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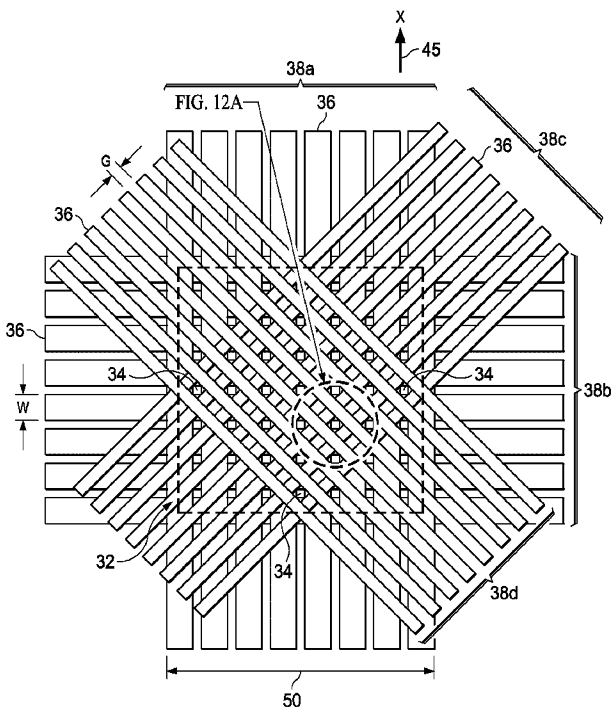
(54) Title: COMPOSITE LAMINATES HAVING HOLE PATTERNS PRODUCED BY CONTROLLED FIBER PLACEMENT



(57) Abrégé/Abstract:
A composite laminate has a pattern of holes therein. The holes are formed by laying down plies of unidirectional pre-preg material having varying fiber orientations. The tows are spaced apart and located to form holes through the laminate.

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(54) **Title**: COMPOSITE LAMINATES HAVING HOLE PATTERNS PRODUCED BY CONTROLLED FIBER PLACEMENT

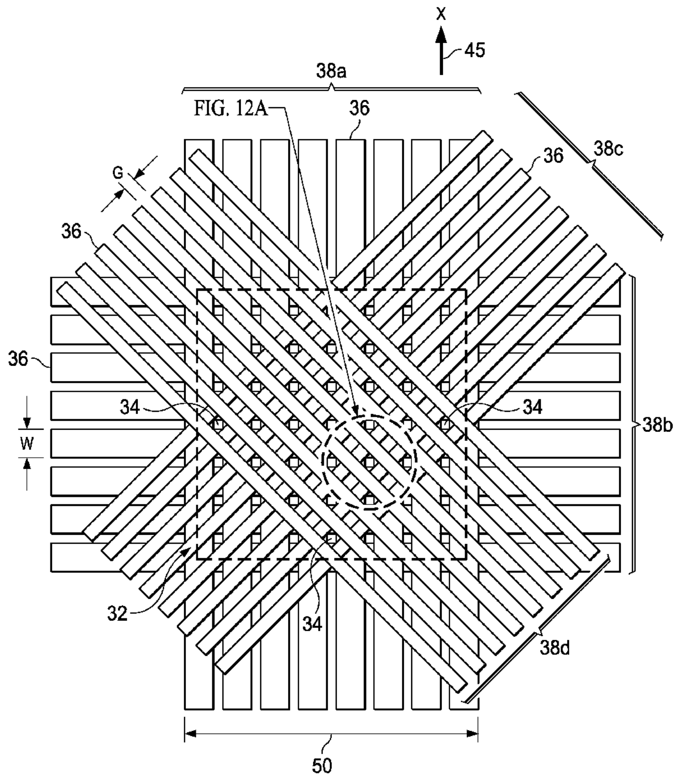

FIG. 12

(57) **Abstract**: A composite laminate has a pattern of holes therein. The holes are formed by laying down plies of unidirectional pre-preg material having varying fiber orientations. The tows are spaced apart and located to form holes through the laminate.

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COMPOSITE LAMINATES HAVING HOLE PATTERNS PRODUCED BY CONTROLLED FIBER PLACEMENT

BACKGROUND INFORMATION

1. Field:

The present disclosure generally relates to processes for fabricating composite laminates, and deals more particularly with a method of producing hole patterns in such laminates using controlled fiber placement, and to laminates having hole patterns produced thereby.

2. Background:

It is sometimes necessary to form a large number of holes or perforations in a composite structure. For example, acoustically treated structures may employ an acoustic panel having an outer composite laminate facesheet provided with thousands of perforations. The facesheet perforations cooperate with a cellular panel core to attenuate sound. Aircraft wing skins may also include composite laminate facesheets that are perforated in order to alter the airflow over the wing.

Current techniques for forming a large number of perforations or holes in a composite laminate can be time consuming, labor intensive and expensive. In one technique, tooling referred to as pin mats is used to create holes as individual fabric plies are pressed over and around the pins, and then cured into the laminate. The pins can be fragile and may be difficult to remove from the cured laminate. In another technique, the holes are formed by drilling individual holes in the laminate after it has been cured. Drilling thousands of individual holes with a drill bit is time consuming and may result in fiber breakout surrounding the holes due to bit wear. It is also possible to form holes in a composite laminate using a combination of masking and sand blasting, wherein a hole pattern is masked onto a cured laminate, and the holes are sandblasted into the laminate. The sandblasting process may also result in undesired fiber breakout. Fiber breakout around a hole may cause the hole diameter, hole finish and/or edges of the hole to be out-of-tolerance.

Accordingly, there is a need for a method of forming a relatively large number of holes or perforations in a composite laminate that is simple, efficient and controllable, and which eliminates the need for tooling and/or drilling processes. There is also a need for a method of forming hole patterns *in situ* in a laminate structure as the laminate is being fabricated. Further, there is a need for a perforated composite laminate having controlled hole patterns in which holes may be formed having various sizes, shapes and distribution patterns.

SUMMARY

The disclosed embodiments provide a method of forming a pattern of holes in a composite laminate such as a skin used in acoustically treated panels for sound attenuation. Hole patterns may be formed in the laminate *in situ* as the laminate is being constructed. The need for specialized tooling such as pin mats is eliminated, and processes such as drilling and sandblasting which may produce fiber breakout are avoided. The method may be carried out using numerically controlled automatic fiber placement equipment, and is therefore efficient, highly repeatable and useful where higher production rates are desired. The method is also well-suited for use in fabricating composite laminates with controlled hole patterns using out-of-autoclave processes. In order to improve acoustic properties of the laminate, woven or non-woven materials such as, without limitation, metal or plastic wire meshes may be embedded into the laminate as the hole pattern is being formed.

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In one embodiment, there is provided a method of producing a composite laminate layup having a pattern of holes therein. The method involves causing an automated fiber placement (AFP) machine to lay up multiple plies of unidirectional pre-preg fiber, by simultaneously laying down bandwidths of pre-preg fiber tows on a substrate, the tows having widths and centerlines. The method further involves causing the AFP machine to cause the composite laminate layup to have the pattern of holes, by: causing a collimator of the AFP machine to space the tows in each of the bandwidths apart from each other to define gaps between the tows as the bandwidths are being laid down to control first locations of the centerlines of the tows as the bandwidths are being laid down and to control the gaps between the tows as the bandwidths are being laid down; causing a roller of the AFP machine to compact the tows of the bandwidths as each of the bandwidths is being laid; and causing the AFP machine to vary fiber orientations of the plies defining the gaps, whereby the gaps define the holes of the pattern of holes. The method further involves curing the layup and selecting a resin having a controlled flow characteristic that prevents the resin from filling in the holes during the curing.

Spacing the tows may include varying the gaps between the tows.

The method may further involve varying the widths of the tows.

The method may further involve embedding at least one of a woven and a non-woven material within the plies of the layup.

The method may further involve selecting hole locations, hole sizes and hole shapes, and programming the automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form the pattern of holes.

The method may further involve causing the AFP machine to space the tows of each of the bandwidths to cause the gaps to define generally polygonal shaped openings between the tows.

According to one disclosed embodiment, a method is provided of producing a composite laminate having a pattern of holes therein. The method

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comprises forming a layup by laying up multiple plies of unidirectional fiber reinforced resin ("pre-preg"), each of the plies having a fiber orientation and including multiple fiber reinforced resin tows having gaps therebetween. The fiber orientations of the plies in the layup are varied to form a pattern of holes in the composite laminate. The method may further comprise controlling the gaps between the tows of each of the plies, and varying a width of the tows. Laying up the multiple plies is performed automatically by a numerically controlled fiber placement machine. The method may also include embedding at least one of a woven or a non-woven material within the multiple plies. The method may further comprise selecting a hole pattern, and programming an automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form the selected hole pattern. The method may include selecting a hole size and shape, and programming the automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form holes having the selected hole size and shape. The method may further comprise curing the layup, and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing. The layup may be cured using an out-of-autoclave that uses vacuum pressure to help control flow of the resin, although autoclave curing may also be possible.

According to another disclosed embodiment, a method is provided of producing a composite laminate layup having pattern of holes therein. A layup is formed by laying up multiple plies of unidirectional pre-preg fiber, wherein each of the plies is laid up by laying down bandwidths of pre-preg fiber tows. The method also includes spacing apart the tows in each of the bandwidths to form gaps between the tows as the bandwidths are being laid down, and controlling locations of the tows as the bandwidths are being laid down. The gaps between the tows are controlled as the bandwidths are being laid down, and the fiber orientations of the plies are varied to form a pattern of holes in the layup. Each of the plies is laid up using a numerically controlled automated fiber placement machine. Spacing the tows includes varying the gaps between the tows. The method may further comprise varying a width of the tows. At least one of a woven or a non-woven material may be embedded within the plies of the layup. The method may also include selecting hole locations, hole sizes and hole shapes, and programming an automated fiber placement machine to automatically layup the plies and vary the fiber orientations of the plies to form the pattern of holes. The method may further comprise curing the layup, and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing.

