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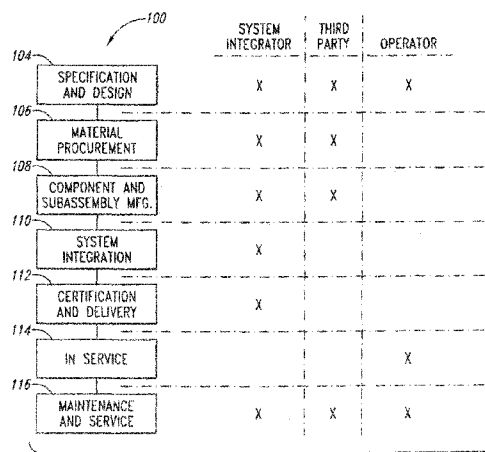


Fig. 1

(57) Abstract: Carbon nanotube interlayer assemblies, methods of manufacturing carbon nanotube interlayer assemblies, and methods of manufacturing composite parts with carbon nanotube interlayer assemblies are disclosed herein. In one embodiment, a method of manufacturing a composite structure in accordance with an embodiment of the invention includes producing a plurality of carbon nanotubes on one or both sides of a substrate, and attaching the substrate to a first fiber layer. The method can further include positioning a second fiber layer adjacent to the first fiber layer to position the plurality of carbon nanotubes between the first and second fiber layers. The method can additionally include infusing the first and second fiber layers with resin, and curing the resin. In one embodiment, the carbon nanotube substrate can be attached to the first fiber layer by melt-bonding. In another embodiment, the carbon nanotube substrate can be attached to the first fiber layer with stitches.

NANOTUBE-ENHANCED INTERLAYERS FOR COMPOSITE STRUCTURES

TECHNICAL FIELD

The following disclosure relates generally to composite structures and, more particularly, to nanotube-enhanced interlayers for use in composite structures.

BACKGROUND

Fiber-reinforced resin materials, or "composite" materials as they are commonly known, are frequently used for aerospace, automotive and marine applications because of high strength-to-weight ratios, corrosion resistance, and other favorable properties. Conventional composite materials typically include glass, carbon, or polyaryamide fiber "plies" in woven and/or non-woven configurations. The fiber plies can be manufactured into composite parts by laminating them together with an uncured matrix material (e.g., an epoxy resin). The laminate can then be cured with the application of heat and/or pressure to form the finished part.

Composite parts can be manufactured from "prepreg" materials, or from dry fiber plies assembled into a "preform." Prepreg is ready-to-mold material in a cloth, mat, roving, tape or other form that has been pre-impregnated with matrix material (e.g., epoxy resin) and stored for use in an uncured or semi-cured state. The prepreg sheets are laid-up on the mold surface in the shape of the finished part. Pressure is then applied to compact the prepreg sheets, and heat can be applied to complete the curing cycle. A preform is different from a prepreg assembly in that a preform is an assembly of dry fabric and/or fibers which have been prepared for a resin infusion process on the mold surface. The preform plies are usually tacked and/or stitched together or otherwise stabilized to maintain their shape before and during final processing. Once the preform has been stabilized, the layers can be infused with resin using a liquid-molding process. The part can then be cured with the addition of pressure and/or heat.

The fiber material in composite parts provides relatively high strength in the direction of the fibers. Impact resistance, however, is generally determined by the properties of the cured matrix. One way to enhance impact resistance is to add

particles of, e.g., a thermoplastic material to the matrix. The thermoplastic material can inhibit crack propagation through the part resulting from, for example, foreign-object debris, which is typically not visible to the naked eye.

Another way to increase the impact resistance and fracture toughness of composite parts is to enhance the structural properties of the bond-line between alternating layers of composite materials (i.e., the interlayer properties). Adding carbon nanotubes to the interlayer is one method for improving the interlayer properties of composite materials. Carbon nanotubes are ordered molecules of pure carbon which form very small cylinders (on the order of 10 nanometers (i.e., 1×10^{-8} meters)). Carbon nanotubes exhibit unusual strength, and may be over 30 times as strong as typical carbon fibers and 100 times stronger than steel of equivalent weight.

One method for introducing carbon nanotubes in between two fiber plies is to add the nanotubes to the bond-line resin. One shortcoming of this approach, however, is that it is often difficult to maintain an even distribution of nanotubes in the liquid resin. Another shortcoming with this approach is that suspending the nanotubes in resin results in random orientation of the nanotubes between adjacent fiber plies. Moreover, the addition of even small amounts of nanotubes to a liquid resin tends to dramatically increase its viscosity and, thus, decrease its processability. Accordingly, it would be advantageous to have a method for evenly distributing carbon nanotubes in the proper orientation between fiber plies in the manufacturer of composite parts.

SUMMARY

The present disclosure is directed generally toward nanotube-enhanced interlayers for composite structures. A method of manufacturing a composite structure in accordance with one aspect of the disclosure includes producing a plurality of carbon nanotubes on a substrate, and attaching the substrate to a first fiber layer. The method further includes positioning a second fiber layer adjacent to the first fiber layer to position the plurality of carbon nanotubes between the first fiber layer and the second fiber layer. The method proceeds by infusing the first and second fiber layers with resin, and curing the resin to harden the composite structure. In one embodiment of this method, the substrate is bonded to the first fiber layer to position the carbon nanotubes before resin infusion. In another embodiment, the substrate is stitched to the first fiber

layer with thread. In yet another embodiment, the substrate is tacked to the first fiber layer with a tackifier.

A composite structure configured in accordance with another aspect of the invention includes an interlayer positioned between first and second fiber layers. The interlayer includes a plurality of carbon nanotubes attached to a substrate so that the nanotubes are at least generally perpendicular and evenly distributed on the substrate. The composite structure can additionally include matrix material infused into the first and second fiber layers. In one embodiment, the plurality of carbon nanotubes can include a first plurality of carbon nanotubes extending from a first side of the substrate, and a second plurality of carbon nanotubes extending from a second side of the substrate.

A system for manufacturing a composite structure in accordance with a further aspect of the disclosure includes means for producing a plurality of carbon nanotubes on a substrate, and means for attaching the substrate to a first fiber layer so that the plurality of carbon nanotubes extends away from the first fiber layer. The system can further include means for positioning a second fiber layer over the substrate to position the plurality of carbon nanotubes between the first fiber layer and the second fiber layer. The system can additionally include means for infusing the substrate and the first and second fiber layers with resin, and means for curing the resin.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a flow diagram of aircraft production and service method;

Figure 2 is a block diagram of an aircraft;

Figure 3A is a cross-sectional side view of a carbon nanotube-enhanced interlayer attached to a fiber layer in accordance with an embodiment of the disclosure, and Figure 3B is an enlarged, cross-sectional side view of the carbon nanotube-enhanced interlayer of Figure 3A.

Figure 4A is a cross-sectional side view of a carbon nanotube-enhanced interlayer attached to a fiber layer in accordance with another embodiment of the disclosure, and Figure 4B is an enlarged, cross-sectional side view of the carbon nanotube-enhanced interlayer of Figure 4A.

Figure 5 is a partially cut-away, isometric view of the carbon nanotube-enhanced interlayer of Figure 4A.

Figure 6A is an isometric view of a first composite laminate having a first carbon nanotube-enhanced interlayer configured in accordance with an embodiment of the disclosure, and Figure 6B is an isometric view of a second composite laminate having a second carbon nanotube-enhanced interlayer configured in accordance with another embodiment of the disclosure.

