight fraction (FWF) controller 2151 mixes a volume of carbon fibers 2130 and a volume of non-carbon fibers 2140 into a homogenous fiber blend 2160. Carbon fibers 2130 plus filler fibers 2141 provide a carbon/filler blend 2162, typically with the percent of carbon by weight ranging from 10% to 100%, and preferably from 50% to 80%. Alternatively, carbon fibers 2130 plus thermoplastic fibers 2144 produce a carbon/thermoplastic blend 2164, typically with the percent of carbon by weight ranging from 10% to 70%. Carbon fiber percentage is not limited to those ranges, but is determined by specified requirements for product application. In one configuration, the tow opener 2122 or a portion of the tow opener 2122 also functions as the fiber blender 2150. Different fiber blends 2160 require different dwell times in the fiber blender 2150, or a series of fiber blenders 2150 for increased throughput efficiencies, to achieve optimized blending 2350.

The homogenous fiber blend 2160, 2162, 2164 then proceeds through the carding and needle punch system 2180. This system 2180 is not limited to a carding line 2182, which more generally may be referred to as a system for aligning the carbon fibers 2130 and non-carbon fibers 2140, but carding with card wire is preferred. From the carding line 2182, the homogenous blend goes to a cross lapper 2184 and a needle loom 2186. Very importantly, alignment of the fibers 2130, 2140

- 65 -

is achieved before they enter the cross lapper 2184 that layers and builds the areal weight of the homogenous blend 2160, and mechanical entanglement in the carding and needle punch system 2180 occurs without electrical conductance of carbon fibers 2130 damaging equipment. From the needle loom 2186, the needle punched fabric 2200 goes to a fabric shaper or cutter 2188, and optionally various surface treatments 2190 or seaming tools 2194. The result is a carbon-reinforced needle punched fabric 2200 that, depending upon configuration, is a carbon/filler fiber fabric 2202 for thermoset (TS) applications, a carbon/thermoplastic fabric 2204 for thermoplastic (TP) applications, or a carbon-only fabric 2208 to be utilized in either TS or TP applications where resin infusion would take place. Carbon-only fabric 2208 is less common; therefore, this specification focuses on the other fabrics 2202, 2204. The present technology is able to output various fiber directions including isotropic, but is preferably oriented into quasi-anisotropic, quasi-isotropic, orthotropic, or anisotropic composite materials to optimize distribution of the reinforcement properties of the carbon fibers 2130 in the selected TS or TP resin matrices 2213, 2144.

Figure 16 expands upon the thermoset forming system 2210 that utilizes carbon/filler fiber needle punched fabric 2202 (or 2208 if the volume of filler fiber is zero) to form a thermoset hardened finished part 2225. Usually, a thermoset resin 2213 such as epoxy, polyester, phenolic resin, vinyl ester, or other TS resin 2213 is applied to “wet out,” infuse, or impregnate the nonwoven fabric 2202. The degree of uniform and thorough coverage by the thermoset resin 2213 of the surfaces of the fibers 2130, 2141 in the fiber blend 2162 determines the successful performance or failure of the finished part 2225. After application of most TS resins 2213, the nonwoven fabric 2202 has little to no ambient shelf life and, if not formed and cured to a finished part 2225 immediately, must be stored and shipped in ultra-cold refrigeration 2215 as a wet prepreg for later use. This limitation of ultra-cold refrigeration 2215 may be avoided by innovation of newer TS resins 2213 that are unaffected by ambient temperature. A backing sheet 2211 may be added to keep the resin-impregnated nonwoven fabric 2202 from sticking to itself when rolled up. A thermoset curing system 2220 generally includes a mold 2222 that ensures appropriate pressure and a thermoset curing agent 2224 such as heat (water or steam) or UV light on the TS resin 2213 to form a TS hardened finished part 2225. Types of molds 2222 include hand layup, RTM, VARTM, vacuum bag, autoclave, pultrusion mold,

- 66 -

compression mold, or a host pipe 4010, for example. A thermoset pipe liner forming subsystem 2230 for cured-in-place pipe (CIPP) includes a tube-shaped or seamed tubular fabric that is a pipe liner fabric 2234, a TS intra-pipe delivery system 2240, and a thermoset timer 2241. Seams 801 are preferably French fell seams 801 for increased strength during handling in utility pipe 4010 installations, but are not limited to such. A pipe liner coating 2235, pre-liner sleeve 2236, or calibration bladder 2245 may be used, particularly if groundwater is present, and the backing sheet 2211 on the inner surface 806 may also act as the calibration bladder 2245. The calibration bladder 2245 may comprise CFA, PEEK, PAEK, silicone rubber, or another material that withstands temperatures of 200-400°F. CIPP applications will be discussed in more detail later.

Figure 17 expands upon the thermoplastic forming system 2260 that utilizes carbon/thermoplastic needle punched nonwoven fabric 2204 to make a hardened finished part 2275 (or utilizes a carbon-only fabric 2208 if a different form of thermoplastic resin 2148, whether solid, viscous, semi-liquid, or liquid, is later infused into the fabric 2208 in the mold 2272). A backing sheet 2261 may be added. The homogenous fiber blend 2164 of the carbon fibers 2130 and TP fibers 2144 dictates successful bonding of the fibers 2130, 2144 and the mode of failure of the carbon/TP (C/TP) finished hardened part 2275. In significant contrast to most thermoset forming 2210, the present carbon/TP fabric 2204 may be stored and handled as a Dry Prepreg™ at ambient temperature with unlimited shelf life. In the thermoforming system 2270, heat is the TP curing agent 2274 utilized with pressure in a mold 2272 to form a C/TP hardened finished part 2275 in a prescribed period of time. Thermoforming may include vacuum or pressure forming, compression molding, or lamination, the processes of which can be replicated in a host utility pipe 4010 for Thermoformed-in-place Pipe™ (TIPP™), for example. Thermoplastic resin 2144 completes its curing process via crystallization as the polymer cools, at a temperature that varies for each type of TP resin 2144. A thermoplastic pipe liner forming subsystem 2280 includes a heat welded tube-shaped or tubular fabric that is a pipe liner 2284, a TP intra-pipe delivery system 2290, a TP timer 2291 for control of dwell time, and dry heat 2274' as the curing agent 2274. Ultrasonically bonded and/or heat welded seams 801 are novel for this application, but are not limiting unless so claimed. A pipe liner coating 2285, pre-liner sleeve 2286, or calibration

- 67 -

bladder 2295 may be used. It is worth noting that the term “curing” has long been associated with thermoset processes, but less associated with the thermoforming process. In this specification, “curing” is recognized as associated with both thermoset and thermoforming. The polymers of cured thermoset products form permanent cross-linked bonds and cannot be re-formed. Polymers of cured thermoformed products can be re-melted or reshaped because they are not cross-linked.

Turning now to Figures 18-20, a method is described that has not previously been possible since the invention of carbon fiber. A method of manufacturing a nonwoven fabric for forming a hardened finished part 2300 generally comprises specifying a nonwoven fabric and final part thickness and performance 2301, isolating equipment and electronics due to carbon fiber electrical conductance 2305, filtering the air in the facility and collecting unseen carbon fibers 2306, preparing fibers 2308, producing a nonwoven needle punched fabric 2380, and delivering the fabric and forming finished parts 2400. During any stage of manufacturing or forming, and often at the end of product life, 100% of the reinforcement carbon fiber may be recycled 2399 via pyrolysis, solvents, or comparable processes.