According to still another embodiment, a composite laminate is provided having a pattern of holes therein. The laminate comprises a plurality of spaced-apart fiber tows having varying fiber orientations arranged to form a pattern of holes in the laminate, and a resin matrix in which the fiber tows are embedded. The fiber tows are arranged in a plurality of plies having differing fiber orientations, and the fiber tows have varying widths. The holes each may have a polygonal shape. The resin matrix may be a thermally curable thermoset material or a thermoplastic, and possesses a flow characteristic that prevents the material from flowing into the holes during thermal curing.

According to another embodiment, a composite laminate layup contains a pattern of holes therein. The laminate layup comprises a plurality of plies of fiber reinforced resin, wherein each of the plies has a unidirectional fiber orientation and including multiple pre-preg tows having gaps therebetween. The plies are arranged such that the gaps between the pre-preg tows form a pattern of holes in the layup. The resin is thermally curable and has flow characteristics during curing that prevent the resin from flowing into the holes. The gaps between the pre-preg tows vary, and the width of the tows varies from ply to ply.

In one embodiment there is provided a method of producing a composite laminate having a pattern of holes therein, including forming a layup by laying up multiple plies of fiber reinforced resin, each of the plies having a fiber orientation and including multiple fiber reinforced resin tows having gaps therebetween; and varying the fiber orientations of the plies in the layup to form a pattern of holes in the composite laminate.

The method may further include controlling the gaps between the tows of each of the plies.

Laying up the multiple plies may include using tows having at least two differing widths respectively in at least two of the plies.

Laying up the multiple plies may be performed automatically by a numerically controlled fiber placement machine.

The method may further include embedding at least one of a woven and a non-woven material within the multiple plies.

The method may further include selecting a hole pattern; and programming an automatic fiber placement machine to automatically lay up the plies using spaced apart tows and to vary the fiber orientations of the plies to form the selected hole pattern.

The method may further include selecting a hole size and shape; and programming the automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form holes having the selected hole size and shape.

The method may further include curing the layup; and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing.

Curing the layup may be performed using one of an out-of-autoclave and an autoclave curing process.

In another embodiment there is provided a method of producing a composite laminate layup having pattern of holes therein, including forming a layup by laying up multiple plies of unidirectional pre-preg fiber, each of the plies being laid up by laying down bandwidths of pre-preg fiber tows; spacing the tows in each of the bandwidths apart from each other to form gaps between the tows as the bandwidths are being laid down; controlling locations of the tows as the bandwidths are being laid down; controlling the gaps between the tows as the bandwidths are being laid down; and varying fiber orientations of the plies to form a pattern of holes in the layup.

Each of the plies may be laid up using a numerically controlled automatic fiber placement machine.

Spacing the tows includes varying the gaps between the tows.

The method may further comprise varying a width of the tows.

The method may further include embedding at least one of a woven and a non-woven material within the plies of the layup.

The method may further include selecting hole locations, hole sizes and hole shapes; and programming an automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form the pattern of holes.

The method may further include curing the layup; and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing.

According to yet another embodiment there is provided a composite laminate having a pattern of holes therein, including a plurality of spaced-apart fiber tows having varying fiber orientations arranged to form a pattern of holes in the laminate; and a resin matrix in which the fiber tows are embedded.

The fiber tows may be arranged in a plurality of plies having differing fiber orientations.

The fiber tows may have varying widths.

The holes may each have a polygonal shape.

The resin matrix may be a thermally curable thermoset material and possesses a flow characteristic that prevents the thermoset material from flowing into the holes during thermal curing.

In another embodiment there is provided a composite laminate layup containing a pattern of holes therein, including a plurality of plies of fiber reinforced resin, each of the plies having a unidirectional fiber orientation and including multiple pre-preg tows having gaps therebetween; and the plies being arranged such that the gaps between the pre-preg tows form a pattern of holes in the layup.

The resin may be thermally curable and has flow characteristics during curing that prevent the resin from flowing into the holes.

The gaps between the pre-preg tows may vary.

Each of the tows may have a width, and the width of the tows may vary from ply to ply.

The features, functions, and advantages can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

Figure **1** is an illustration of a perspective view of a composite laminate having a hole pattern formed according to the disclosed method.

Figure **1**A is an illustration of the area designated as “FIG. **1**A” in Figure **1**.

Figure **2** is an illustration of the area designated as FIG. **2** in Figure **1**.

Figure **3** is an illustration of a sectional view taken along the line **3-3** in Figure **2**.

Figure **3**A is an illustration similar to Figure **3** but showing an alternate embodiment of the composite laminate having an embedded layer of porous material.

Figure **4** is an illustration of a plan view of the area designated as FIG. **4** in Figure **2**.

Figure **5** is an illustration of a plan view showing a hole having a hexagonal shape.

Figure **6** is an illustration of a plan view of a hole having an octagonal shape.

Figure **7** is an illustration of a plan view of a hole having a round shape.

Figure **8** is an illustration of a plan view showing a ply having a **0**° fiber orientation.

Figure **8**A is an illustration of the area designated as FIG. **8**A in Figure **8**.

Figure **9** is illustration of a plan view of a ply having a **90**° fiber orientation.

Figure **10** is an illustration of a plan view of a ply having a +**45**° fiber orientation.

Figure **11** is an illustration of a plan view of a ply having -**45**° fiber orientation.

Figure **12** is an illustration of a plan view of several overlaid courses of tows arranged to form a desired hole pattern according to the disclosed method.

Figure **12**A is an illustration of the area designated as FIG. **12**A in Figure **12**.

Figure **13** is an illustration of a typical ply schedule for fabricating a composite laminate having a controlled hole pattern.

Figure **14** is an illustration of a combined block and diagrammatic view showing the components of an automated fiber placement system used to fabricate composite laminates having controlled hole patterns.

Figure **15** is an illustration of a block diagram showing individually controllable tow control modules forming part of a tape applicator head shown in Figure **14**.

Figure **16** is an illustration of a perspective view of a portion of a wing showing an engine having an acoustically treated inlet employing the disclosed composite laminate.

Figure **17** is an illustration of a cross-sectional view of a portion of an acoustic panel taken along the line **17**-**17** in Figure **16**.

Figure **18** is illustration of a flow diagram of a method of fabricating a composite laminate having a controlled hole pattern.

Figure **19** is an illustration of a flow diagram of a method of producing a composite laminate layup having a controlled hole pattern.

Figure **20** is an illustration of a flow diagram of aircraft production and service methodology.

Figure **21** is illustration of a block diagram of an aircraft.

DETAILED DESCRIPTION

Referring to Figures **1**-**3**, a composite laminate **30** includes a plurality of perforations or holes **34** therein which are arranged in a pattern **32**, sometimes hereinafter referred to as a hole pattern **32**. In the illustrated embodiment, the holes **34** pass completely through the depth "**D**" of the laminate **30**, however it may be possible to form the holes **34** only partially through the thickness of "**D**". In the illustrated embodiment, the hole pattern **32** is a regular pattern in which the holes **34** arranged in a matrix, however in other embodiments the hole pattern **32** may be irregular, depending upon the application. The laminate **30** comprises a plurality of plies **33** (Figure **1**A) of a fiber reinforced resin such as, without limitation, carbon fiber epoxy or other thermoset, or a fiber reinforced thermoplastic.

In some embodiments, as shown in Figure **3**A, one or more layers **35** of material may be embedded between the plies **33** in order to tailor the laminate **30** to particular applications. The embedded layer **35** may be a woven or non-woven material, or a combination of woven and non-woven materials. For example, the embedded layer **35** may comprise a plastic or wire mesh that functions to improve the acoustical properties of the laminate **30**.

Referring to Figures **1** and **4**, each of the plies **33** may comprise unidirectional fiber reinforced resin. For example, and without limitation, the unidirectional fiber reinforced resin may comprise fiber tape or tows **36** (slit tape) pre-impregnated with a thermoset or thermoplastic resin. The tows **36** may be produced, for example and without limitation, by slitting pre-preg tape to a desired width "**W**". As will be discussed below in more detail, the tows **36** are spaced apart from each other and have fiber orientations that result in holes **34** which pass through the plies of **33**.

In the embodiment illustrated in Figures **1-4**, the holes **34** have a substantially square shape, however other hole shapes are possible. For example, and without limitation, the plies of **33** may be laid up in a manner to produce holes **34**a having a hexagonal shape shown in Figure **5**, or an octagonal shape **34**b shown in Figure **6**. Depending upon the number of plies **33**, it may be possible to produce holes **34**c having a nearly circular shape as shown in Figure **7**. In addition to controlling the shape of the holes **34**, the size or maximum cross sectional dimension "**D**" may also be controlled using the disclosed method.

The laminate **30** is formed by laying up multiple plies **33** (see Figure **1**) of unidirectional pre-preg fiber in which the plies have a varying fiber orientations. For example, referring to Figures **8**, **9**, **10** and **11**, the laminate **30** may comprise plies **33**a, **33**b, **33**c, **33**d respectively having fiber orientations of **0**°, **90**°, +**45**° and -**45**° respectively. Other ply orientations are possible depending upon the application, and the desired size and shape of the holes **34**. Referring to Figure **8**A, each of the plies of **33** may be formed by laying down substantially parallel courses **38** of pre-preg tows **36**, wherein the tows **36** in each course **38** are spaced apart from each other a desired distance to form gaps "**G**" between the tows **36**. The size, shape and location of the holes **34** in the hole pattern **32** are determined by the fiber orientation of the plies **33**, the location of the tows **36**, the width "**W**" of the tows **36** and the size of the gaps "**G**".

Attention is now directed to Figures **12** and **12**A which illustrate four superimposed courses **38**a, **38**b, **38**c, **38**d which respectively form part of the plies **33**a, **33**b, **33**c, **33**d shown in Figures **8-11**. The tows **36** in each course **38** have a desired width "W" and are spaced apart to form a desired gap "G" therebetween. The gaps "G" are formed by controlling the positions of the tows **36** relative to each other as the courses **38** are being laid down to form the plies **33**. The tows **36** in each course **38** may be laid down in a single bandwidth **50** using, for example, automated fiber placement equipment, discussed below in more detail. The courses **38**, and thus the plies **33** have fiber orientations arranged relative to a reference direction, which in the illustrated example, is the X direction (**45**) which corresponds to a **0**° orientation.