Figure 7A is an enlarged, cross-sectional isometric view of a portion of the first composite laminate of Figure 6A, and Figure 7B is an enlarged, cross-sectional isometric view of a portion of the second composite laminate of Figure 6B.

Figure 8 is a flow diagram illustrating a method for manufacturing composite parts in accordance with an embodiment of the disclosure.

Figure 9 is a flow diagram illustrating a method of manufacturing a composite structure in accordance with another embodiment of the disclosure.

DETAILED DESCRIPTION

The following disclosure describes nanotube-enhanced interlayers for composite structures, methods for producing nanotube-enhanced interlayers, and methods for manufacturing composite parts for aircraft and other structures with nanotube-enhanced interlayers. Certain details are set forth in the following description, and in Figures 1A-9 to provide a thorough understanding of various embodiments of the disclosure. Other details describing well-known structures and systems often associated with composite parts and composite part manufacturing are not set forth in the following disclosure to avoid unnecessarily obscuring the description of the various embodiments.

Many of the details, dimensions, angles and other features shown in the Figures are merely illustrative of particular embodiments. Accordingly, other embodiments can have other details, dimensions, angles and features without departing from the spirit or scope of the present invention. In addition, further embodiments of the disclosure can be practiced without several of the details described below.

In the Figures, identical reference numbers identify identical or at least generally similar elements. To facilitate the discussion of any particular element, the most

significant digit or digits of any reference number refer to the Figure in which that element is first introduced. For example, element 310 is first introduced and discussed with reference to Figure 3A.

Referring more particularly to the drawings, embodiments of the disclosure may
5 be described in the context of an aircraft manufacturing and service method 100 as shown in Figure 1 and an aircraft 102 as shown in Figure 2. During pre-production, method 100 may include specification and design 104 of the aircraft 102 and material procurement 106. During production, component and subassembly manufacturing 108 and system integration 110 of the aircraft 102 takes place. Thereafter, the aircraft 102
10 may go through certification and delivery 112 in order to be placed in service 114. While in service by a customer, the aircraft 102 is scheduled for routine maintenance and service 116 (which may include modification, reconfiguration, refurbishment, and so on).

Each of the processes of method 100 may be performed or carried out by a
15 system integrator, a third party, and/or an operator (e.g., a customer), as indicated by the "X" in the grid to the right of the flow diagram of Figure 1. For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may
20 be an airline, leasing company, military entity, service organization, and so on.

As shown in Figure 2, the aircraft 102 produced by exemplary method 100 may include an airframe 118 with a plurality of systems 120 and an interior 122. Examples of high-level systems 120 include one or more of a propulsion system 124, an electrical system 126, a hydraulic system 126, and an environmental system 130.

25 Apparatus and methods embodied herein may be employed during any one or more of the stages of the production and service method 100. For example, components or subassemblies corresponding to production process 108 may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft 102 is in service. Also, one or more apparatus
30 embodiments, method embodiments, or a combination thereof may be utilized during the production stages 108 and 110, for example, by substantially expediting assembly of or reducing the cost of an aircraft 102. Similarly, one or more of apparatus

embodiments, method embodiments, or a combination thereof may be utilized while the aircraft 102 is in service, for example and without limitation, to maintenance and service 116.

Figure 3A is a cross-sectional side view of an interlayer assembly 300 configured
5 in accordance with an embodiment of the disclosure. In the illustrated embodiment, the interlayer assembly 300 includes an interlayer 310 attached to a fiber layer 302. The fiber layer 302 can include various types of fiber materials known in the art including unidirectional, woven, non-woven, braided, and/or warp-knit fibers of, e.g., carbon, glass, polyaramide, etc. in multiple orientations. For example, in one embodiment, the
10 fiber layer 302 can include carbon fibers in a bi-directional weave. In another embodiment, the fiber layer 302 can include carbon fibers in a unidirectional orientation.

Figure 3B is an enlarged, cross-sectional side view of the interlayer 310 of Figure 3A. The interlayer 310 includes a relatively even distribution of carbon nanotubes 314 in a generally vertical orientation on a veil or substrate 312. The substrate 312 can
15 include, without limitation, carbon fibers, glass fibers, ceramic fibers (e.g., alumina fibers) and/or other flexible materials that can withstand the relatively high temperatures often necessary for producing or "growing" carbon nanotubes. The substrate 312 can also include, without limitation, polyamide, polyimide, polyester, polybutadiene, polyurethane, polypropylene, polyetherimide, polysulfone, polyethersulfone,
20 polyphenylsulfone, polyester-polyarylate (e.g., Vectran®), polyaramid (e.g., Kevlar®), polybenzoxazole (e.g., Zylon®), Viscose (e.g., Rayon®), etc. The substrate 312 can further include a binder (e.g., a thermoplastic resin; not shown) if necessary to maintain the substrate fibers in the proper orientation during the nanotube growing process.

The carbon nanotubes 314 can be "grown" or otherwise produced on the
25 substrate 312 using any suitable method known in the art. Such methods can include, for example, arc discharge methods, laser ablation methods, and chemical vapor deposition (CVD) methods. Producing carbon nanotubes with CVD is essentially a two-step process consisting of catalyst preparation followed by nanotube synthesis. The catalyst can be prepared by sputtering or otherwise applying a transition metal (e.g., Fe, Cu, Ti, etc.) onto the substrate 312, and then patterning the catalyst by chemical etching
30 or thermal annealing to induce catalyst particle nucleation. This results in catalyst cluster formation on the substrate 312 from which the carbon nanotubes 314 can grow.

A gas consisting of a source of carbon (such as methane, ethylene, or carbon monoxide), either by itself or in a mixture with other gases, is flowed over the patterned catalyst at temperatures ranging from about 650°C to about 900°C.

After the carbon nanotubes 314 have been grown on one side of the substrate 312, a bond layer 316 can be applied to the other side of the substrate 312. The bond layer 316 can include, for example, without limitation, a melt-bondable adhesive, such as a thermosetting or thermoplastic resin (e.g., a nylon-based or polyester-based resin), or other suitable adhesive known in the art.

In the illustrated embodiment, the carbon nanotubes 314 on the substrate 312 are attached to the fiber layer 302 by bonding (e.g., by melt-bonding) the bond layer 316 to the fiber layer 302. Melt-bonding is achieved by elevating the temperature of the bond layer 316 so that the material (e.g., the thermoplastic resin) melts and thereby bonds to the fiber layer 302. Melt-bonding of interlayers to fiber layers is described in detail in U.S. Patent Application Serial No. 10/428,500, which was filed on May 2, 2003,. Bonding the interlayer 310 to the fiber layer 302 in this manner can provide a relatively even distribution of the carbon nanotubes 314 over the surface of the fiber layer 302 in a generally vertical orientation.

Figure 4A is a cross-sectional side view of an interlayer assembly 400 configured in accordance with another embodiment of the invention. The interlayer assembly 400 includes an interlayer 410 attached to a fiber layer 402. Figure 4B is an enlarged, cross-sectional side view of the interlayer 410. As shown in Figure 4B, the interlayer 410 includes a first plurality of carbon nanotubes 414a on a first side 413a of a substrate 412, and a second plurality of carbon nanotubes 414b on a second side 413b of the substrate 412. The substrate 412 can be at least generally similar in structure and function to the substrate 312 described above with reference to Figures 3A and 3B. Similarly, the first and second pluralities of carbon nanotubes 414 can be grown on the first and second sides 413a and 413b of the substrate 412, respectively, using any suitable method known in the art as explained above. The presence of the carbon nanotubes 414 on both sides of the substrate 412 may hinder bonding the interlayer 410 to the fiber layer 402. In such embodiments, the interlayer assembly 410 can be attached to the fiber layer 402 using other methods, such as stitching, tackfying and/or

other forms of structural or mechanical fastening, as described in greater detail below with reference to Figure 5.