A method of preparing fibers 2308 generally includes three steps. Prepping carbon fibers 2310 entails making the carbon fibers discontinuous 2312, opening tows to produce individual fibers 2322, and optionally chemically adjusting the carbon fibers 2335. Preparing non-carbon fibers 2340 after they are sourced includes prepping any filler fibers 2341 or chemically adjusting fibers 2345, as needed, and may include opening tows of non-carbon fibers 2340. Blending the fibers 2350 includes controlling the fiber weight fraction 2351 when creating a carbon/filler fiber blend 2362 or creating a carbon/thermoplastic blend 2364. The use of rCF 2130 in this method 2300 reduces both energy usage and CO₂ emissions by about 90% each in comparison to production of virgin carbon fibers 2130 for producing composite materials.

A method of producing a nonwoven needle punched fabric 2380 generally includes aligning the fibers (particularly the carbon fibers 2130) and orienting layers of fibers 2382 of the homogenous blend 2160 to build the areal weight 2384 for needle punching 2386. The resultant nonwoven fabric 2200 is thus structured for delivery and for forming a hardened finished part 2400. The nonwoven broadgood

- 68 -

2200 may be further cut or shaped 2388, surface treated 2390, or seamed 2394 to suit specific applications. Thermoset and thermoforming processes (2410 and 2460, respectively) will be discussed in a moment. For thicker finished parts 2225, 2275, the needle loom 2186 completes fabrication of a 1-ply broadgood 2385 by punching
5 or orienting carbon fibers 2130 through the thickness 502 of the cross-lapped layers to integrate the cross-lapped layers into a single ply 2385 composite. Punched carbon fibers 2130 bend or break, but do not protrude beyond the thickness 502.

Figure 21 is a simple illustration of the structure of a basic carbon/filler fiber fabric 3200, 3202 produced by the above method(s) to be utilized in thermoset
10 forming 2410. The vertical lines represent carbon fibers 3130 that are punched relatively vertically (in the “Z” direction) through the thickness 502 of the cross-lapped layers 3183 (represented by dashed ovals) to reduce or eliminate inter-layer weakness (or inter-ply delamination that is common in woven carbon fiber fabrics, if one argues that layers are plies, for the present disclosure multiple fiber layers 3183 in
15 the present nonwoven composite are considered to be a single compilation or a single ply). For simplicity, only two fiber layers/orientations 3183 are drawn. The cluster of fibers 3130, 3141 at the top left are at 90° and essentially shown in cross-section. The cluster of fibers 3130, 3141 to the right are at 0° (machine direction). Filler fibers 3141 typically have a non-linear structure 3147 due to crimps produced in their
20 manufacture, or a natural waviness, but are not limited to a non-linear structure 3147. This configuration is 70% carbon fibers 3130 by weight, 10% para-aramid or polyester as first filler fiber 3142, 3141, and 20% OPAN as a second filler fiber 3143, 3141. The TS nonwoven fabric 3202 of Fig. 21 is utilized in the method of thermoset forming 2410 of Figure 19 to produce a finished thermoset part 2425, which generally
25 includes storing the TS carbon/filler fiber fabric 3202 at ambient temperature 2412 until thermoset resin is added 2413, at which time the composite typically must be refrigerated at ultra-cold temperature 2415, and then curing a thermoset part 2420 by placing the TS nonwoven fabric 3202 with TS resin 2213 in a mold or host utility pipe under pressure 2422 and applying the TS curing agent 2424 (which may be heat, UV,
30 or other thermoset curing agents 2224) for a dwell time specific to each resin 2213. As mentioned earlier, one might add a backing sheet 2411 to one or both sides of the fabric 3200 in certain circumstances to prevent adhesion of the resin 2213 to itself. A thermoset pipe liner forming sub-method 2430 for CIPP generally includes seaming a

- 69 -

pipe liner fabric 2434 into a tubular shape before the resin 2213 is applied, preferably by a flat fell seam uniquely designed for these materials, though seaming is not limited to a flat fell seam, and placing a calibration bladder into a host pipe 2445 with the pipe liner fabric 2234 to supply pressure. Adding an air-tight, water-tight coating 2435 to the pipe liner fabric 2234 is an option, as is using a pre-liner sleeve 2436, and the pipe liner fabric 2234 may be pulled into the host pipe or delivered by inversion 2440.

Figure 22 is a simplistic illustration of a basic carbon/thermoplastic fabric 3200, 3204 produced by the above method(s) to be utilized in thermoforming 2460.

10 The vertical lines represent carbon fibers 3130 that are needle punched relatively vertically (in the “Z” direction) through the thickness 502 of the cross-lapped layers 3183 (represented by dashed ovals) to reduce inter-ply weakness. For simplicity, only two fiber layers/orientations 3183 are drawn. The cluster of fibers 3130, 3144 at the top left are at 90° and essentially shown in cross-section, and the cluster to the right

15 are at 0° (machine direction). The thermoplastic fibers 3144 typically have a non-linear structure 3147 due to natural or manufactured crimping, but are not limited to a non-linear structure 3147. This configuration is 30% carbon fibers 3130 by weight and 70% polypropylene or modified polypropylene fibers 3144. The carbon/TP resin nonwoven fabric 3204 of Fig. 22 is utilized in the method of thermoplastic forming

20 2260 of Figure 20 to finish a carbon/TP part 2475, which generally includes storing the carbon/TP resin fabric at ambient temperature 2462 and thermoforming the fabric 2470 by placing it in a mold or existing host pipe to produce a final part shape under pressure 2472 and applying heat as the TP curing agent 2474 for a period of time specific to each resin 3144. In an embodiment comprising a carbon-only fabric 2208,

25 a viscous or other TP resin is added 2348, and a backing sheet 2461 may be used. A thermoplastic pipe liner forming sub-method 2480 for Thermoformed-in-place Pipe™ generally includes seaming a pipe liner 2484, preferably by heat welding or by ultrasonic welding, though seaming may be accomplished by sewing, tapes, adhesives, or a number of other common methods of seaming. Optional steps include

30 adding a coating 2485 before or after seaming 2484, using a pre-liner sleeve 2486, delivering the pipe liner intra-pipe via “pull-in” or inversion methods 2490, placing a calibration bladder into the host pipe 2495 with the pipe liner 2284 to supply pressure, and applying dry heat 2474’. A pipe liner coating 2285, such as a spray-on TPU, or

- 70 -

other surface treatment 2190 such as a minimal but sufficient melting of the outer surface 3206 of the pipe liner 2284 to make the pipe liner 2284 fluid-tight will allow the pipe liner 2284 to maintain pressure without a calibration bladder 2295. Such a partial melt (surface treatment 2190) is novel and eliminates the step and cost of applying a coating 2285. Or the backing sheet 2261 may also act as the calibration bladder 2295 as it contains the air pressure during inflation. Dry heat 2274' is preferred for efficient and speedy thermoforming 2470 at low pressure in damaged underground utility pipes 4010.