Figure **13** is a typical ply schedule for a composite laminate **30** (Figure **1**) having a desired hole pattern **32**. In this example, the ply schedule calls for a laminate comprising **8** plies **33**, respectively having fiber orientations **56** of **0**°, **+45**°, **90**°, **-45**°, **-45**°, **90**°, **+45**°, and **0**°. The tow courses **38**a, **38**b, **38**c, **38**d shown in Figure **12** respectively form portions of plies **1-4** shown in the ply schedule of the Figure **13**. The gaps "G" are determined by the location of the centerlines **55** (Figure **12**) of the tows **36**. The gaps "**G**", the width "**W**" of the tows **36** and the fiber orientation of the plies of **33** determine the size, location and shape of the holes **34** in the hole pattern **32**.

Each of the plies of **33** of the laminate **30** may be laid up using any of several known automated fiber placement (AFP) machines. For example, the components of one known AFP machine are broadly shown in Figure **14**. A fiber applicator head **58** may be mounted on a manipulator **77** which is controlled by a controller **76** operated by one or more numeric control programs **74**. The controller **76** may comprise a general purpose computer or a programmable logic controller (PLC). The controller **76** and the manipulator **77** move applicator head **58** over a substrate **64** in a desired direction **66** to lay down multiple courses **38** of tows **36** with a desired fiber orientation according to a ply schedule chosen for the application.

The gaps "**G**" between the tows **36** are not shown in Figure **14** for simplicity of illustration. The tows **36** may be fed through a collimator **70** which aligns and spaces the tows **36** apart. The aligned tows **36** are delivered through feed and guide rollers **72** and are cut to a desired course length by one or more cutters **60**. The tows **36** are then applied to the substrate **64** and compacted by a roller **68**. In some embodiments, a single applicator head **58** may be used to layup all of the plies **33** in the laminate **30**. However, multiple applicator heads supplied with tows of differing widths "W" may be used to layup the laminate. For example, in Figure **14**, a second applicator head **81** mounted on a second manipulator **79** is operated by the controller **76** in synchronization with applicator head **58** in order to speed up the layup process.

The applicator heads **58**, **81** shown in Figure **14** may employ a known tow control arrangement of the type illustrated in Figure **15**. A plurality of on-board tow feeds **85** deliver tows **36** from an onboard tow supply (not shown) to individual tow control modules **83**. The tow control modules **83** are laterally movable **91** to adjust the gap "**G**" between adjacent tows **36** in each course **38**.

As previously discussed, the laminate **30** having a controlled hole pattern **32** may be used in a variety of acoustical treatment applications. For example, referring now to Figure **16**, a high bypass engine **78** is mounted to an aircraft wing **82** by a pylon **80**. The engine **78** includes a surrounding engine nacelle **84** having an air inlet **86**. The air inlet **86** includes an acoustically treated area **88** in the form of an acoustic panel **87** for reducing noise caused by the spinning blades in the engine **78**.

Attention is now directed to Figure **17** which is a cross sectional view illustrating additional details of the acoustic panel **87**. The panel **87** broadly comprises a cellular honeycomb core **89** sandwiched between inner and outer facesheet **92**, **102**, respectively. The inner facesheet **92** includes a multiplicity of perforations therethrough **44** which allow soundwaves including noise to pass through the inner facesheet **92** into the core **89**. The disclosed composite laminate **30** having a controlled hole pattern may be used as the inner facesheet **92**. The inner facesheet **92** is attached to the face of the honeycomb core **89** by an adhesive bond line **94**. Similarly, the outer facesheet **102** is attached to the other face of the honeycomb core **89** by an adhesive bond line **100**.

In the illustrated embodiments, the inner and outer facesheets **92**, **102** respectively each comprise a laminated composite such as a CFRP (carbon fiber reinforced plastic) or a fiber reinforced thermoplastic however, either of these facesheets may include other materials such as, without limitation, a ceramic or a metal such as aluminum. The honeycomb core **89** may comprise a metal such as aluminum, a polymer or other materials and is formed of a multiplicity of individual polygonal cells **96**. In the illustrated example, the cells **96** are hexagonal, however other cell geometries are possible. The honeycomb core **89** is septumized by a plurality of individual septums **98** that are positioned within the cells **96** at a preselected depth "**D**". The septa **98** assist in dampening and attenuating soundwaves entering honeycomb core **89** through the perforations **90** in the inner facesheet **92**.

Figure **18** broadly illustrates the overall steps of a method of producing a composite laminate having a desired pattern **32** of holes **34** therein. At step **104**, a multi-ply layup **30** is formed using pre-preg tows **36** which have gaps "**G**" therebetween. At **106**, the fiber orientations of the plies **33** are varied in order to form a pattern **32** of holes **34** in the laminate **30**.

Figure **19** broadly illustrates the overall steps of a method of producing a composite laminate layup having a pattern **32** of holes **34** therein. At step **108**, the layup is formed by laying a multiple plies **33** of unidirectional pre-preg fibers. Laying up the plies **33** may be carried out by laying down bandwidths **50** of pre-preg fiber tows **36**. At step **110**, the tows **36** in each of the bandwidths **50** are spaced apart from each other to form a gaps "**G**" between the tows **36** as the bandwidths **50** are being laid down. At step **112**, the locations of the tows **36** are controlled as the bandwidths **50** are being laid down. Similarly, at step **114**, the gaps "**G**" between the tows **36** are controlled as the bandwidths **50** are being laid down. At step **116**, the fiber orientations of the plies **33** are varied in order to form a pattern **32** of holes **34** in the layup. The completed laminate may be cured using an out-of-autoclave process in which vacuum pressure is employed to help control flow of the resin, and prevent the resin from filling in the holes **34** during curing. Alternatively, it may be possible to cure the laminate **30** in an autoclave, providing that a resin is used having a higher viscosity which provides the resin with flow characteristics that prevents the resin from filling in the holes **34** during curing.

Embodiments described herein may find use in a variety of potential applications, particularly in the transportation industry, including for example, aerospace, marine, automotive applications and other application where composite laminates having controlled hole patterns may be used. Thus, referring now to Figures **20** and **21**, embodiments of the disclosure may be used in the context of an aircraft manufacturing and service method **118** as shown in Figure **20** and an aircraft **120** as shown in Figure **21**. Aircraft applications of the disclosed embodiments may include, for example, without limitation, acoustical panels to attenuate sound, or to alter air flow over airfoils. During pre-production, exemplary method **118** may include specification and design **122** of the aircraft **120** and material procurement **124**. During production, component and subassembly manufacturing **126** and system integration **128** of the aircraft **120** takes place. The disclosed embodiments may be employed during component and subassembly manufacturing of parts having controlled hole patterns. Thereafter, the aircraft **120** may go through certification and delivery **130** in order to be placed in service **132**. While in service by a customer, the aircraft **120** is scheduled for routine maintenance and service **134**, which may also include modification, reconfiguration, refurbishment, and so on. During maintenance and service **134**, replacement components or subassemblies may be installed on the aircraft **122** which may include hole patterns formed by the disclosed method.

Each of the processes of method **118** may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). 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 be an airline, leasing company, military entity, service organization, and so on.

As shown in Figure **21**, the aircraft **120** produced by exemplary method **118** may include an airframe **136** with a plurality of systems **138** and an interior **140**. Examples of high-level systems **138** include one or more of a propulsion system **142**, an electrical system **144**, a hydraulic system **146** and an environmental system **148**. Any number of other systems may be included. The disclosed method may be employed to produce components and subassemblies forming part of the airframe **136** and/or propulsion system **142**. For example, the disclosed method may be used to produce acoustic panels having controlled hole patterns that reduce noise generated by engines forming part of the propulsion system **142**. Similarly, the disclosed method may be used to produce panels or skins having controlled hole patterns that form part of the airframe **136**, or which are used in the interior **140** to reduce noise. Although an aerospace example is shown, the principles of the disclosure may be applied to other industries, such as the marine and automotive industries.

Systems and methods embodied herein may be employed during any one or more of the stages of the production and service method **118**. For example, components or subassemblies corresponding to production process **126** may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft **120** is in service. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the production stages **126** and **128**, for example, by substantially expediting assembly of or reducing the cost of an aircraft **120**. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft **120** is in service, for example and without limitation, to maintenance and service **134**.

As used herein, the phrase "at least one of", when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, "at least one of item A, item B, and item C" may include, without limitation, item A, item A and item B, or item B. This example also may include item A, item B, and item C or item B and item C. The item may be a particular object, thing, or a category. In other words, at least one of means any combination items and number of items may be used from the list but not all of the items in the list are required.

In one embodiment there is provided a method of producing a composite laminate having a pattern of holes therein. The method involves forming a layup by laying up multiple plies of fiber reinforced resin, each of the plies having a fiber orientation and including multiple fiber reinforced resin tows having gaps therebetween, and varying the fiber orientations of the plies in the layup to form a pattern of holes in the composite laminate.

The method may further involve controlling the gaps between the tows of each of the plies.

Laying up the multiple plies may include using tows having at least two differing widths respectively in at least two of the plies.

Laying up the multiple plies may be performed automatically by a numerically controlled fiber placement machine.

The method may further involve embedding at least one of a woven and a non-woven material within the multiple plies.

The method may further involve selecting a hole pattern and programming an automatic fiber placement machine to automatically lay up the plies using spaced apart tows and to vary the fiber orientations of the plies to form the selected hole pattern.

The method may further involve selecting a hole size and shape and programming the automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form holes having the selected hole size and shape.

The method may further involve curing the layup and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing.

Curing the layup may be performed using one of an out-of-autoclave and an autoclave curing process.