Figure 5 is a partially cut-away isometric view of the interlayer assembly 400 of Figure 4A. In the illustrated embodiment, the interlayer 410 is stitched (e.g., knit-stitched or sewed) to the fiber layer 402 with thread 520. The thread 520 extends through the interlayer 410 and the fiber layer 402. The stitching can be in various patterns, densities, and/or stitch-lengths depending on the nature of the fiber layer 402, the interlayer 410, the thread 520, etc. For example, in the illustrated embodiment, the thread 520 forms a tricot stitch. In other embodiments, however, other stitch patterns can be used including, for example, without limitation, a lock stitch, a chain stitch, etc. The thread 520 can be selected from a variety of suitable materials in various thicknesses including, for example, without limitation, polyester-polyarylate (e.g., Vectran®), polyaramid (e.g., Kevlar®), polybenzoxazole (e.g., Zylon®), Viscose (e.g., Rayon®), acrylic, polyamid, carbon, fiberglass, etc. The knitting or sewing step can be manually or automatically carried out prior to use of the interlayer assembly 400 in a preform, or after the initial layup of the fiber layer 402 in a preform. Various methods for stitching the interlayer 410 to the fiber layer 402 are described in detail in U.S. Patent Application Serial No. 10/974,426, which was filed on October 27, 2004. Although the interlayer 410 is stitched to the fiber layer 402 with thread 520 in Figure 5, in other embodiments, the interlayer 410 can be attached to the fiber layer 402 with other types of fasteners. For example, in another embodiment, the interlayer 410 can be attached to the fiber layer 402 with mechanical fasteners, such as, without limitation, plastic rivets, inserts, staples, etc.

Figure 6A is an isometric view of a first composite laminate 630a configured in accordance with an embodiment of the disclosure, and Figure 6B is an isometric view of a second composite laminate 630b configured in accordance with another embodiment. Referring first to Figure 6A, the first composite laminate 630a includes a plurality of interlayer assemblies 600 (identified individually as a first interlayer assembly 600a and a second interlayer assembly 600b) assembled on a mold surface 640. In the illustrated embodiment, the interlayer assemblies 600 are at least generally similar in structure and function to the interlayer assembly 300 described above with reference to Figures 3A and 3B. More specifically, each of the interlayer assemblies 600 includes an interlayer 310 (identified individually as a first interlayer 310a and a second interlayer 310b) melt-

bonded or otherwise attached to a corresponding fiber layer 302 (identified individually as a first fiber layer 302a and a second fiber layer 302b). The interlayer assemblies 600 are stacked so that they form an alternating fiber layer/interlayer/fiber layer arrangement. A third fiber layer 602a can be placed over the second interlayer assembly 600b.

Although three fiber layers and two interlayers are shown in Figure 6A for purposes of illustration, any number of interlayers and fiber layers in various orientations (e.g., a +45/0/-45/90 orientation) can be used in accordance with the disclosure. For example, various embodiments can include three or more fiber layers with a corresponding nanotube enhanced interlayer between each fiber layer and/or on the outside of the lay-up. In addition, the various interlayers and fiber layers can have different thicknesses, different material compositions, etc.

Once the desired number of the interlayer assemblies 600 and the fiber layer 602a has been assembled on the mold surface 640 in the desired orientations, the first composite laminate 630a can be formed into a finished composite part using a variety of liquid-molding processes known in the art. Such methods include, for example, vacuum-assisted resin transfer molding (VARTM). In VARTM, a vacuum bag is placed over the preform, and resin is infused into the preform using a vacuum-generated pressure differential. The laminate can then be placed in an autoclave, oven, etc. and heated to cure the resin. Other liquid-molding processes include resin transfer molding (RTM) and resin film infusion (RFI). In RTM, resin is infused under pressure into the preform in a closed mold. In RFI, a semi-solid resin is placed underneath or on top of the preform, and a tool is positioned on top of the laminate. The laminate assembly is then vacuum-bagged and placed in an autoclave to melt the semi-solid resin, causing it to infuse into the preform.

In another embodiment, the interlayer assemblies 600 and/or the third fiber layer 602 can be impregnated with resin (i.e., "prepreg") before being placed on the mold surface 640. The part can then be cured by placing the laminate under a vacuum-bag and curing the matrix material at an elevated temperature and/or pressure. As the foregoing examples illustrate, embodiments are not limited to a particular liquid-molding process, or to liquid-molding, for that matter.

Referring next to Figure 6B, the second composite laminate 630b includes a plurality of interlayer assemblies 650 (identified individually as a first interlayer assembly 650a and a second interlayer assembly 650b) in a stacked arrangement on the mold surface 640. In the illustrated embodiment, the interlayer assemblies 650 are at least generally similar in structure and function to the interlayer assembly 400 described above with reference to Figures 4A and 4B. For example, each of the interlayer assemblies 650 includes an interlayer 410 (identified individually as a first interlayer 410a and a second interlayer 410b) stitched or otherwise fastened to a corresponding fiber layer 402 (identified individually as a first fiber layer assembly 402a and a second fiber layer 402b) with the thread 520. The interlayer assemblies 650 are stacked so that they form an alternating fiber layer/interlayer/fiber layer arrangement. A third fiber layer 602b can be placed over the second interlayer assembly 650b. Although three fiber layers and two interlayers are shown in Figure 6B for purposes of illustration, any number of interlayers and fiber layers can be used in various orientations (e.g., a 0/90/0 orientation) in accordance with the present disclosure. In addition, the various interlayers and fiber layers can have different thicknesses, different material compositions, etc.

Once the desired number of the interlayer assemblies 650 and the fiber layer 602b has been assembled on the mold surface 640, the second composite laminate 630b can be formed into a finished part using a variety of liquid-molding processes known in the art. As described above with reference to Figure 6B, such methods can include, for example, vacuum-assisted resin transfer molding (VARTM), resin transfer molding (RTM), and resin film infusion (RFI). In another embodiment, the interlayer assemblies 650 and/or the third fiber layer 602b can be infused with resin in prepreg form before being placed on the mold surface 640. Whether liquid-molding or prepreg methods are used, the second composite laminate 630b can be compacted (debulked) using vacuum pressure and then hardened by elevating the temperature and curing the matrix material.

Figure 7A is an enlarged cross-sectional view of a portion of the first composite laminate 630a of Figure 6A, and Figure 7B is an enlarged cross-sectional view of a portion of the second composite laminate 630b of Figure 6B. As shown in Figure 7A, the carbon nanotubes 314 extend upwardly from the first interlayer assembly 600a and into the adjacent fiber layer 302b. This configuration can enhance the strength of the

interface between the two fiber layers 302, and thereby increase the fracture toughness and impact resistance of the finished composite part.

As shown in Figure 7B, the first plurality of carbon nanotubes 414a extend from the first side 413a of the first interlayer 410a, and the second plurality of carbon nanotubes 414b extend outwardly from the second side 413b of the first interlayer 410a. As a result, the first plurality of carbon nanotubes 414a extend into a portion of the first fiber layer 402a, and the second plurality of carbon nanotubes 414b extend into a portion of the second fiber layer 402b. The two-sided nanotube configuration illustrated in Figure 7B may provide even more interlayer strength and fracture toughness than the single-sided nanotube arrangement of Figure 7A.