Turning now to Figures 8a and 23-37, the use of the nonwoven needle punched fabric 2200 is further described for in situ rehabilitation of water mains and pressure pipes via CIPP (Cured In Place Pipe utilizing thermoset resins) or TIPPTM (Thermoformed In Place PipeTM utilizing thermoplastic resins). In Fig. 8a, seamed 801 pipe liner fabric 2234, 2284 comprises an opening 807 through its length and is sized to be about 2% to 10% (preferably 7-8%) smaller than the inner diameter 11017 of the conduit, duct, or host pipe 809 to allow for expansion under pressure and sufficient contact with the host pipe 809. After seaming, the carbon and non-carbon fibers 2130, 2140 are oriented in the circumferential direction 805 of the seamed pipe liner fabric 2234, 2284 and provide maximum hoop strength to carry loads including overburden pressure from soil weight and live loads on the surface (for example, airplanes, trains, and trucks) and other loads. For pipe liners, flexural modulus and strength are of increased importance.

Figures 23-24 illustrate thermoset forming for CIPP 2230, 2210. In Fig. 23, seamed pipe liner fabric 4234, 4202 comprising infused thermoset resin 4213 is placed into an existing host pipe 4422, which acts as the mold 4010, 4222. Fibers 2130, 2141 are oriented in the circumferential direction 4196 and visible through multiple cracks 4013 in the host pipe 4010. In Fig. 24, the thermoset resin 4213 is cured 2424 to form a finished hardened part 2425 that is a pipe liner 2225 that is less thick than the thickness 4205 of the uncured pipe liner 2284, 2204. The hardened pipe liner 4225 seals off fluid flow through the cracks 4013 and may adhere to the host pipe 4010 itself.

Figures 25-26 illustrate thermoplastic forming for TIPPTM 2280, 2260. In Fig. 25, seamed tubular fabric 4284, 4204 comprising thermoplastic resin 2144 is placed into an existing host pipe 2472, which acts as the mold 4010, 4272. Fibers 2130,

- 71 -

2144 are oriented in the circumferential direction 4196 and visible through multiple cracks 4013 in the host pipe 4010. In Fig. 26, the fabric 4284, 4204 is thermoformed 2470 to form a finished hardened part 2475 that is a pipe liner 4275 having thickness 4205, which is significantly thinner than the thickness 4205 of the uncured TP fabric 5 4284, 4204 (for example, reducing from 12 mm thick to 2-3 mm thick). The hardened pipe liner 4275 seals off fluid flow through the cracks 4013 and may adhere to the host pipe 4010 itself.

Figure 27 illustrates the results of the thermoplastic pipe liner forming subsystem 4280 in cross-section. Host pipe 4010 has an outer diameter 4016 and an 10 inner diameter and inner surface 4017 that defines the aperture or opening 4019 through the length of the host pipe 4010, which acts as the mold 4272. A first hardened finished pipe liner 4275 (comprising a carbon/TP tubular fabric 4284) has an inner diameter or inner surface 4297, thickness 4205, and an outer surface 4206 that expands to the inner surface 4017 of the host pipe 4010. This first pipe liner 4275 15 is typically formed at 3-30 psi in 20-90 minutes. As a novel solution for added strength, an optional second hardened finished pipe liner 4275' (also comprising a carbon/TP pipe liner fabric 4284) is installed inside the first pipe liner 4275. In that case, second pipe liner 4275' has an inner diameter or inner surface 4297', thickness 4205, and an outer surface 4206 that adheres to the inner surface 4297 of the first pipe 20 liner 4275. This second pipe liner 4275' is typically formed at 100-120 psi in 10-20 minutes, and in as little as 2 minutes. Thus, either the inner diameter/surface 4297, 4297' of the first or second pipe liner 4275, 4275' defines the new aperture or opening 4209 through the pipe liner 4284 and the host pipe 4010. No other manufacturer installs any pipe liner at 30+ psi, much less 100+ psi. In the present case, the second 25 pipe liner 4275' utilizes the strength of the first installed/cured pipe liner 4275 as a mold 4272, thus permitting the second pipe liner 4275' to be thermoformed with a short dwell time at the higher pressure and a more tightly controlled temperature limit of 405° F. My tests with polypropylene 2144, as an example, show that increasing the pressure from 15 psi to 105 psi increases the flexural modulus by about 30%. Thus, 30 the second pipe liner 4275' delivers increased performance alone and in combination with the first pipe liner 4275 as the two are adhered to one another.

Figure 28 is a comparison of cross-sections that illustrates material thicknesses of various pipe liner types. Damaged host pipe 4010 may be made of any number of

- 72 -

thinner materials, but as shown is a commonly thick concrete product having an outer diameter 4016 and an inner diameter/inner surface 4017 that defines the opening 4019 through the length of the host pipe 4010. Prior art thermoset pipe liner 4030 used in CIPP often has a significant thickness as represented by the dashed circle when

5 adhered to the inner surface 4017 of the host pipe 4010; the thickness of the prior art pipe liner 4030 is defined by the distance from its inner diameter 4037 to the inner diameter or inner surface 4017 of the host pipe 4010. The most common prior art material accounting for about 90% of the market is a polyester felt with epoxy resin 4030, which produces a thickness of 0.08" to 0.16" (2-4 mm) in an 8" host pipe 4010,

10 and up to 0.47" (12 mm) in a larger host pipe 4010, and allows a certain water level or other fluid level or fluid flow 4001 through the prior art pipe liner 4030. In contrast, either TS pipe liner 4225 or carbon/TP pipe liner 4275 of the present specification may be installed to provide better strength and increased fluid flow 4501 with thinner walls. (TS and carbon/TP pipe liners 4225, 4275 are not usually installed together in

15 the same host pipe 4010.) If thermoset pipe liner 4225 having an inner diameter/surface 4247 is adhered to the inner surface 4017 of the host pipe, its thickness 4205 typically is less than that of the prior art pipe liner 4030. As discussed above, the thermoset sample 4225 of "Example 1" at 12 psi has a thickness 4205 of 0.05" (1.27 mm). If carbon/thermoplastic pipe liner 4275 having an inner

20 diameter/surface 4297 is adhered to the inner surface 4017 of the host pipe, it also has a thickness 4205 less than that of the prior art pipe liner 4030. New fluid level 4501 is lower than the prior art fluid level 4001, which also indicates a greater capacity for fluid flow 4501, which often is critical to a host pipe's 4010 function of carrying products or waste and greatly improves the revenue for the utility pipe owner.

25 Figure 29 graphically compares the current carbon/thermoplastic pipe liner forming system 5280, 2280 and method 5480, 2480 to the prior art thermoset pipe liner forming 5030, specifically illustrating ease of handling and time required for installation. Uncured prior art thermoset pipe liners 5030 have a very limited shelf life once their resin is applied. This limitation is also true of the current thermoset

30 pipe liner forming system 2230 and method 2430 if the same resin 2213 is used. Ultra-cold refrigeration is a costly requirement during storage and shipping, and once a prior art TS pipe liner 5030 is removed from refrigeration for transport to the job site and installation, workers have limited jobsite prep time 5033, including the time

- 73 -

required to insert the pipe liner 5030 into the conduit, duct, or host pipe 4010.