In another embodiment there is provided a method of producing a composite laminate layup having pattern of holes therein. The method involves forming a layup by laying up multiple plies of unidirectional pre-preg fiber, each of the plies being laid up by laying down bandwidths of pre-preg fiber tows, spacing the tows in each of the bandwidths apart from each other to form gaps between the tows as the bandwidths are being laid down, controlling locations of the tows as the bandwidths are being laid down, controlling the gaps between the tows as the bandwidths are being laid down, and varying fiber orientations of the plies to form a pattern of holes in the layup.

Each of the plies may be laid up using a numerically controlled automatic fiber placement machine.

Spacing the tows may include varying the gaps between the tows.

The method may further involve varying a width of the tows.

The method may further involve embedding at least one of a woven and a non-woven material within the plies of the layup.

The method may further involve selecting hole locations, hole sizes and hole shapes and programming an automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form the pattern of holes.

The method may further involve curing the layup and selecting a resin having a controlled flow characteristic that substantially prevents the resin from filling in the holes during the curing.

In another embodiment there is provided a composite laminate having a pattern of holes therein including a plurality of spaced-apart fiber tows having varying fiber orientations arranged to form a pattern of holes in the laminate, and a resin matrix in which the fiber tows are embedded.

Fiber tows may be arranged in a plurality of plies having differing fiber orientations.

The fiber tows may have varying widths.

The holes may each have a polygonal shape.

Resin matrix may be a thermally curable thermoset material and possesses a flow characteristic that prevents the thermoset material from flowing into the holes during thermal curing.

In another embodiment there is provided a composite laminate layup containing a pattern of holes therein, including a plurality of plies of fiber reinforced resin, each of the plies having a unidirectional fiber orientation and including multiple pre-preg tows having gaps therebetween, and the plies being arranged such that the gaps between the pre-preg tows form a pattern of holes in the layup.

The resin may be thermally curable and has flow characteristics during curing that prevent the resin from flowing into the holes.

The gaps between the pre-preg tows may vary.

Each of the tows may have a width, and the width of the tows may vary from ply to ply.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different advantages as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED IS DEFINED AS FOLLOWS:

1. A method of producing a composite laminate layup having a pattern of holes therein, comprising:

causing an automated fiber placement (AFP) machine to lay up multiple plies of unidirectional pre-preg fiber, by simultaneously laying down bandwidths of pre-preg fiber tows on a substrate, the tows having widths and centerlines;

causing the AFP machine to cause the composite laminate layup to have the pattern of holes, by:

causing a collimator of the AFP machine to space the tows in each of the bandwidths apart from each other to define gaps between the tows as the bandwidths are being laid down to control first locations of the centerlines of the tows as the bandwidths are being laid down and to control the gaps between the tows as the bandwidths are being laid down;

causing a roller of the AFP machine to compact the tows of the bandwidths as each of the bandwidths is being laid; and

causing the AFP machine to vary fiber orientations of the plies defining the gaps, whereby the gaps define the holes of the pattern of holes;

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curing the layup; and

selecting a resin having a controlled flow characteristic that prevents the resin from filling in the holes during the curing.

2. The method of claim **1**, wherein spacing the tows includes varying the gaps between the tows.

3. The method of claim **1**, further comprising varying the widths of the tows.

4. The method of claim **1**, further comprising:

embedding at least one of a woven and a non-woven material within the plies of the layup.

5. The method of claim **1**, further comprising:

selecting hole locations, hole sizes and hole shapes; and

programming the automatic fiber placement machine to automatically lay up the plies and vary the fiber orientations of the plies to form the pattern of holes.

6. The method of any one of claims **1**-**5** further comprising causing the AFP machine to space the tows of each of the bandwidths to cause the gaps to define generally polygonal shaped openings between the tows.

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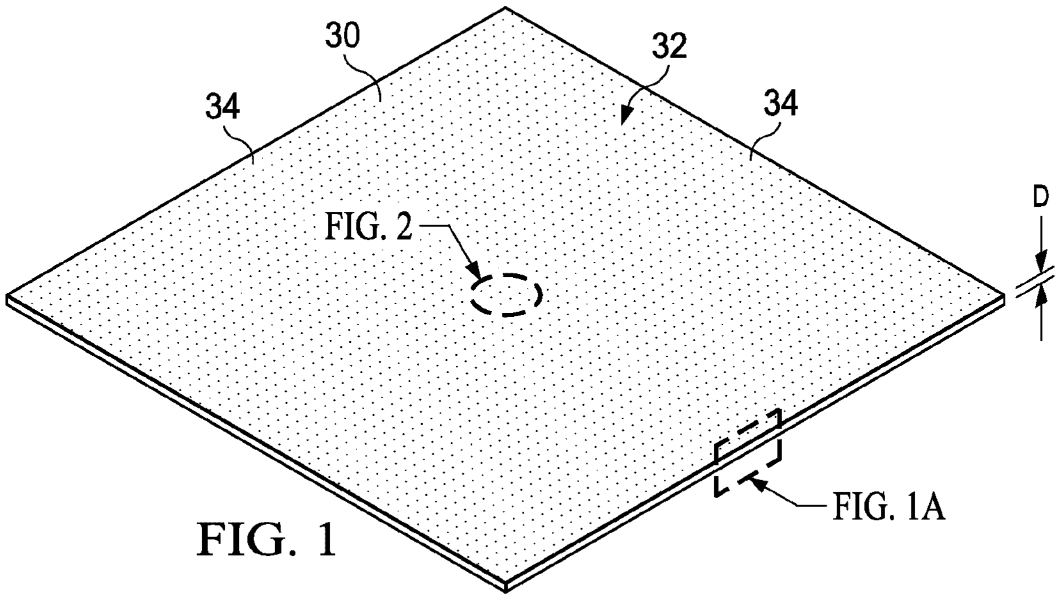