Figure 8 is a flow diagram illustrating a method for manufacturing a composite part with a carbon nanotube interlayer assembly in accordance with an embodiment of the invention. The method begins in block 802, where carbon nanotubes are grown on a first side of a substrate or on both the first side of the substrate and a second side of the substrate. If the carbon nanotubes are grown on just the first side of the substrate, the method proceeds to block 804 and applies a bond layer (e.g., a thermoplastic bond layer, adhesive, binder, etc.) to the second side of the substrate. In block 806, the method bonds (e.g., by melt-bonding) the nanotube-coated substrate to a fiber layer to form an interlayer assembly. After block 806, the method proceeds to decision block 808.

Returning to block 802, if the carbon nanotubes are grown on both sides of the substrate, the method proceeds to block 810 and mechanically fastens (e.g., by stitching with a thread or other suitable material) the nanotube-coated substrate to a fiber layer to form an interlayer assembly. After block 810, the method proceeds to decision block 808.

In decision block 808, the decision is made whether to pre-impregnate the interlayer assembly with matrix (e.g., epoxy resin) and store the prepreg assembly for later use, or use the dry interlayer assembly in a preform. If the decision is made to pre-impregnate the interlayer assembly, the method proceeds to block 818 and infuses the interlayer assembly with matrix material (e.g., epoxy resin). Here, the interlayer assembly can be infused with uncured matrix material using any suitable method known in the art for preparing prepreg fiber layers. In block 820, the prepreg interlayer

assembly can be stored, if desired, for an extended period of time prior to use. When the prepreg interlayer assembly is ready for use, the method proceeds to block 822 and combines the prepreg interlayer assembly with one or more prepreg fiber layers and/or one or more additional prepreg interlayer assemblies on a mold surface in a desired orientation. In block 824, the method vacuum-bags the prepreg assembly to compact the lay-up, and cures the assembly with the application of heat and/or pressure to harden composite part. After block 824, the method ends.

Figure 9 is a flow diagram illustrating a method 900 for manufacturing a composite structure in accordance with another embodiment of the disclosure. In block 902, the method includes producing a plurality of carbon nanotubes on a substrate. In block 904, the method involves attaching the substrate to a first fiber layer. In block 906, a second fiber layer is positioned adjacent to the first fiber layer so that the plurality of carbon nanotubes are positioned between the first and second fiber layers. In block 908, the first and second fiber layers are infused with resin, and the resin is cured in block 910. After block 910 the method ends.

Returning to decision block 808, if the decision is made to assemble the dry interlayer assembly into a preform, the method proceeds to block 812 and combines the interlayer assembly with one or more fiber layers and/or one or more additional interlayer assemblies on the mold surface. In block 814, the method infuses the preform with matrix material using any suitable liquid-molding process known in the art. In block 816, the method evacuates the resin-infused assembly to remove air bubbles, and then cures the assembly with the application of heat and/or pressure to form the finished composite part. After block 816, the method ends.

The methods described above can be used to manufacture composite parts for a wide variety of different structures, including aircraft structures. For example, these methods can be used to form aircraft skins, frames, stiffeners, and/or various portions thereof. The composite parts can be assembled together to form aircraft structures (e.g., fuselages, wings, tail surfaces, etc.) using adhesives, fasteners, and/or other suitable attachment methods known in the art.

From the foregoing, it will be appreciated that specific embodiments of the invention have been described herein for purposes of illustration, but that various modifications may be made without deviating from the spirit and scope of the various

embodiments of the invention. Further, while various advantages associated with certain embodiments of the invention have been described above in the context of those embodiments, other embodiments may also exhibit such advantages, and not all embodiments need necessarily exhibit such advantages to fall within the scope of the invention. Accordingly, the invention is not limited, except as by the appended claims.

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CLAIMS

I/We claim:

1. A method of manufacturing a composite structure, the method comprising:
producing a plurality of carbon nanotubes on a substrate;
5 attaching the substrate to a first fiber layer;
positioning a second fiber layer adjacent to the first fiber layer to position the
plurality of carbon nanotubes between the first fiber layer and the second
fiber layer;
infusing the first and second fiber layers with resin; and
10 curing the resin to harden the composite structure.
2. The method of claim 1 wherein attaching the substrate to the first fiber layer
includes bonding the substrate to the first fiber layer.
3. The method of claim 1 wherein the substrate includes a bond-layer, and
wherein attaching the substrate to the first fiber layer includes heating the bond-layer
15 and the first fiber layer to melt-bond the substrate to the first fiber layer.
4. The method of claim 1 wherein attaching the substrate to the first fiber layer
includes mechanically fastening the substrate to the first fiber layer.
5. The method of claim 1 wherein attaching the substrate to the first fiber layer
includes stitching the substrate to the first fiber layer with a thread.
- 20 6. The method of claim 1 wherein producing a plurality of carbon nanotubes on
a substrate includes growing a plurality of carbon nanotubes on a flexible substrate.
7. The method of claim 1 wherein the substrate has a first side and a second
side, and wherein producing a plurality of carbon nanotubes on the substrate includes
producing a first portion of carbon nanotubes extending at least generally
25 perpendicularly from the first side of the substrate, and producing a second portion of

carbon nanotubes extending at least generally perpendicularly from the second side of the substrate.

8. The method of claim 1 wherein positioning the plurality of carbon nanotubes between the first fiber layer and the second fiber layer includes orienting the plurality of carbon nanotubes to extend at least generally perpendicular to the first and second fiber layers.

9. The method of claim 1 wherein infusing the substrate and the first and second fiber layers with resin includes preimpregnating the substrate and the first fiber layer with a first portion of resin, and preimpregnating the second fiber layer with a second portion of resin, before positioning the second fiber layer adjacent to the substrate.

10. The method of claim 1 wherein producing a plurality of carbon nanotubes on a substrate includes growing a first plurality of carbon nanotubes on a first flexible substrate, wherein attaching the substrate to the first fiber layer includes heating the first flexible substrate and the first fiber layer to melt-bond the first flexible substrate to the first fiber layer, and wherein the method further comprises

growing a second plurality of carbon nanotubes on a second flexible substrate;

heating the second flexible substrate and the second fiber layer to melt-bond the second flexible substrate to the second fiber layer; and

positioning a third fiber layer adjacent to the second fiber layer to position the second plurality of carbon nanotubes between the second fiber layer and the third fiber layer, wherein infusing the first and second fiber layers with resin includes infusing the first and second flexible substrates and the first, second, and third fiber layers with resin.

11. The method of claim 10, further comprising laminating additional carbon nanotube enhanced fiber layers onto the third fiber layer.

13. The method of claim 1 wherein the composite structure is a composite aircraft structure, and wherein the method further comprises assembling the hardened
5 composite structure into a portion of an aircraft.

13. A method of producing a carbon nanotube-enhanced interlayer assembly for composite structures, the method comprising:
growing a plurality of carbon nanotubes on a flexible substrate; and
attaching the flexible substrate to a fiber layer.

10 14. The method of claim 13 wherein growing a plurality of carbon nanotubes on a flexible substrate includes growing a plurality of carbon nanotubes on a transition metal catalyst with chemical vapor deposition, and wherein attaching the flexible substrate to a fiber layer includes heating the substrate and the fiber layer to melt at least a portion of the substrate and bond the carbon nanotubes to the fiber layer.