Thermoset resins 2213 exposed to temperatures above freezing are at risk of premature cross-linking and curing. On the other hand, the current thermoplastic pipe liner fabric 2284 stores, ships, and is workable at ambient or environmental

5 temperature 2462, which is about 56° F in soil 6' deep, giving workers unlimited jobsite prep time 5281. The carbon/thermoplastic fabric's 2204, 2284 cure time 5294 is equally impressive, with a first 100- to 300-yard thermoformed pipe liner 5275 cured in 20-90 minutes at 3-30 psi (preferably 8-15 psi) and a second 100- to 300-yard thermoformed pipe liner 5275' cured in 10-20 minutes at 100-120 psi (preferably 105
10 psi) inside the first liner 5275. In the lab or manufacturing plant at optimum pressures, thermoforming 2470 takes as little as 2-3 minutes. In contrast, the prior art thermoset pipe liner 4030 usually requires 8-12 hours of cure time 5034.

Figures 30-37 illustrate methods of intra-pipe delivery 6440, 6490 for inserting
seamed pipe liner fabric 6234, 6284 into a host pipe 6010 below a street 6008, as well
15 as a heat delivery system 11250. A noticeable crack 6013 is seen in the top of the old host pipe 6010. Figure 30 shows either a carbon/filler fiber nonwoven fabric 2202 or a carbon/thermoplastic nonwoven fabric 2204 going down a manhole 6009 and being pulled into a host pipe 6010 by a winch 6258 and cable 6259 or similar arrangement of equipment. The cable 6259 pulls a seamed pipe liner fabric 6234, 6284 that may
20 enwrap an inflatable calibration bladder 6245, 6295 designed to provide even pressure at 3-120 psi to hold the pipe liner fabric 6234, 6284 against the inner surface 7017 of the host pipe 6010 during curing 2422, 2472, depending upon the forming system 2220, 2270 employed. The calibration bladder 6245, 6295 is eventually removed. As mentioned previously, a coating 2235, 2285 or other surface treatment 2190 that
25 allows the pipe liner fabric 6234, 6284 to inflate may preclude the need for a calibration bladder 6245, 6295. In particular, a light melt of the outer surface 4206 of a carbon/TP fabric 2204 is a novel fluid-tight solution for this end use, eliminating the cost of an airtight coating 2235, 2285 of the outside surface of the pipe liner fabric 6234, 6284.

30 Figure 31 illustrates the method of forming a hardened finished pipe liner 7420, 7470 in a host pipe 7010 using a pig 7510 instead of a calibration bladder 7295 to provide both pressure and dry heat 7274' through the inner surface 7207 of the seamed pipe liner fabric 7234, 7284. First, a length of seamed pipe liner fabric 7234,

- 74 -

7284 and a cable 7259 fed through its length is placed into the host pipe 7010. Then the cable 7259 is attached to the nose or front cone 7520 of the pig 7510, which is placed into the seamed pipe liner fabric 7234, 7284 at an opening 7019 of the host pipe 7010. The cable 7259 pulls the pig 7510 into contact with the inner surface 7207 of the seamed pipe liner fabric 7234, 7284, which parts and opens over the front cone 7520. The outer surface 7206 of the seamed pipe liner fabric 7234, 7284 is pressed by the pig frame 7512 against the inner surface 7017 of the host pipe 7010. A heat delivery system 11250 is engaged, and preferably dry heat 7274' ranging from at least 400° F to 450°, and at times up to 475° (204-246° C), enters the pig 7510 and cures the resin 2213, 2144 on the seamed pipe liner fabric 7234, 7284. Target temperature is dependent in large part upon the selected resin 2213, 2144. One significant benefit to thermoforming a carbon/TP pipe liner 7470 is that the thermoplastic 2144 heats without producing styrene or other harmful off-gases. A pig 7510 may be employed with thermoset nonwoven fabric 2202 and resins 2213 that form with curing agents 2224 other than heat 2224, 2274.

The pig 7510 generally comprises the pig frame 7512, front cone 7520 and rear cone 7522, pig core and heating zone 7515 located between the front and rear cones 7512, 7520, and wheels or rollers 7516 on the frame 7512 that allow the pig to travel without damaging the seamed pipe liner fabric 7234, 7284. The pig 7510 and its frame 7512 is typically about 5' long or 20' to 40' long comprising articulated sections, each similar to a 5' pig 7510, but may be any length that is maneuverable through the host pipe 7010 and cures 2424, 2474 sufficient portions of the seamed pipe liner fabric 7234, 7284 at one time. Heating 2424, 2474 in increments is often easier than controlling temperature for a full 100 linear yard length of pipe liner fabric 7234, 7284, although other configurations without the pig allow simultaneous curing of the entire 100 linear yards. In practice, the pig 7510 may advance in a continuous motion or advance after each 2-10 minutes of initial cure 2424, 2474. The pig 7510 is shown in cross-section, but is largely tubular in shape to fit the host pipe 7010. As the front sensor 7521 in the front cone 7520 measures temperature, pressure, and other data, it calls for heat 7274. In this configuration, heat 7274 is applied as the curing agent 7474 through a first braided steel hose 7530 having venting apertures 7529 that release or supply heated air 7274, preferably dry heat 7274', into the pig's heating zone 7515. Heat 7274 radiates through pores 7519 in the perimeter of the pig frame

- 75 -

7512 to cure 2424, 2474 the resin 2213, 2144. A rear sensor 7523 in the rear cone 7522 also measures temperature, pressure, and other data, operating pressure valve 7525 as needed and calling for removal or return of latent heat 7274" from behind the rear cone 7522 through venting apertures 7529 in a trailing second braided steel hose 5 7532. The first and second braided steel hoses 7530, 7532 may be attached by a clamp 7534 in order to travel together, and a hose sleeve 7531 may cover portions of the first braided steel hose 7530 to prevent heat 7274 from escaping the first braided steel hose 7530 outside of the heating zone 7515. In this manner, the portions of pipe liner fabric 7234, 7284 are not underheated or overheated as the pig 7510 travels and 10 forms a hardened finished part 2425, 2475 that is a pipe liner 7225, 7275. One of skill in the art will understand that many components of the pig 7510 will be made of metal, plastics, or composites that will withstand the environment within which the pig 7510 operates, including high temperatures and pressure.