FIG. 1

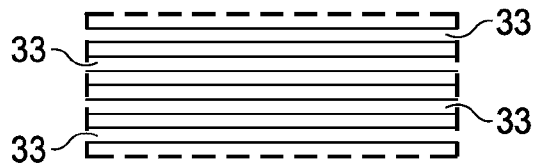


FIG. 1A

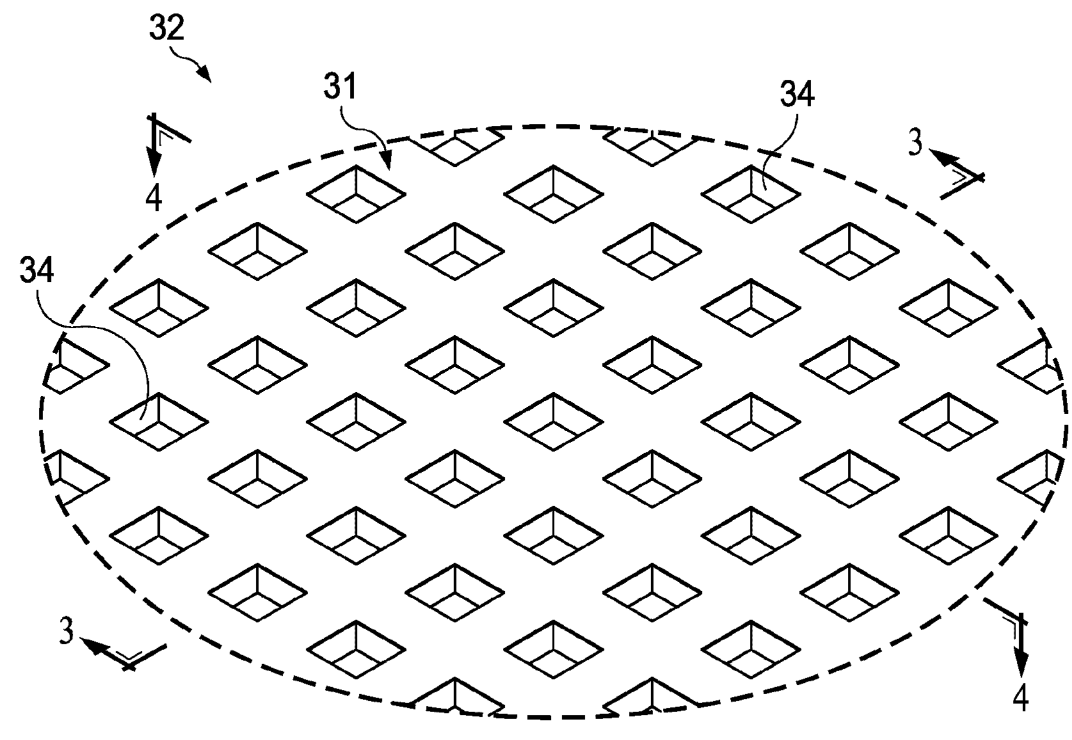


FIG. 2

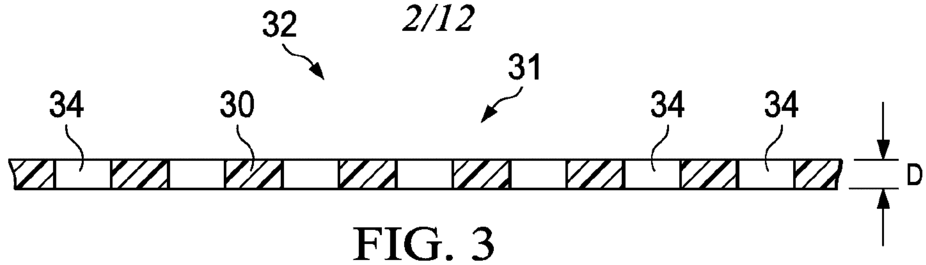


FIG. 3

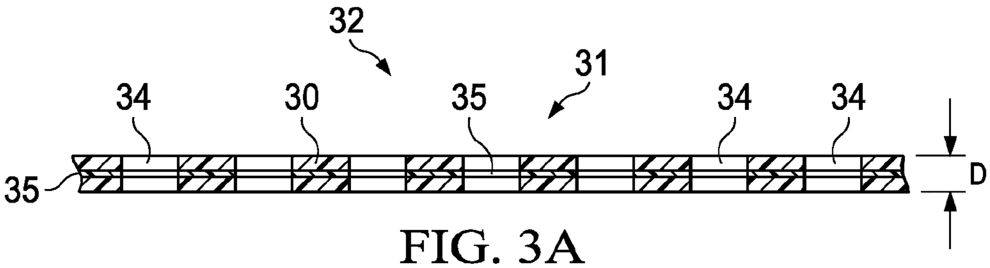


FIG. 3A

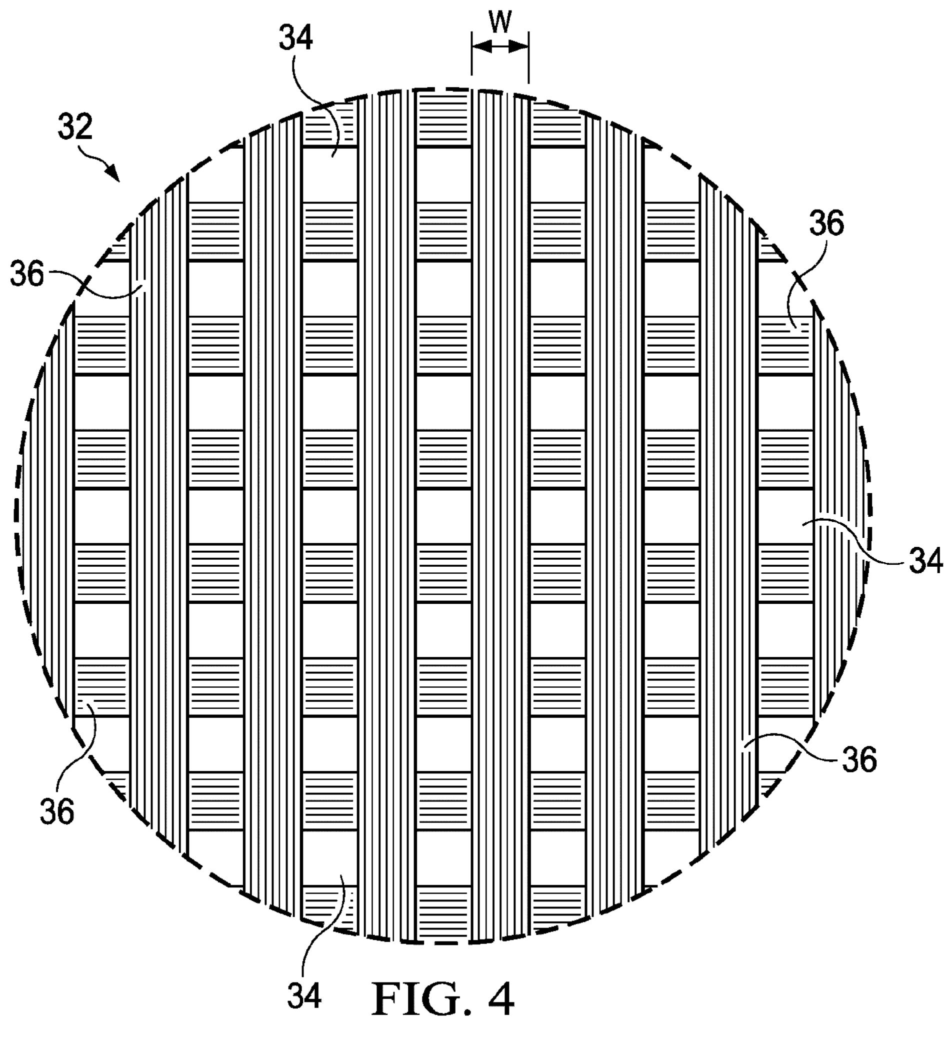


FIG. 4

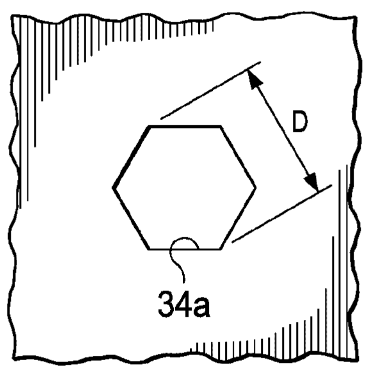


FIG. 5

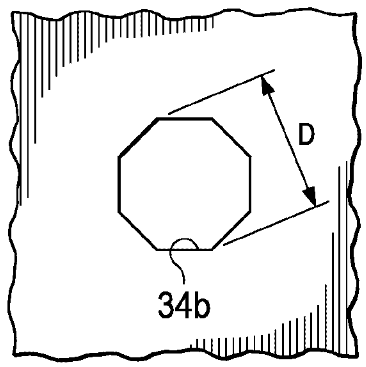


FIG. 6

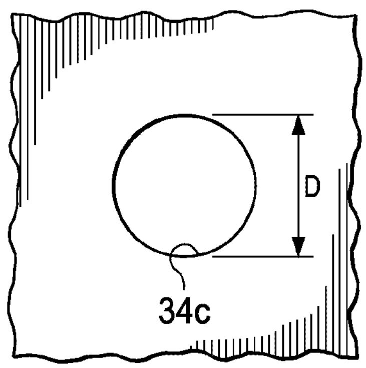


FIG. 7