15 15. The method of claim 13 wherein the substrate has a first side and a second side, and wherein growing a plurality of carbon nanotubes on a flexible substrate includes producing a first portion of carbon nanotubes extending at least generally perpendicularly from the first side of the substrate, and producing a second portion of carbon nanotubes extending at least generally perpendicularly from the second side of
20 the substrate.

16. The method of claim 13 wherein attaching the flexible substrate to a fiber layer includes coating the fiber layer with a generally even distribution of approximately perpendicular carbon nanotubes.

17. The method of claim 13, further comprising applying a bond layer to the
25 flexible substrate, wherein attaching the flexible substrate to a fiber layer includes melting at least a portion the bond layer.

18. The method of claim 13 wherein growing a plurality of carbon nanotubes on a flexible substrate includes growing a first plurality of carbon nanotubes on a first side of the flexible substrate and growing a second plurality of carbon nanotubes on a second side of the flexible substrate, and wherein attaching the flexible substrate to a fiber layer includes stitching at least a portion the flexible substrate to the fiber layer.
19. A composite structure comprising:
first fiber layer;
a second fiber layer;
an interlayer positioned between the first and second fiber layers, wherein the interlayer includes:
a substrate; and
a plurality of carbon nanotubes attached to the substrate, wherein the plurality of carbon nanotubes are at least generally perpendicular to the substrate; and
matrix material infused into the first and second fiber layers.
20. The composite structure of claim 19 wherein the plurality of carbon nanotubes is a first plurality of carbon nanotubes extending from a first side of the substrate, and wherein the interlayer further includes a second plurality of carbon nanotubes extending from a second side of the substrate.
21. The composite structure of claim 19 wherein the substrate is melt-bonded to the first fiber layer.
22. A system for manufacturing a composite structure, the system comprising:
means for producing a plurality of carbon nanotubes on a substrate;
means for attaching the substrate to a first fiber layer so that the plurality carbon nanotubes extend away from the first fiber layer; and
means for positioning a second fiber layer over the substrate to position the plurality of carbon nanotubes between the first fiber layer and the second fiber layer.

23. The method of claim 22, further comprising:
means for infusing the substrate and the first and second fiber layers with resin; and
means for curing the resin.

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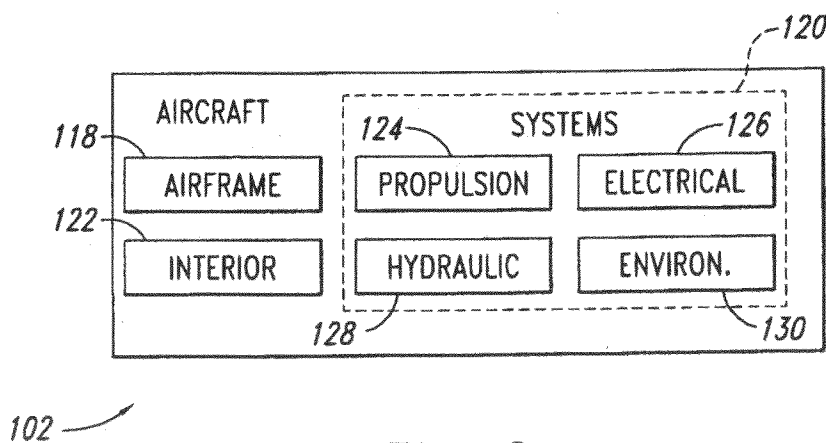
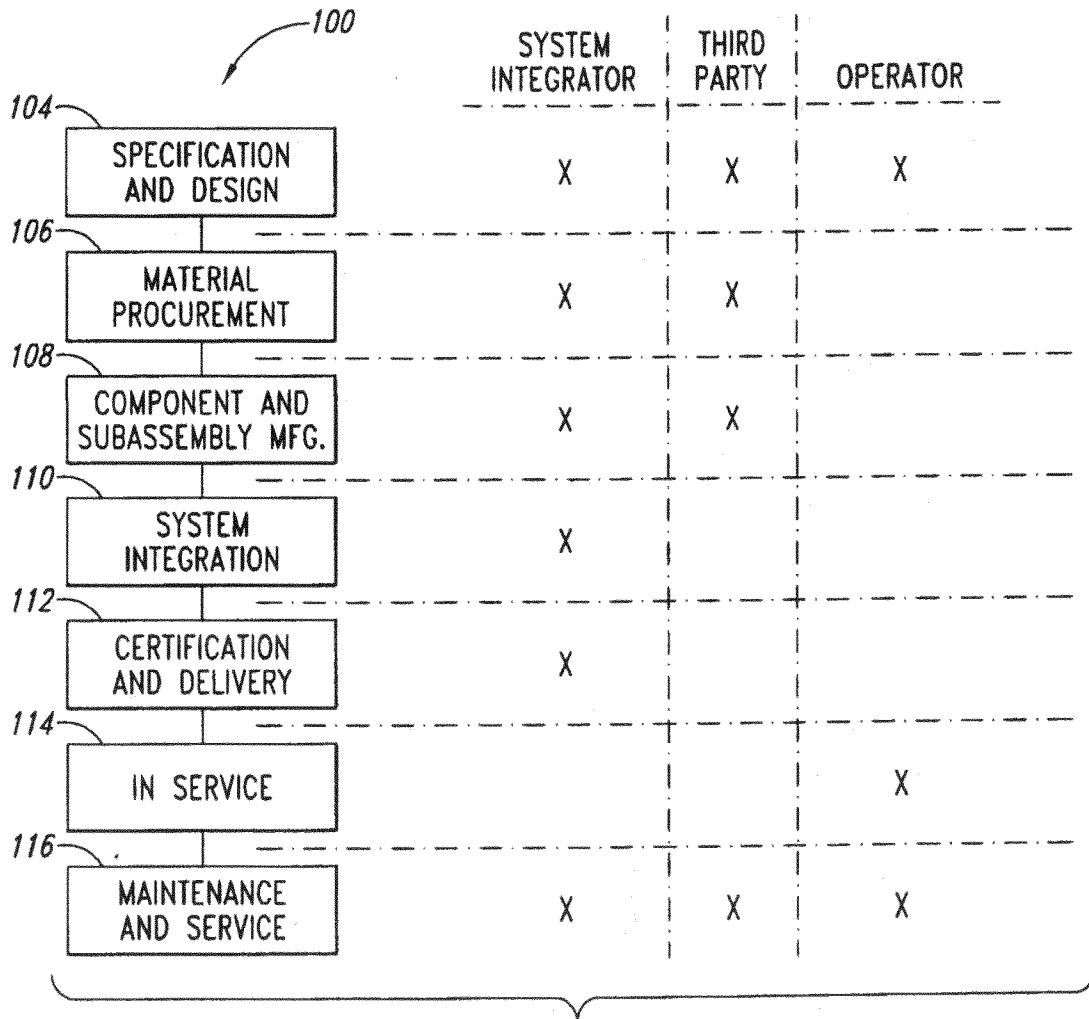
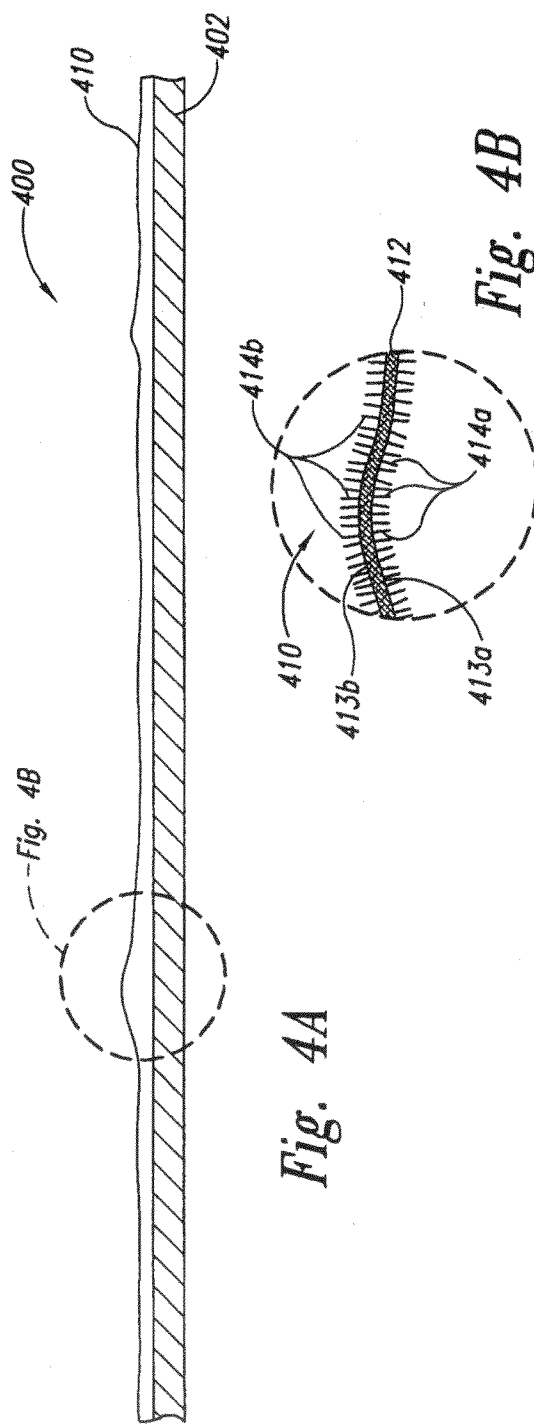
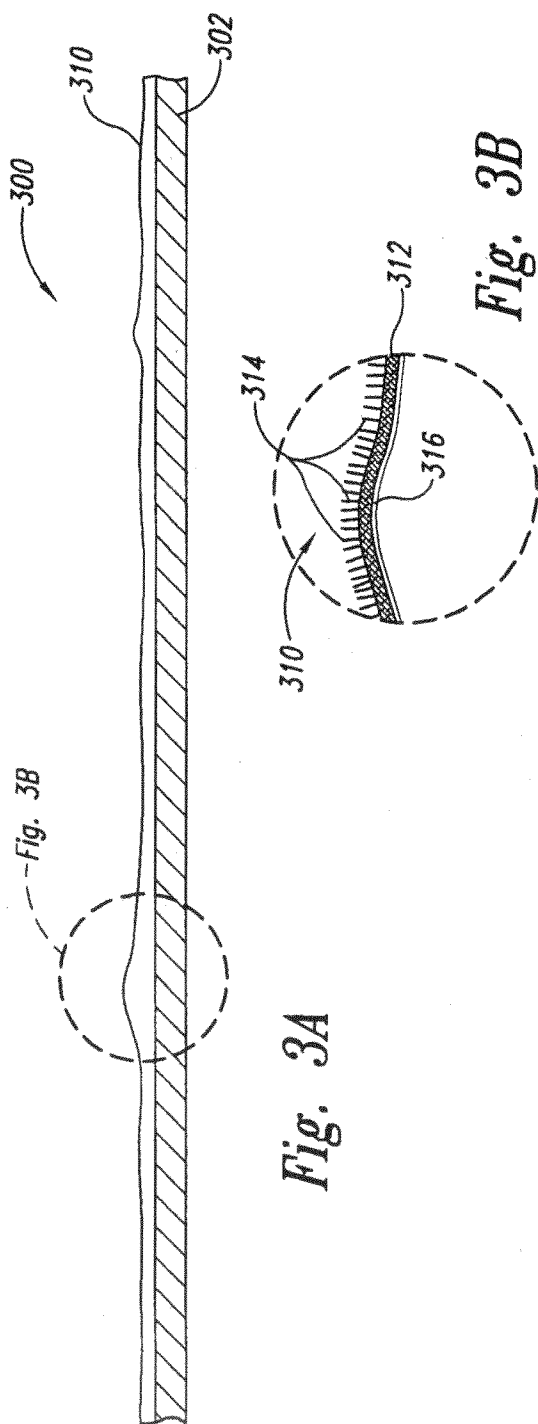