Figures 32-33 show either a carbon/filler fiber nonwoven fabric 2202 or a 15 carbon/thermoplastic nonwoven fabric 2204 with inflatable calibration bladder 7245, 7295 being inserted by inversion into a host pipe 7440, 7490. A fluid (gas or liquid) 7249 creates pressure as it expands and pushes the calibration bladder 7245, 7295 and seamed pipe liner fabric 7234, 7284 into the host pipe 7010, providing even pressure from 3-120 psi to hold the outer surface 7206 of the pipe liner fabric 7234, 7284 20 against the inner surface 7019 of the host pipe 7010 during curing 2422, 2472, depending upon the forming system 2220, 2270 employed. As mentioned previously, a coating 2235, 2285 or other surface treatment 2190 that allows the pipe liner fabric 7234, 7284 to inflate and hold specified pressure and may preclude the need for a calibration bladder 7245, 7295. In particular, a light melt of the outer surface 7206 of 25 a carbon/TP fabric 2204 is a novel fluid-tight solution for either inversion or pull-in-place installations. Fig. 33 shows inversion 8440, 8490 with the fluid pressure 8249 inverting the pipe liner fabric 8225, 8275 (7234, 7284) beyond the opening 8019 of the host pipe 8010. Such excess material is removed during any intra-pipe delivery method 2440, 2490 (note the clean terminations in Fig. 37).

30 Figure 35 illustrates in cross-section the location of various parts—in relationship to the TS or carbon/TP seamed pipe liner fabric 10234, 10284—of the thermoset pipe liner forming subsystem 10230 and the carbon/thermoplastic pipe liner forming subsystem 10280 as discussed above. Optional surface treatment(s) 10190

- 76 -

on pipe liner fabric 10234, 10284 typically occur on the outer surface 7206, but are not limited to the outer surface 7206. TS or TP resins 10213, 10144 are generally located within the thickness 4205 of the pipe liner fabric 10234, 10284. Depending upon the resin 10213, 10144 selected, backing sheet 10211, 10261 may be needed to
5 keep the resin-filled roll 509 of fabric 2200 from sticking to itself, and the backing sheet 10211, 10261 may be peeled away or otherwise removed during installation. Here, the backing sheet 10211, 10261 is illustrated on the inner surface 3207, but may be on the outer surface 3206. A pre-liner sleeve 10236, 10286 may be placed in the host pipe 4010 to ease intra-pipe delivery inside the sleeve 10236, 10286. In a
10 configuration without a fluid-tight surface treatment 10190, an inflatable calibration bladder 10245, 10295 is positioned to harness the pressure that will be applied outward on the pipe liner fabric 10234, 10284. In certain configurations, and without water present, the pipe liner fabric 10234, 10284 may be thick and sturdy enough at 10-30 mil to hold air pressure and allow resin 10213, 10144 to cure in place. One of
15 skill in the art will understand that these various components also may be utilized to form hardened finished parts 2225, 2275 for any industry and are not limited to pipe liners.

Figure 36 is a heat delivery system 11250 housed on a truck or other transport 11251 for delivering dry heat 7474' into a seamed pipe liner fabric 11234, 11284 in a
20 conduit, duct, or host pipe 11010. A crack 11013 is visible on the host pipe 11010 that is situated below grade 11008 between two manholes 11009. Transport 11251 comprises large side service doors 11252 (preferably having louvers 11571 for fresh air intake), a heater assembly 11253, a fluid circulation tubing 11254, one or more vent stacks or vent pipes 11256 that are mobile or fixed on the transport 11251, a
25 water tank with treatment system 11257, and various controls including timers 11241, 11291. The water tank 11257 may be 50+ gallons and located above the cab of the truck 11251. Figure 34 shows a skid-mounted heater assembly 9253, 11253 measuring about 72" x 72" x 72" designed for easy loading and mobility. The heater assembly 9253 generally includes a skid 9575 that supports a boiler 9576, a moisture
30 separator 9578 necessary for producing hot, dry air 11274' that is always at least 99.0% dry (preferably at least 99.5%), and a heater control panel 9580. The purpose of dry heat 11274' is not to dry, but to maintain heat more efficiently and reduce or eliminate cure-hampering moisture, leading to a shorter job and lower job cost, plus

- 77 -

negating the current industry need to dispose of process water; because no water is used for the curing medium, there is no contamination. The transport 11251 preferably includes a heater 11570 for the box of the truck 11251, as the boiler 9576 functions best in a 45° F or higher operating environment. Latent heat 11274" may be used to boost the truck box heater 11570 as the boiler design 9576 allows.

Returning to Fig. 36, the seamed pipe liner fabric 11234, 11284 with calibration bladder 11245, 11295 and a first braided steel hose 11530 is inserted through the host pipe 11010, attached at one end to the fluid circulation tubing 11254 via one or more heat transfer connections 11255, and attached at the other end to a mobile vent pipe 11256 via a heat transfer connection 11255. The mobile vent pipe 11256 or the vent pipe 11256 on the top of the transport 11251 must have sufficient height of about 8-10' to enable a controlled release of latent heat 11274" into the atmosphere well out of reach of bystanders when the in-pipe pressure reaches a set limit. Latent heat 11274" is preferably recycled for efficiency, but recapture of latent heat 11274" is not required. As an option to the pig 7510 described previously, one or more fabric tube spreaders or openers 11550 having rollers 11516 on spring-like feet are placed inside the tubular pipe liner fabric 11234, 11284 before connections are made. A fabric tube opener 11550 may be pulled or driven by a motor 11555 and remotely controlled 11556 to move forward and press the pipe liner fabric 11234, 11284 against the inner surface 11017 of the host pipe 11010. One tube opener 11550 or multiple openers 11550 may be used, as may hose sleeves 11531 according to the configuration of venting apertures 7529 in the braided steel hose(s) 11530, 7532. When curing thermoset parts 7420, different components and curing agents 2224 than those used for heat 2274 may be employed per the particular requirements of the selected resin 10213. Other characteristics of the previously described pig 7510 may be included.

Figure 37 illustrates a completed installation. Crack 12013 is sealed by the hardened finished part 12225, 12275 that is a pipe liner 12225, 12275 that runs between two manholes 12009 inside the host pipe 12010. In oil and gas lines, for example, that do not involve manholes, the pipe liner 12225, 12275 simply runs between two end points of the host pipe 12010. Fluid flow 12501 is restored without fear of further breaks 12013 in that section of pipe 12010.

EXAMPLESEXAMPLE 1 (THERMOSET) — 12.7% fiber, 87.3% epoxy resin

Carbon fibers (having a diameter of 7 micrometers), para-aramid fibers (having a diameter of 12 micrometers), and oxidized polyacrylonitrile (OPAN) fibers (having a diameter of 9.0-11.6 micrometers) were provided. From them, a nonwoven fabric in accordance with the seventh aspect of the disclosure was prepared (by separating the carbon fibers, blending the separated carbon fibers with the para-aramid and OPAN fibers to provide a homogeneous fiber blend, aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer, cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric, in accordance with the methods and using the apparatus described herein), comprising by weight 70 % recycled carbon fibers, 10 % para-aramid, 20 % OPAN and taking the form of a 250 gsm, 0.25 inch (6 mm) thick needle punched nonwoven fabric in a single ply.

A material was then prepared in accordance with the ninth aspect of the disclosure, comprising by weight 12.7 % of the nonwoven fabric and 87.3% epoxy.

Curing of the material was affected for 60 minutes at 12 psi and 212 °F. This produced a finished material in the form of a part of thickness 0.05 inches (1.27 mm).

The part was found to contain less than 2 % by volume of void space measured in accordance with ASTM D2734.