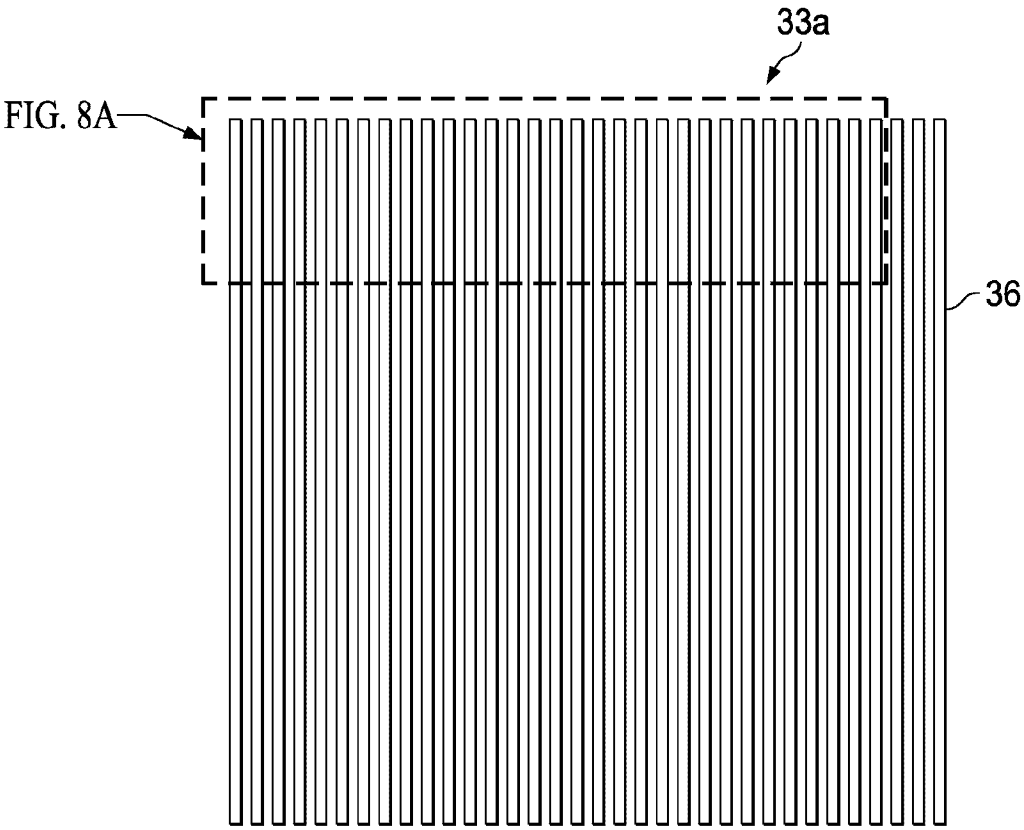


FIG. 8

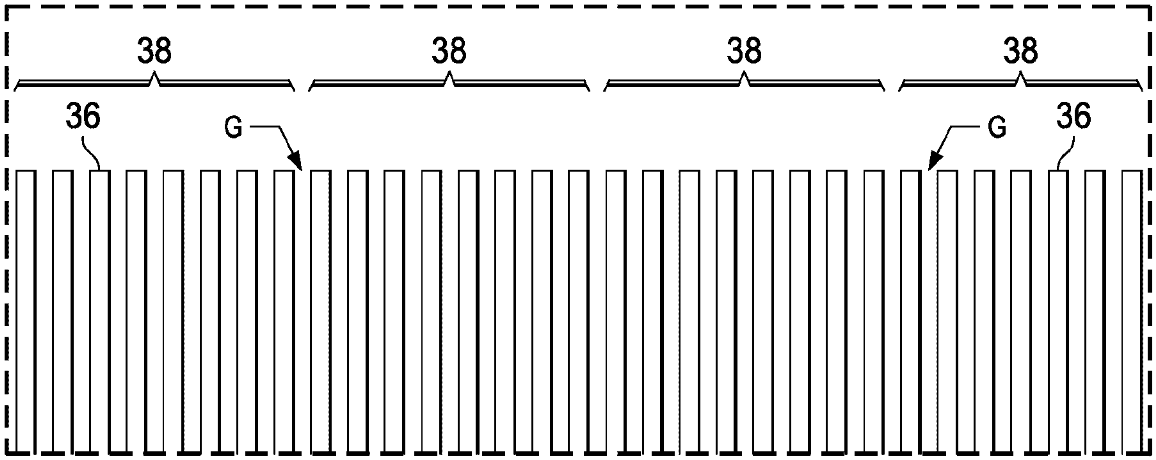


FIG. 8A

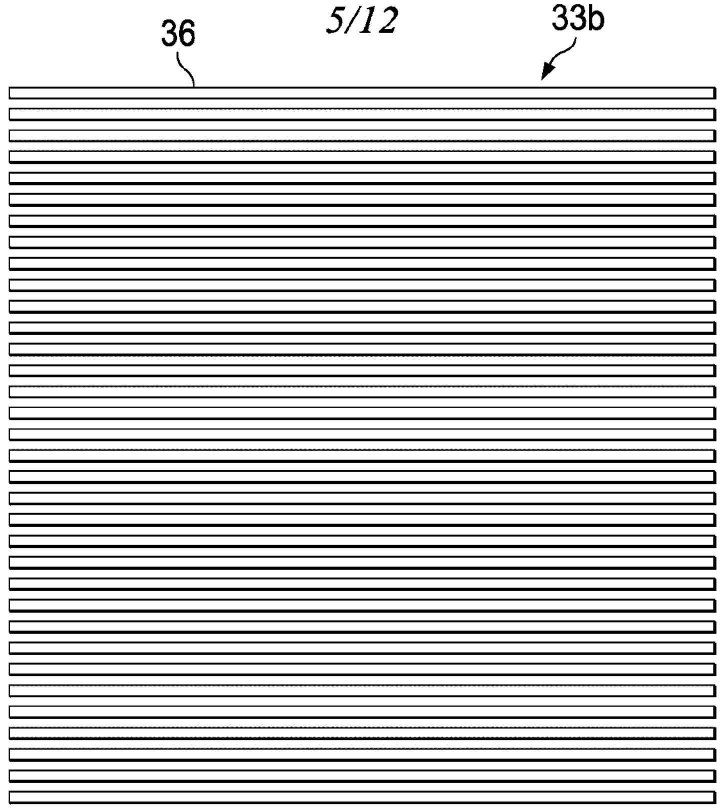


FIG. 9

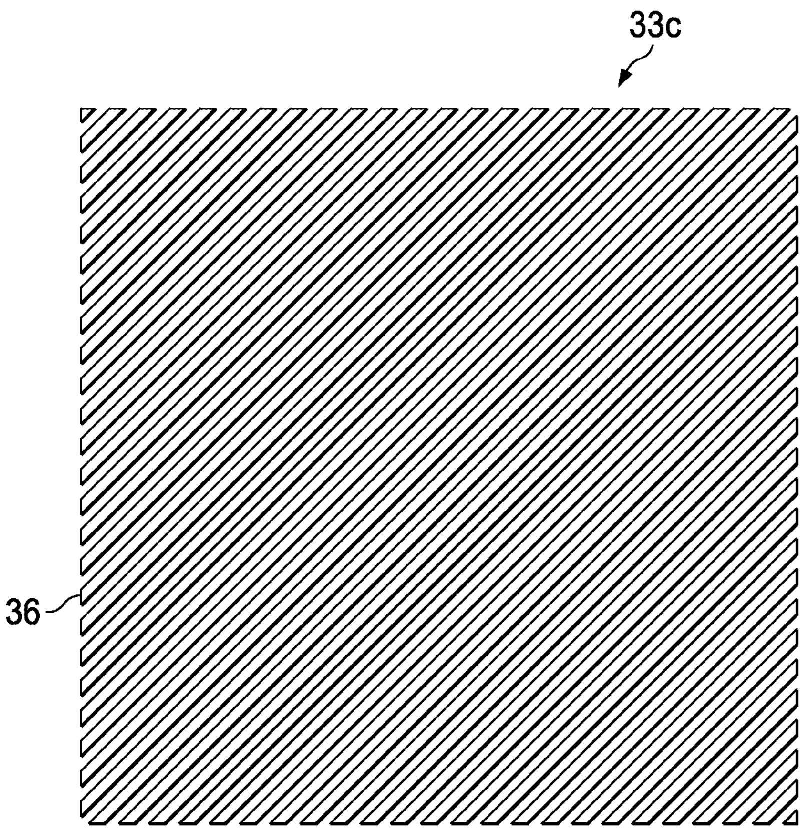


FIG. 10

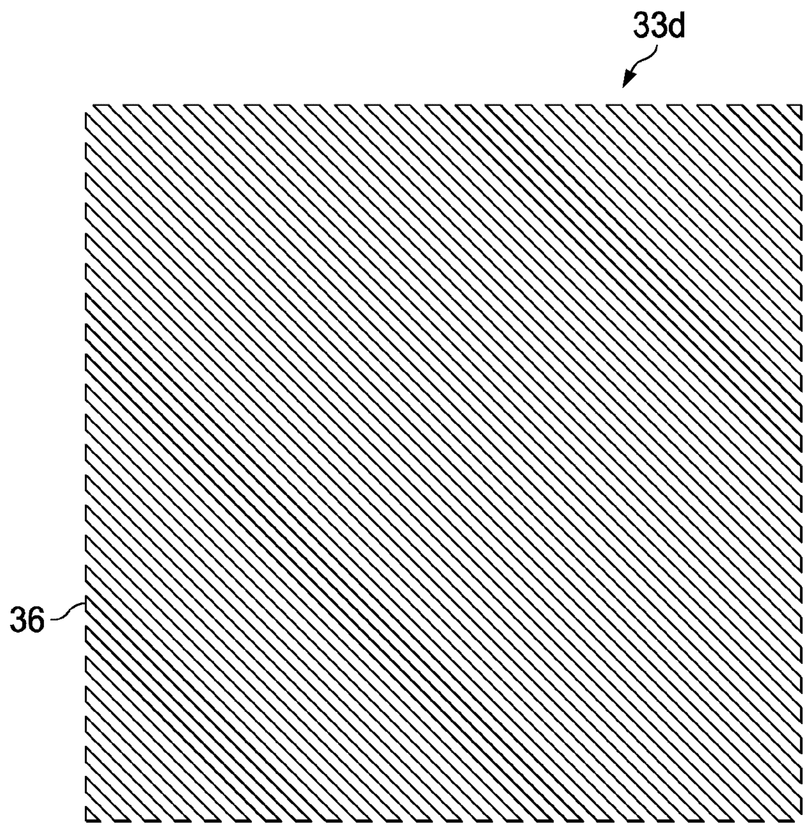


FIG. 11

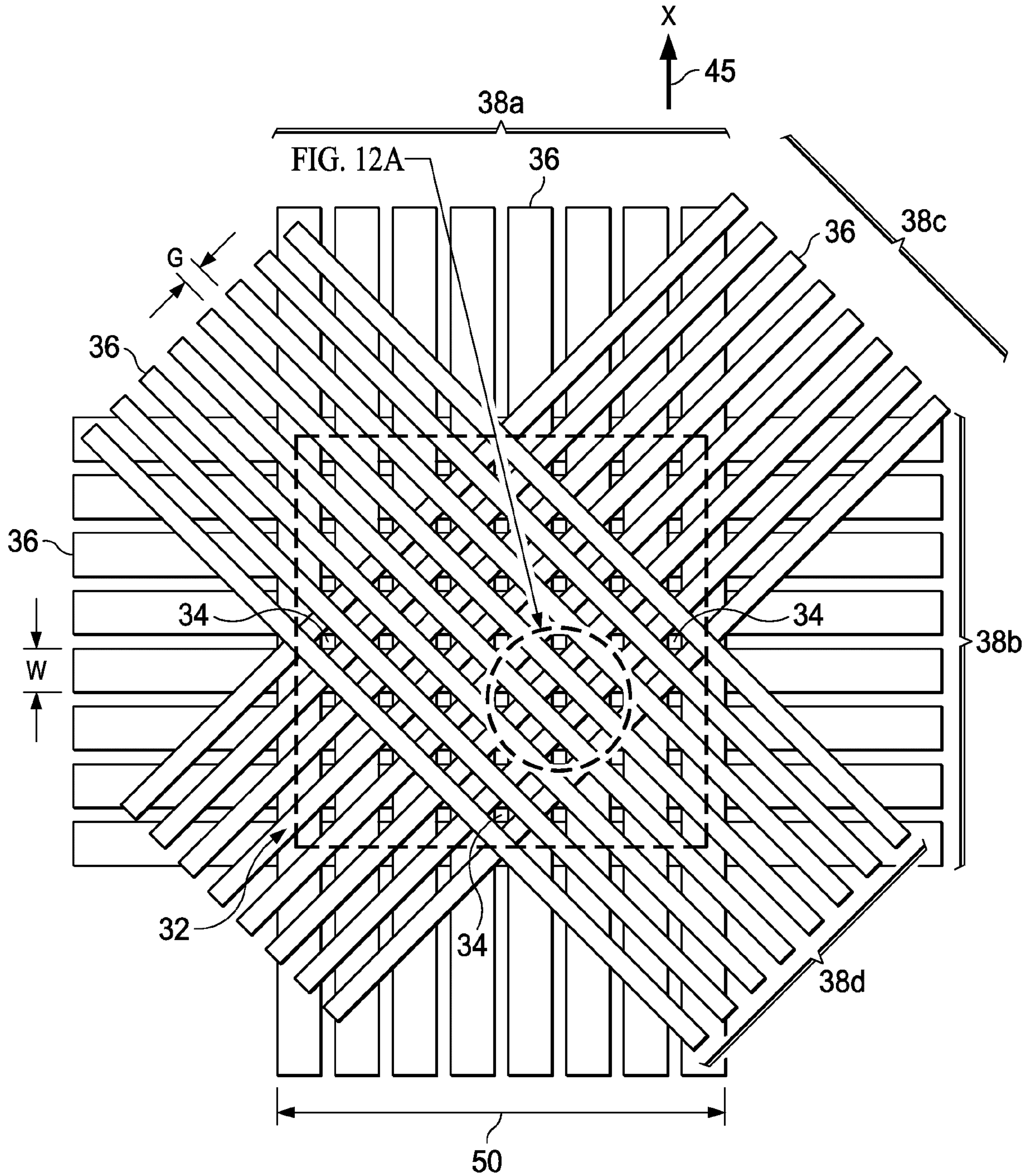


FIG. 12

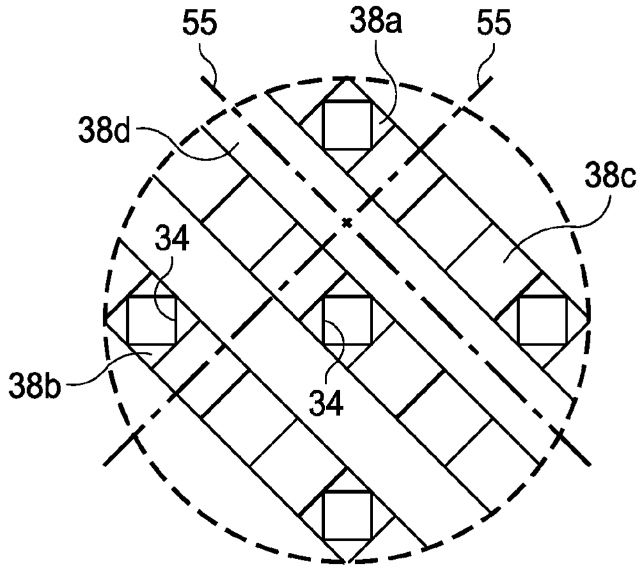


FIG. 12A

33 56

PLY	ORIENTATION
1	0°
2	45°
3	90°
4	-45°