Fig. 2

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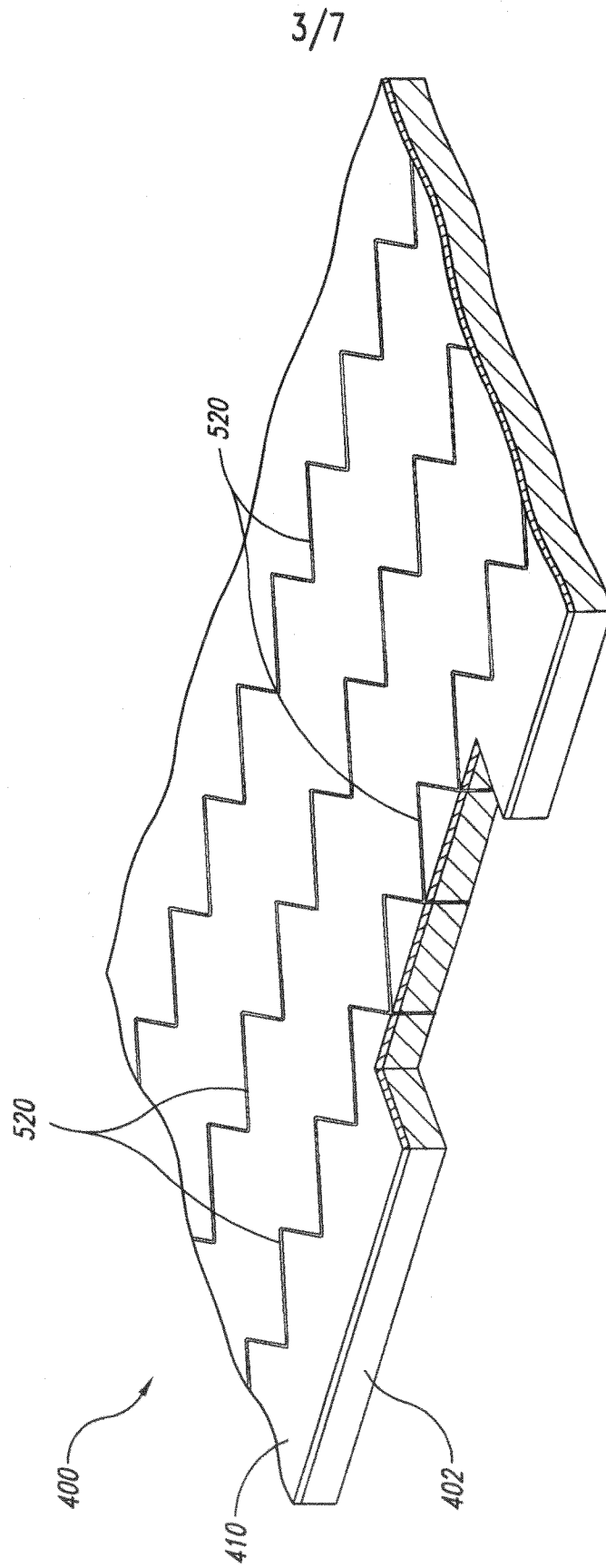