The tensile strength of the part was found to be 94.26 MPa (13,671 psi), measured in accordance with ASTM D638. For comparison, the minimum requirement (in accordance with ASTM F1216-22) for polyester felt for pipe repair is typically 27.58 MPa (4,000 psi).

The tensile modulus of the part was found to be 5,720 MPa (829,552 psi), measured in accordance with ASTM D638.

The flexural strength of the part was found to be 210.50 MPa (30,532 psi), measured in accordance with ASTM D790. For comparison, the minimum requirement (in accordance with ASTM F1216-22) for polyester felt for pipe repair is typically 34.47 MPa (5,000 psi).

The flexural modulus of the part was found to be 12,650 MPa (1,822,333 psi), measured in accordance with ASTM D790. For comparison, the minimum

- 79 -

requirement (in accordance with ASTM F1216-22) for polyester felt for pipe repair is typically 2,068 MPa (300,000 psi).

EXAMPLE 2 (THERMOSET) — 34.0% fiber, 66.0% vinyl ester resin

5 Carbon fibers (having a diameter of 7 micrometers), para-aramid fibers (having a diameter of 12 micrometers), and OPAN fibers (having a diameter of 9.0-11.6 micrometers) were provided. From them, a nonwoven fabric in accordance with the seventh aspect of the disclosure was prepared (by separating the carbon fibers, blending the separated carbon fibers with the para-aramid and OPAN fibers to provide
10 a homogeneous fiber blend, aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer, cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric, in accordance with the methods and using the apparatus described herein), comprising by weight 70 % recycled carbon fibers, 10 % para-
15 aramid, 20 % OPAN and taking the form of a 254 gsm, 0.25 inch (6 mm) thick needle punched nonwoven fabric in a single ply.

A material in accordance with the ninth aspect of the disclosure was then prepared comprising by weight 34.0 % of the nonwoven fabric and 66.0 % vinyl ester resin.

20 Curing of the material was affected for 60 minutes at 8 psi and 212 °F. This produced a finished material in the form of a part of thickness 0.122 inches (3.1 mm).

The part was found to contain less than 2 % by volume of void space measured in accordance with ASTM D2734.

The tensile strength of the part was found to be 203.31 MPa (29,486 psi),
25 measured in accordance with ASTM D638. The density was found to be 1.23 g/cm³, measured in accordance with ASTM D792. This translates to a specific tensile strength of 165 kN*m/kg. In comparison, the tensile strength of an analogous aluminum part is 102 kN*m/kg.

The tensile modulus of the part was found to be 15,706.81 MPa (2,278,000
30 psi) measured in accordance with ASTM D638. The flexural modulus of the part was found to be 15,796.45 MPa (2,291,000 psi) measured in accordance with ASTM D790. The flexural strength of the part was found to be 280.04 MPa (40,615 psi) measured in accordance with ASTM D790.

EXAMPLE 3 (THERMOPLASTIC) — CF 30% / common PP 70%

Carbon fibers (having a diameter of 7 micrometers) and polypropylene (PP) fibers (having a diameter of 30 micrometers) were provided (the PP fibers were
5 common PP fibers, in contrast to the PP fibers of Example 4 below, treated with MAPP). From them, a nonwoven fabric in accordance with the seventh aspect of the disclosure was prepared, comprising by weight 30 % recycled carbon fibers and 70% PP fibers (by separating the carbon fibers, blending the separated carbon fibers with the PP fibers to provide a homogeneous fiber blend, aligning the fibers in the
10 homogeneous fiber blend to form an aligned fiber layer, cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric, in accordance with the methods and using the apparatus described herein), taking the form of a 3,000 gsm, 0.55" (14 mm) thick needle punched nonwoven fabric in a single ply.

15 Thermoforming for 60 minutes at 102 psi and 475 °F produced a material in accordance with the eighth aspect of the disclosure, which was 0.125 inches (3 mm) thick, having less than 3 % by volume of void space measured in accordance with ASTM D2734.

Figure 9 is a scanning electron microscope (SEM) image (magnification:
20 x150) after destructive lab testing of the part. Separated carbon fibers (901) stand out against a darker matrix of thermoformed (melted) PP resin, with some lighter areas of resin (902) in the foreground. Aligned x-y layers of carbon fibers are identifiable in this quasi-anisotropic structure, even after destructive testing, as are some carbon fibers needle punched in the z direction.

25 "Fiber pull-out", i.e. molecular adhesion of the carbon fibers to the PP matrix was measured. As shown in Figure 10, the part made in Example 3 has a tensile strength of 124 MPa (17,985 psi), measured in accordance with ASTM D638-08; and a density or specific gravity of 1.02 g/cm³, measured in accordance with ASTM D792, translating to a specific tensile strength of 122 kN*m/kg. In comparison, the
30 tensile strength of an analogous aluminum part is 102 kN*m/kg.

The part made in Example 3 has a tensile modulus of 10,500 MPa (1,522,896 psi), measured in accordance with ASTM D638.

- 81 -

EXAMPLE 4 (THERMOPLASTIC) — CF 30 % / MAPP-treated PP 70 %

Carbon fibers (having a diameter of 7 micrometers) and modified polypropylene (PP) fibers (comprising maleic anhydride grafted polypropylene, MAgPP, and having a diameter of 30 micrometers; formed from a PP melt treated with MAPP, which was found to increase bonding to the carbon fibers, thus referred to herein as “PP/MAgPP”) were provided. From them, a nonwoven fabric in accordance with the seventh aspect of the disclosure was prepared, comprising by weight 30 % recycled carbon fibers and 70% PP/MAgPP fibers (by separating the carbon fibers, blending the separated carbon fibers with the PP/MAgPP fibers to provide a homogeneous fiber blend, aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer, cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric, in accordance with the methods and using the apparatus described herein), taking the form of a 2,000 gsm, 0.50 inches (12 mm) thick needle punched nonwoven fabric in a single ply.

Thermoforming for 60 minutes at 105 psi and 475 °F produced a material in accordance with the eighth aspect of the disclosure, which was 0.078 inches (2 mm) thick, having less than 3 % by volume of void space measured in accordance with ASTM D2734.

Figure 11 is a scanning electron microscope (SEM) image (magnification: x150) after destructive lab testing of the part. Separated carbon fibers (1101) aligned in layers (1103) stand out against a darker matrix of thermoformed (melted) PP resin, with some lighter areas of resin (1102) in the foreground. Aligned x-y layers of carbon fibers (1103) are identifiable in this quasi-anisotropic structure, even after destructive testing, as are some carbon fibers needle punched in the z direction. An estimated minimum of 80 % to 90% volume of carbon fiber lies in the 80° to 50° and 160° to 120° fiber orientation, with z fiber entanglement.

Figure 12 shows a closer SEM view (magnification: x400) and reveals, visually, a very strong carbon-resin bond (1104). The separated carbon fibers (1101) and lighter areas of resin (1102) are also easily visible at this magnified view. Figure 13 shows a yet closer SEM view (magnification: x3500) of the strong carbon-resin bond (1104).