5	-45°
6	90°
7	45°
8	0°

FIG. 13

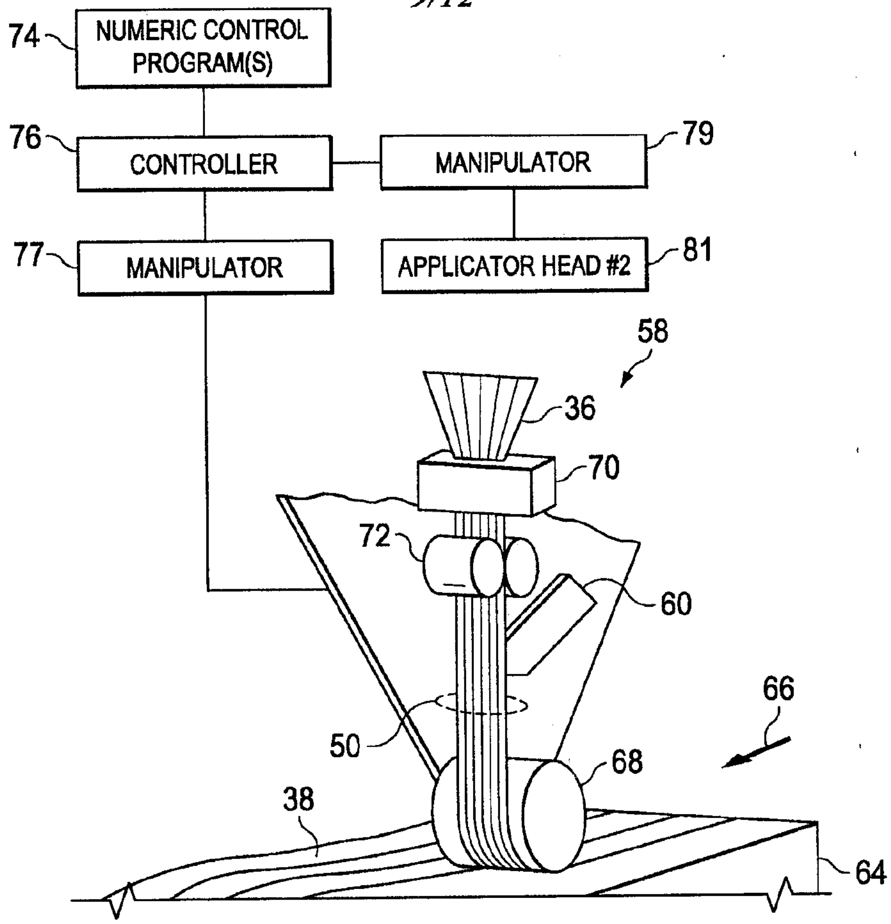

74
NUMERIC CONTROL PROGRAM(S)
76
CONTROLLER
MANIPULATOR
79
77
MANIPULATOR
APPLICATOR HEAD #2
81
58
36
70
72
60
66
50
68
38
64

FIG. 14

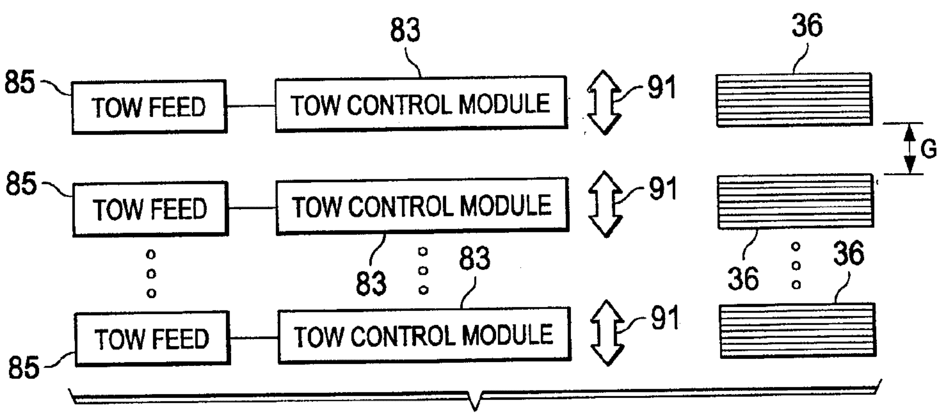
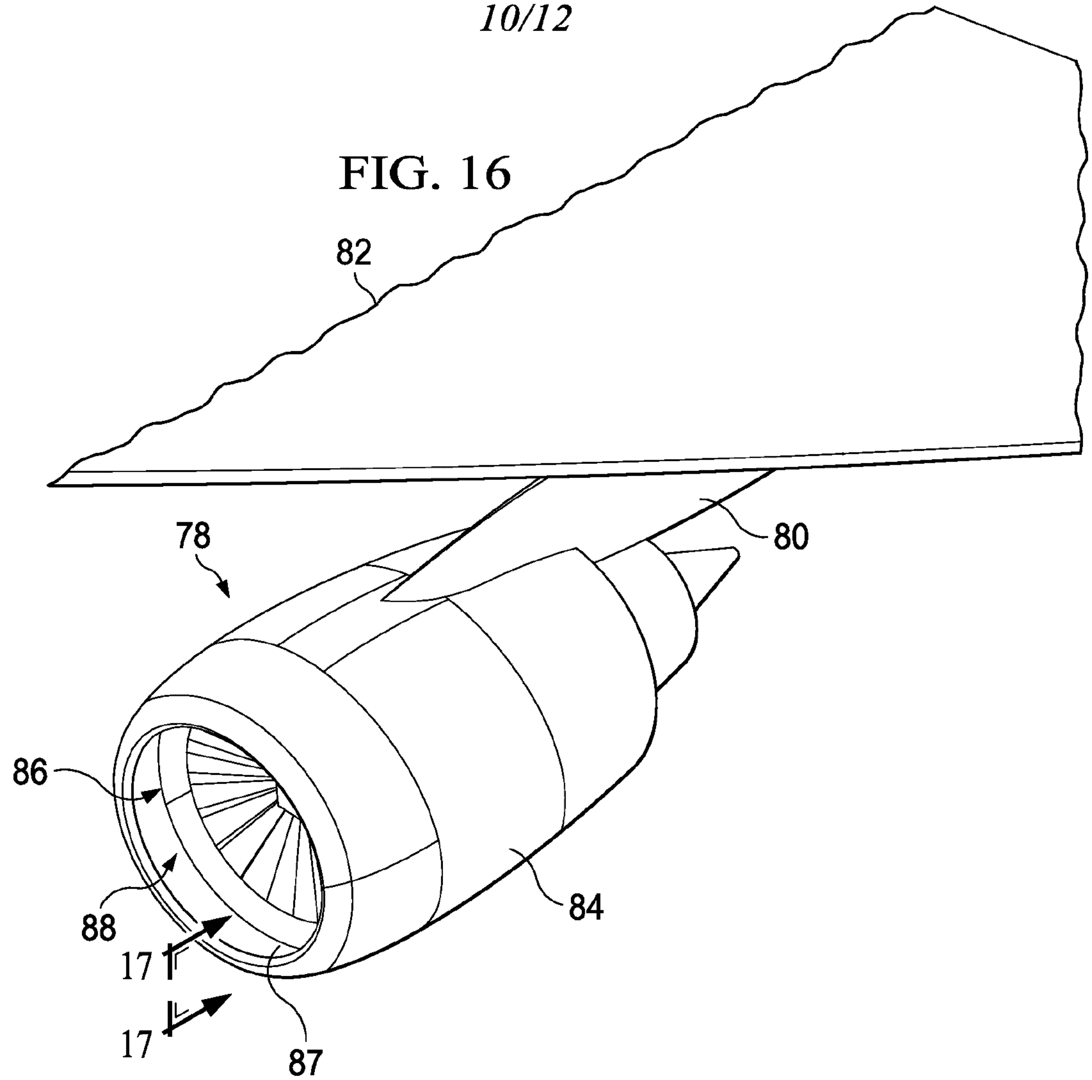

83
36
85
TOW FEED
TOW CONTROL MODULE
91
G
85
TOW FEED
TOW CONTROL MODULE
91
83
83
36
36
TOW FEED
TOW CONTROL MODULE
91
85