Fig. 5

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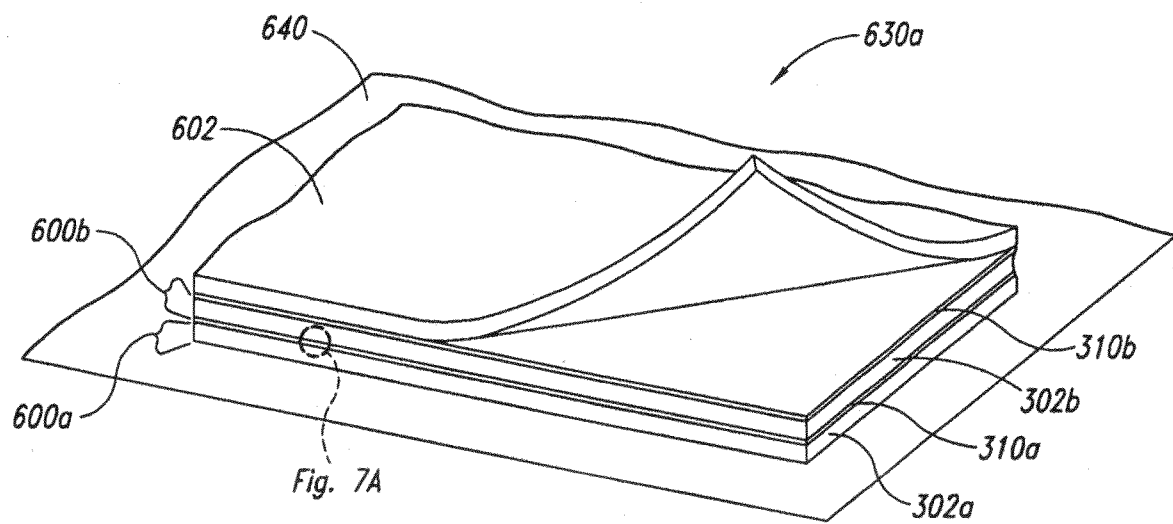


Fig. 6A

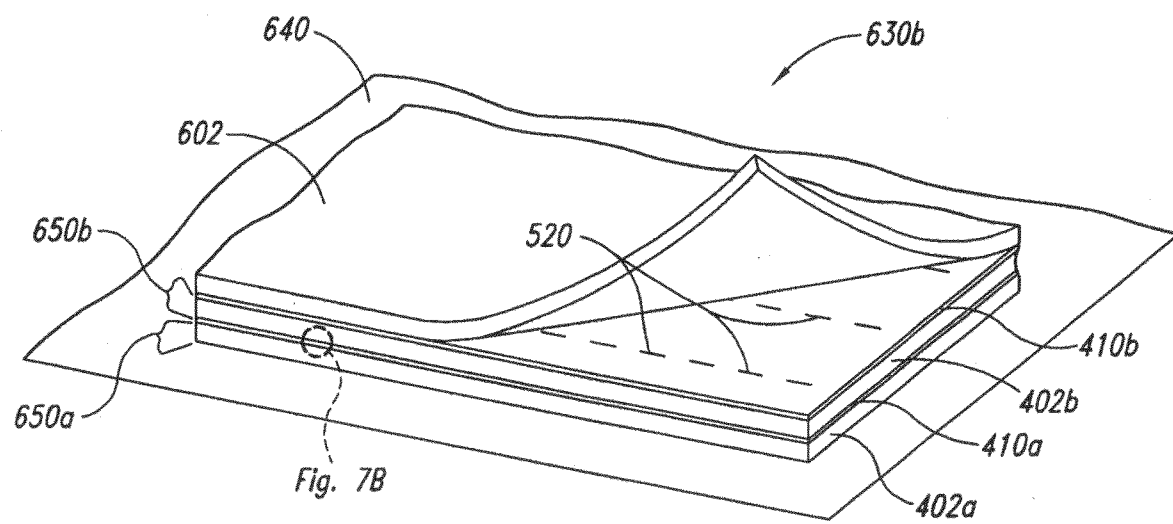


Fig. 6B

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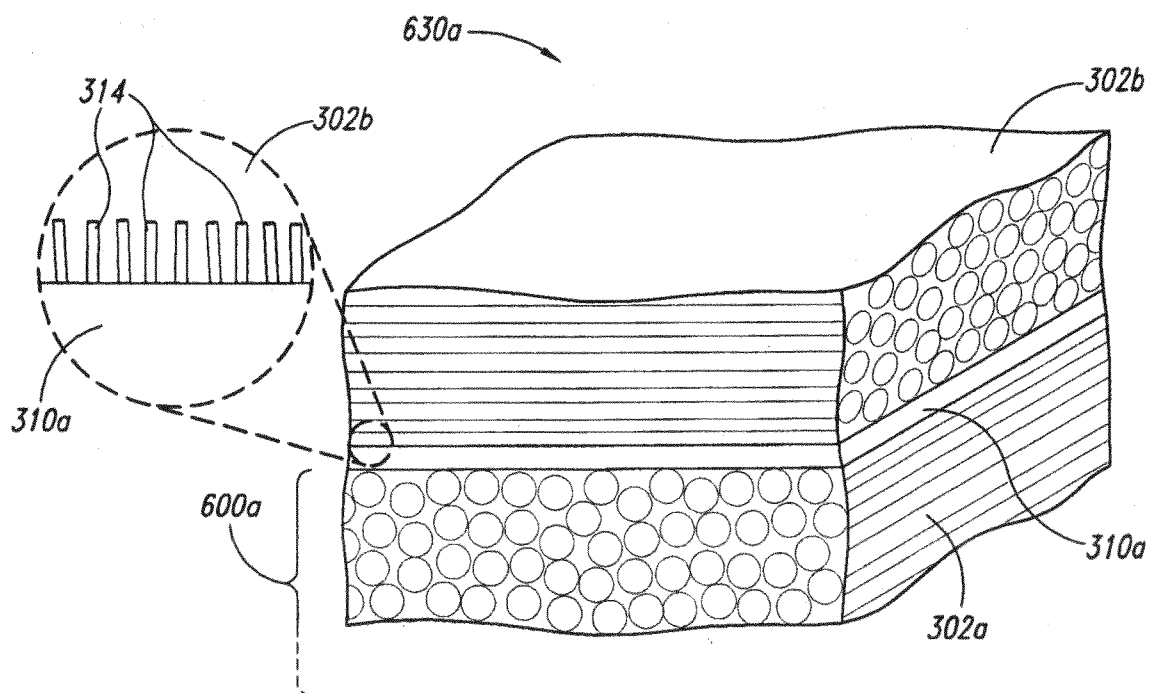