- 82 -

“Fiber pull-out”, i.e. molecular adhesion of the carbon fibers to the PP/MAGPP matrix, in accordance with the carbon fiber-resin bonding, was measured. As shown in Fig. 14, the part made in Example 4 has a tensile strength of 278 MPa (40,331 psi), measured in accordance with ASTM D638-08; and a density or specific gravity of 1.04 g/cm³, measured in accordance with ASTM D792, translating to a specific tensile strength of 267 kN*m/kg. In comparison, the specific tensile strength of an analogous aluminum part is 102 kN*m/kg. The part made in Example 4 has a tensile modulus of 15,514 MPa ((2,250,000 psi; ASTM D638). Its flexural modulus is 15,093 MPa (2,189,000 psi; ASTM D790), and its flexural strength is 284 MPa (41,252 psi; ASTM D790). This is an exceptionally strong and lightweight material, therefore.

The following numbered Paragraphs provide further detail of the present disclosure. The Paragraphs (P#) are not to be confused with the claims.

- P1. A method of separating attached carbon fibers, comprising:
- directing the attached carbon fibers onto the moving surface of a conveyor such that a plurality of protrusions on the moving surface of the conveyor pass between and separate carbon fibers on the moving surface of the conveyor, and
 - directing a turbulent fluid flow to further separate the carbon fibers.
- P2. The method of Paragraph 1, wherein the attached carbon fibers have a mean length of about 5 centimeters to about 12 centimeters.
- P3. The method of Paragraph 1 or Paragraph 2, wherein the turbulent fluid flow is generated by one or more engines and/or one or more motors configured to blow one or more jets of fluid at the carbon fibers.
- P4. The method of any preceding Paragraph, wherein the attached carbon fibers are attached to each other by binding material on the surface of the carbon fibers, wherein separating the carbon fibers is or comprises detaching binding material.
- P5. The method of any preceding Paragraph, wherein once separated, about 80 % or more of the carbon fibers are unattached from each other.
- P6. The method of any preceding Paragraph, wherein the surface of the conveyor is disposed at an incline; and directing the attached carbon fibers onto the moving surface of the conveyor is or comprises directing the attached carbon fibers onto the inclined moving surface of the conveyor against gravity.

- 83 -

P7. The method of any preceding Paragraph, further comprising brushing the carbon fibers using one or more agitator rolls.

P8. A method of cutting and separating carbon fibers, comprising a step of cutting attached carbon fibers to have a mean length of about 5 centimeters to about 12 centimeters, prior to separating the cut yet attached carbon fibers by a method in accordance with any preceding Paragraph.

P9. A carbon fiber separation device comprising:
- a conveyor having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and
- one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers.

P10. The carbon fiber separation device of Paragraph 9, wherein the one or more generators of a turbulent fluid flow is or are one or more engines and/or one or more motors configured to blow one or more jets of fluid at the carbon fibers.

P11. The carbon fiber separation device of Paragraph 9 or Paragraph 10, wherein the conveyor is configured to be disposed at an incline.

P12. A carbon fiber cutting and separation apparatus, the carbon fiber cutting and separation apparatus comprising the carbon fiber separation device of any one of Paragraphs 9 to 11 and a cutting device upstream of the carbon fiber separation device.

P13. A plurality of separated carbon fibers obtained or obtainable by the method of any one of Paragraphs 1 to 8.

P14. A method of blending carbon fibers with a plurality of further fibers, the method comprising:
- directing the carbon fibers and the further fibers onto a moving surface of a conveyor such that the carbon fibers and the further fibers are blended by a plurality of protrusions on the moving surface, and
- directing a turbulent fluid flow to further blend the carbon fibers with the further fibers,
thereby forming a homogeneous fiber blend.

P15. The method of Paragraph 14, wherein the carbon fibers have a mean length of about 5 centimeters to about 12 centimeters.

- 84 -

P16. The method of Paragraph 14 or Paragraph 15, wherein the turbulent fluid flow is generated by one or more engines and/or one or more motors configured to blow one or more jets of fluid at the carbon fibers.

5 P17. The method of any one of Paragraphs 14 to 16, wherein the conveyor is configured to be disposed at an incline, and directing the carbon fibers and the further fibers onto the moving surface of the conveyor is or comprises directing the carbon fibers and the further fibers onto the inclined moving surface of the conveyor against gravity.

10 P18. A fiber blending device configured to receive carbon fibers and further fibers, and to form a homogeneous fiber blend, the device comprising:

- a conveyor having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured for blending the carbon fibers with the further fibers, and
- one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further blend the carbon fibers with the further fibers.

15

P19. The fiber blending device of Paragraph 18, wherein the one or more generators of a turbulent fluid flow is or are one or more engines and/or one or more motors configured to blow one or more jets of fluid at the carbon fibers.

20 P20. The fiber blending device of Paragraph 18 or Paragraph 19, wherein the conveyor is configured to be disposed at an incline.

P21. A homogeneous fiber blend obtainable or obtained by the method of any one of Paragraphs 14 to 17.

P22. A method of forming a nonwoven fabric, comprising:

- 25 - optionally, separating carbon fibers in accordance with the method of any one of Paragraphs 1 to 8,
- blending the optionally separated carbon fibers with further fibers in accordance with the method of any one of Paragraphs 14 to 17, thereby forming a homogeneous fiber blend,
- 30 - aligning the fibers in the homogeneous fiber blend to form an aligned fiber layer,
- cross-lapping the aligned fiber layer to form a cross-lapped fiber layer, and

- 85 -

- mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric.

P23. Apparatus for forming a nonwoven fabric, comprising:

- optionally, a carbon fiber separation device in accordance with any one of Paragraphs 9 to 11 or a carbon fiber cutting and separation apparatus in accordance with Paragraph 12;
- a fiber blending device in accordance with any one of Paragraphs 18 to 20;
- a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by aligning fibers in the received homogeneous fiber blend;
- a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and
- a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.

P24. A nonwoven fabric, comprising:

- a plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters to about 12 centimeters, and
 - a plurality of further fibers;
- wherein the carbon fibers are dispersed amongst the further fibers.

P25. The nonwoven fabric of Paragraph 24, which is obtainable by or a product of the method of Paragraph 22.

P26. The nonwoven fabric of Paragraph 24 or Paragraph 25, which is in the form of a single ply.

P27. The nonwoven fabric of any one of Paragraphs 24 to 26, wherein the carbon fibers are recycled carbon fibers.

P28. A material which is a thermoformed product of the nonwoven fabric of any one of Paragraphs 24 to 27 or which is obtainable by thermoforming the nonwoven fabric of any one of Paragraphs 24 to 27, wherein the further fibers are non-carbon thermoplastic fibers.

- 86 -

P29. A material comprising a thermoset resin and the nonwoven fabric of any one of Paragraphs 24 to 27, wherein the further fibers are non-carbon filler fibers.

It should be noted that ratios, concentrations, amounts, and other numerical data may be expressed herein in a range format. It is to be understood that such a range format is used for convenience and brevity, and thus, should be interpreted in a flexible manner to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. To illustrate, a concentration range of “about 0.1 percent to about 5 percent” should be interpreted to include not only the explicitly recited concentration of about 0.1 weight percent to about 5 weight percent but also include individual concentrations (e.g., 1 percent, 2 percent, 3 percent, and 4 percent) and the sub-ranges (e.g., 0.5 percent, 1.1 percent, 2.2 percent, 3.3 percent, and 4.4 percent) within the indicated range. The term “about” can include traditional rounding according to significant figures of the numerical value. In addition, the phrase “about ‘x’ to ‘y’” includes “about ‘x’ to about ‘y’”.