FIG. 15

FIG. 16


82
78
80
86
84
88
17
17
87

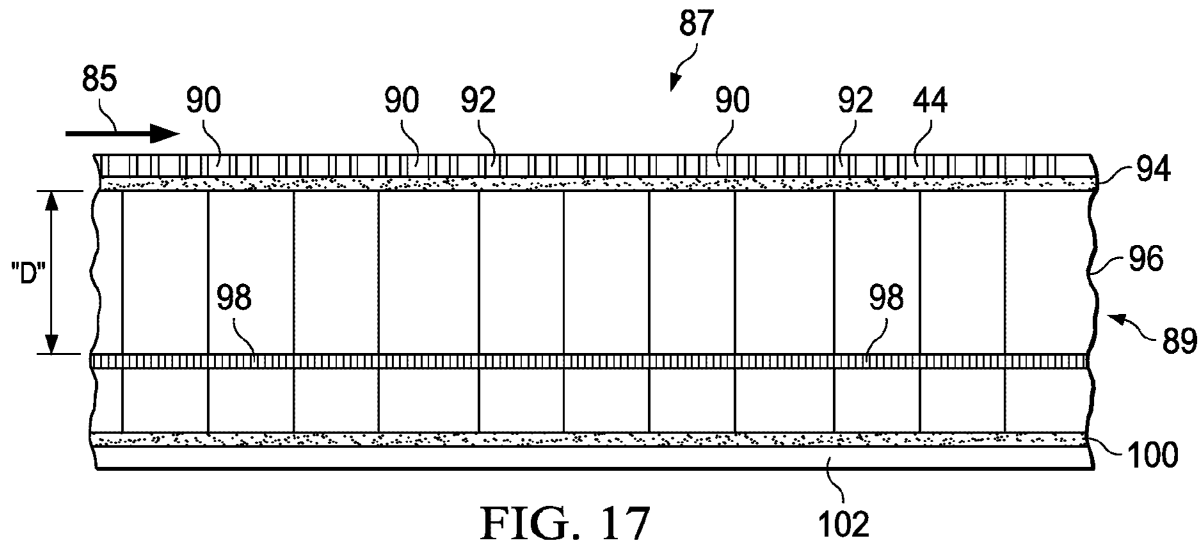

87
85
90
90
92
90
92
44
94
"D"
96
98
98
89
100
102

FIG. 17

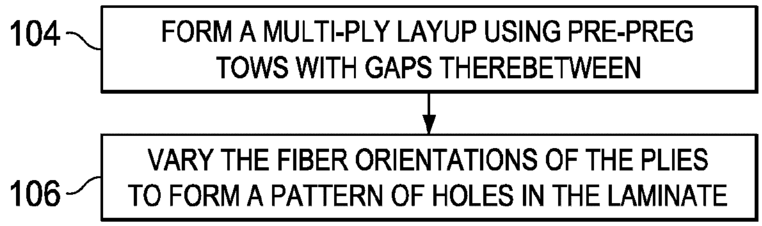

104
FORM A MULTI-PLY LAYUP USING PRE-PREG TOWS WITH GAPS THEREBETWEEN
106
VARY THE FIBER ORIENTATIONS OF THE PLIES TO FORM A PATTERN OF HOLES IN THE LAMINATE

FIG. 18

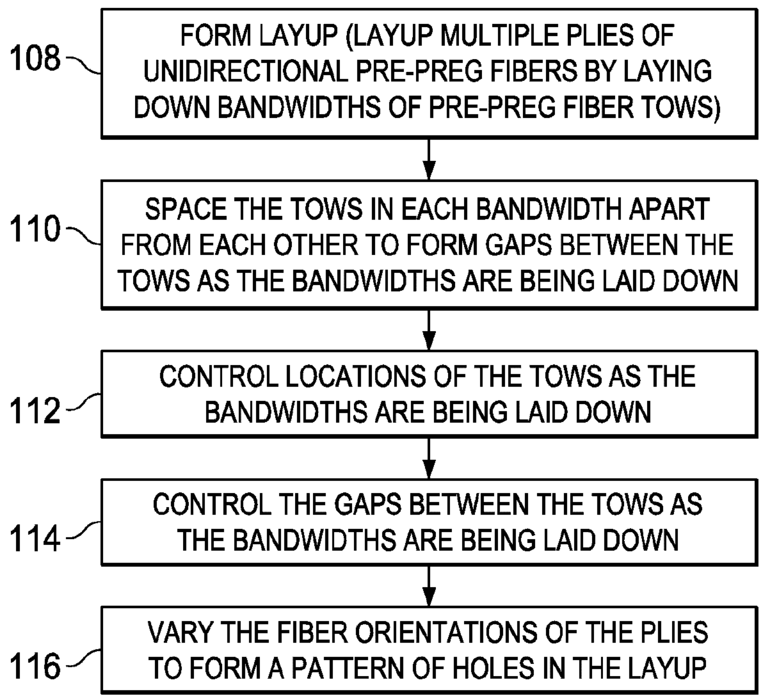

108
FORM LAYUP (LAYUP MULTIPLE PLIES OF UNIDIRECTIONAL PRE-PREG FIBERS BY LAYING DOWN BANDWIDTHS OF PRE-PREG FIBER TOWS)
110
SPACE THE TOWS IN EACH BANDWIDTH APART FROM EACH OTHER TO FORM GAPS BETWEEN THE TOWS AS THE BANDWIDTHS ARE BEING LAID DOWN
112
CONTROL LOCATIONS OF THE TOWS AS THE BANDWIDTHS ARE BEING LAID DOWN
114
CONTROL THE GAPS BETWEEN THE TOWS AS THE BANDWIDTHS ARE BEING LAID DOWN
116
VARY THE FIBER ORIENTATIONS OF THE PLIES TO FORM A PATTERN OF HOLES IN THE LAYUP

FIG. 19

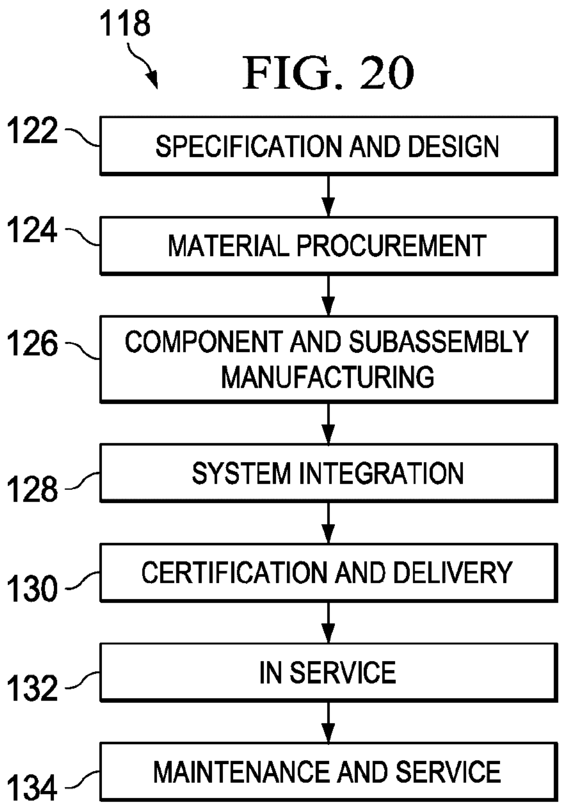

118
122
SPECIFICATION AND DESIGN
124
MATERIAL PROCUREMENT
126
COMPONENT AND SUBASSEMBLY MANUFACTURING
128
SYSTEM INTEGRATION
130
CERTIFICATION AND DELIVERY
132
IN SERVICE
134
MAINTENANCE AND SERVICE

FIG. 20

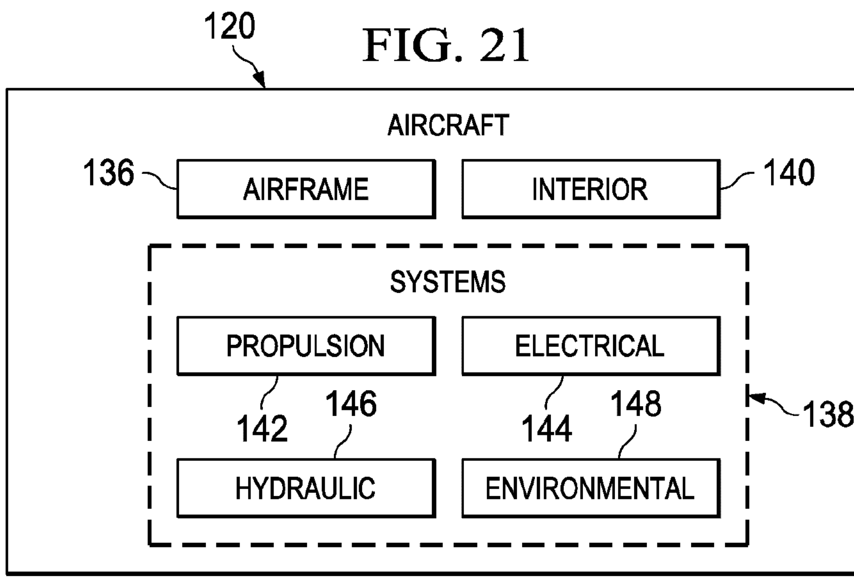
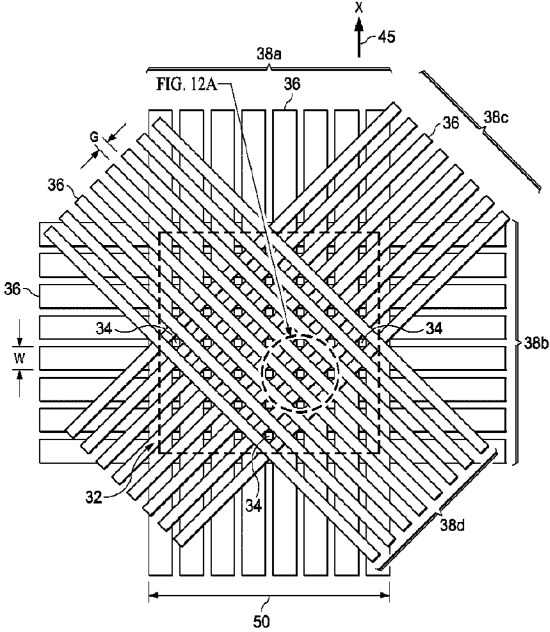

120
AIRCRAFT
136
AIRFRAME
INTERIOR
140
SYSTEMS
PROPULSION
ELECTRICAL
142
146
144
148
138
HYDRAULIC
ENVIRONMENTAL

FIG. 21


X
45
38a
FIG. 12A
36
38c
G
36
36
36
34
34
W
38b
32
34
38d
50