Fig. 7A

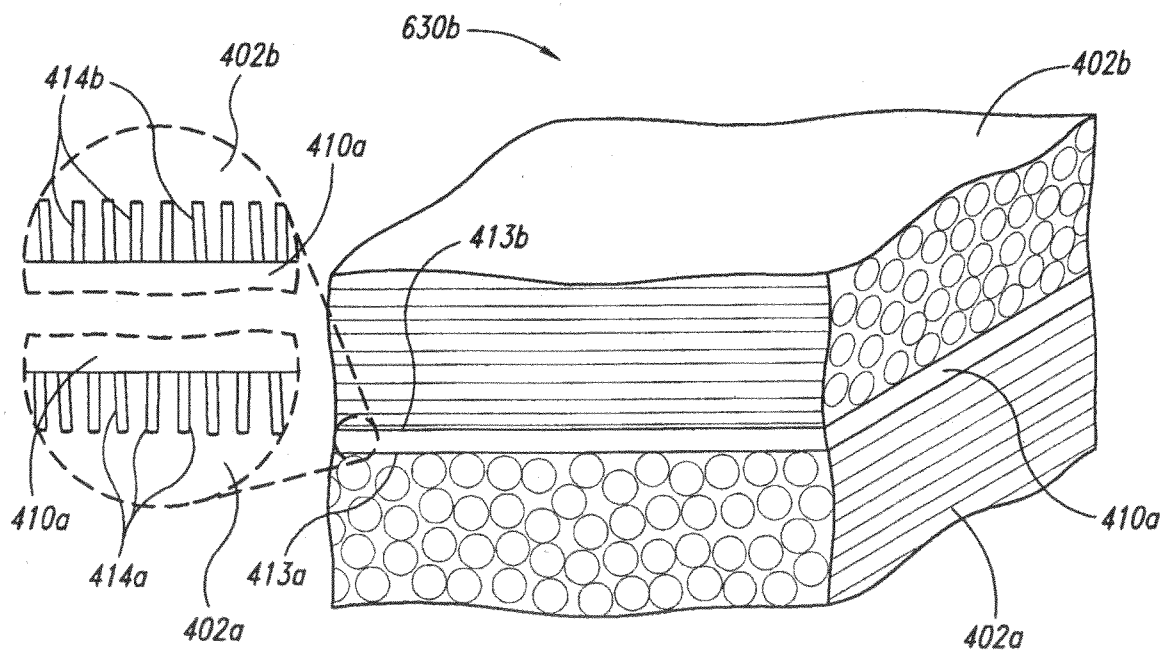


Fig. 7B

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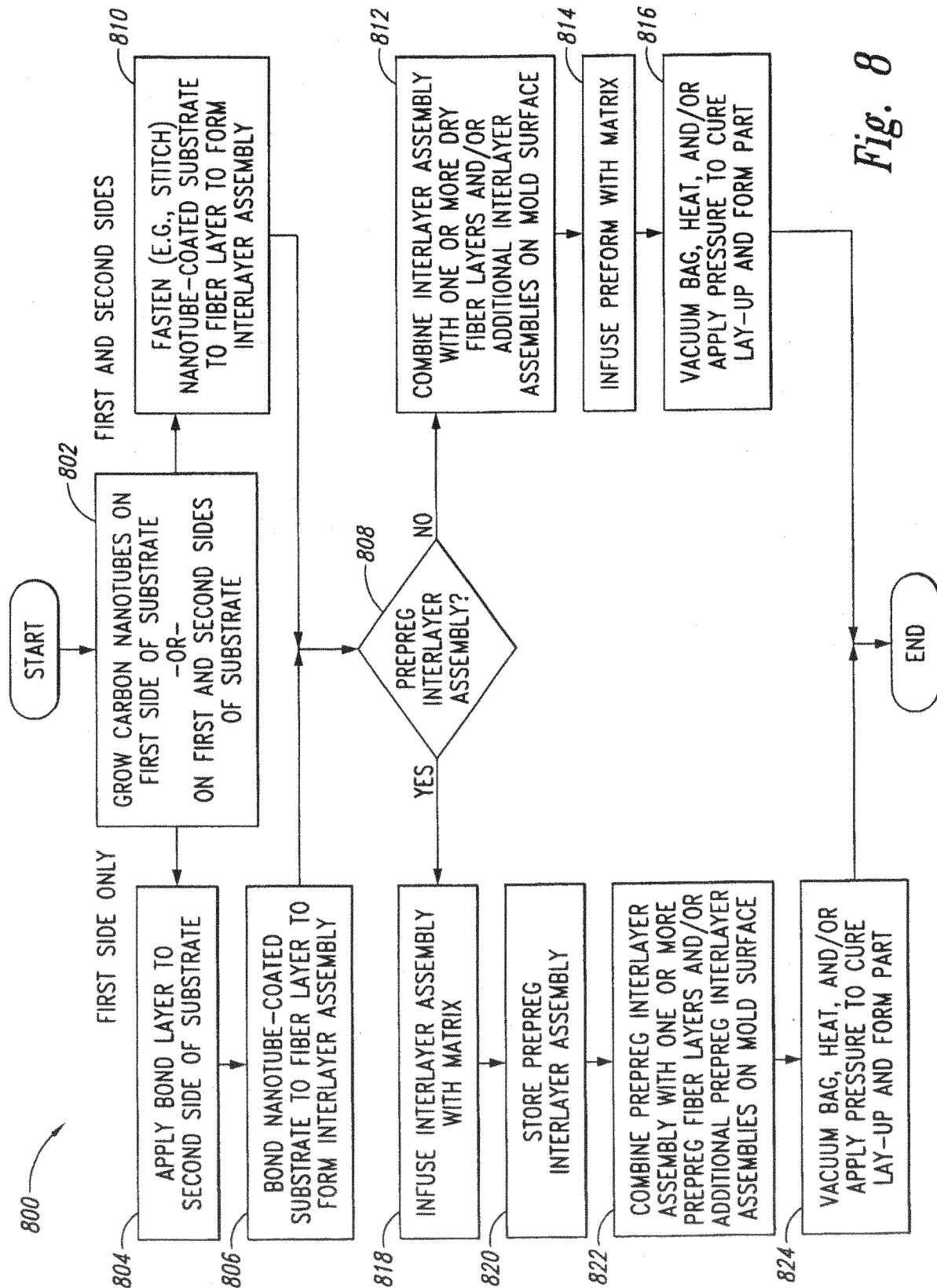
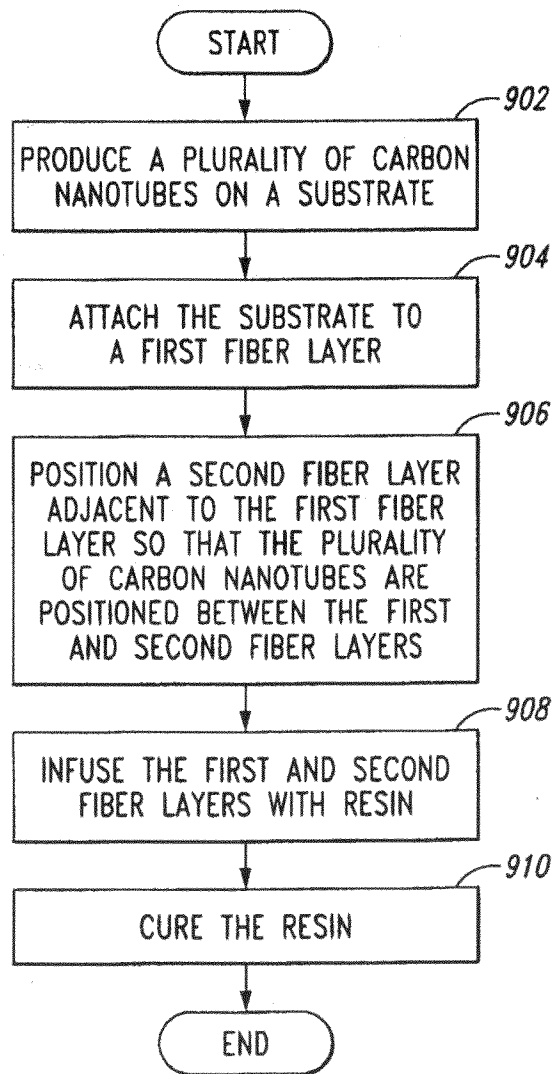


Fig. 8

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*Fig. 9*