Many variations and modifications may be made to the above-described aspects. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

- 87 -

CLAIMS

1. A method of separating attached carbon fibers, comprising:
 - directing the attached carbon fibers to the moving surface of a conveyance,
 - 5 - separating, at least partially, the carbon fibers on the moving surface of the conveyance, and
 - directing a turbulent fluid flow to further separate the carbon fibers.
2. The method of claim 1, wherein the conveyance is a conveyor, wherein the
10 conveyor includes a plurality of protrusions on the moving surface of the conveyor which pass between and separate carbon fibers on the moving surface of the conveyor.
3. The method of claim 1 or 2, wherein the attached carbon fibers have a mean
15 length of about 5 centimeters to about 12 centimeters.
4. The method of any one of claims 1-3, wherein the turbulent fluid flow is generated by one or more engines, one or more motors, or both one or more engines and one or more motors, where the one or more engines and the one or more motors
20 are each configured to blow one or more jets of fluid at the carbon fibers.
5. The method of any one of claims 1-4, wherein the attached carbon fibers are attached to each other by binding material on the surface of the carbon fibers, wherein separating the carbon fibers is or comprises detaching binding material with carbon
25 fiber breakage at about 25% or less.
6. The method of any one of claims 1-5, wherein once separated, about 80% or more of the carbon fibers are substantially unattached from each other.
- 30 7. The method of claim 2, wherein the surface of the conveyor is disposed at an incline; and directing the attached carbon fibers onto the moving surface of the conveyor includes directing the attached carbon fibers onto the inclined moving surface of the conveyor against gravity.

- 88 -

8. The method of any one of claims 1-7, further comprising brushing the carbon fibers using one or more agitator rolls.
9. A method of forming a nonwoven fabric, comprising:
- 5 blending carbon fibers with further fibers, wherein a turbulent fluid flow blends the carbon fibers with the further fibers, thereby forming a homogeneous fiber blend; and
- aligning the carbon fibers in the homogeneous fiber blend to form an aligned fiber layer.
- 10
10. The method of claim 9, wherein blending further comprises directing the carbon fibers and the further fibers onto a moving surface of a conveyance such that the carbon fibers and the further fibers are blended by a plurality of protrusions on the moving surface.
- 15
11. The method of claims 9 or 10, prior to blending the method further comprises: directing the attached carbon fibers onto the moving surface of a conveyance; separating, at least partially, the carbon fibers on the moving surface of the conveyance; and
- 20 directing a turbulent fluid flow to further separate the carbon fibers.
12. The method of claim 11, wherein the conveyance is a conveyor, wherein separating includes directing the carbon fibers onto the moving surface of the conveyor such that the carbon fibers are separated by a plurality of protrusions on the
- 25 moving surface.
13. The method of claim 9, further comprising: cross-lapping the aligned fiber layer to form a cross-lapped fiber layer.
- 30 14. The method of claim 13, further comprising: mechanically entangling the cross-lapped fiber layer, thereby forming the nonwoven fabric.

- 89 -

15. The method of claim 9, further comprising: mechanically entangling the aligned fiber layer.
16. The method of claim 9, wherein the further fibers are a second amount of carbon fibers.
17. The method of claim 9, wherein the further fibers are selected from the group consisting of: a thermoplastic fiber, a thermoset fiber, a non-carbon filler fiber, and a combination thereof.
18. An apparatus for forming a nonwoven fabric, comprising:
- a fiber blending device configured to receive carbon fibers and further fibers, and to form a homogeneous fiber blend, using turbulent fluid flow;
 - a fiber aligning device configured to receive a homogeneous fiber blend from the fiber blending device and further configured to form an aligned fiber layer by aligning carbon fibers in the received homogeneous fiber blend;
 - a cross-lapper configured to receive an aligned fiber layer from the fiber aligning device and further configured to form a cross-lapped fiber layer by cross-lapping the received aligned fiber layer; and
 - a mechanical entanglement device configured to receive a cross-lapped fiber layer from the cross-lapper and further configured to form a nonwoven fabric by mechanically entangling the received cross-lapped fiber layer.
19. The apparatus of claim 18, further comprising: a carbon fiber separation device configured to separate carbon fibers from attached carbon fibers using turbulent fluid flow to form separated carbon fibers.
20. The apparatus of claim 19, wherein the carbon fiber separation device includes: a conveyance having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and

- 90 -

one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further separate the carbon fibers.

21. The apparatus of claim 18, wherein the fiber blending device comprises:
5 wherein the conveyance is a conveyor, wherein the conveyor has a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured for blending the carbon fibers with the further fibers, and one or more generators of a turbulent fluid flow, which is or are configured to direct a turbulent fluid flow to further blend the carbon fibers with the further fibers.
10
22. A nonwoven fabric, comprising:
a plurality of carbon fibers separated from each other and having a mean length of about 2.5 centimeters to about 12 centimeters, and
a plurality of further fibers;
15 wherein the carbon fibers are dispersed and aligned amongst the further fibers.
23. The nonwoven fabric of claim 22, wherein the further fibers are a second amount of carbon fibers.
- 20 24. The nonwoven fabric of claim 22, wherein the further fibers are selected from the group consisting of: a thermoplastic fiber, a thermoset fiber, a non-carbon filler fiber, and a combination thereof.
- 25 25. The nonwoven fabric of any one of claims 22-24, which is in the form of a single ply.
26. The nonwoven fabric of any one of claims 22-25, wherein the carbon fibers are recycled carbon fibers.
- 30 27. A carbon fiber separation device comprising:
a conveyance having a moveable surface, with a plurality of protrusions protruding from the moveable surface, the protrusions being configured to pass between and separate the carbon fibers, and

- 91 -

one or more generators of a turbulent fluid flow, which is or are
configured to direct a turbulent fluid flow to further separate the carbon fibers.

28. A method of forming a nonwoven fabric, comprising:
5 blending carbon fibers by directing the carbon fibers onto a moving surface,
wherein the carbon fibers are blended on the moving surface, and wherein a turbulent
fluid flow further blends the carbon fibers, thereby forming a homogeneous fiber
blend; and
aligning the carbon fibers in the homogeneous fiber blend to form an aligned
10 fiber layer.

29. The method of claim 28, wherein blending includes directing the carbon fibers
onto the moving surface of the conveyor such that the carbon fibers are blended by a
plurality of protrusions on the moving surface.

15 30. The method of claim 28, prior to blending further comprising:
directing the attached carbon fibers onto the moving surface of a conveyor;
separating, at least partially, the carbon fibers on the moving surface of the
conveyor; and
20 directing a turbulent fluid flow to further separate the carbon fibers.

31. The method of claim 30, wherein separating includes directing the carbon
fibers onto the moving surface of the conveyor such that the carbon fibers are
separated by a plurality of protrusions on the moving surface.

25

30