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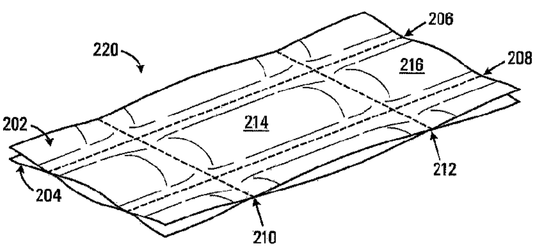
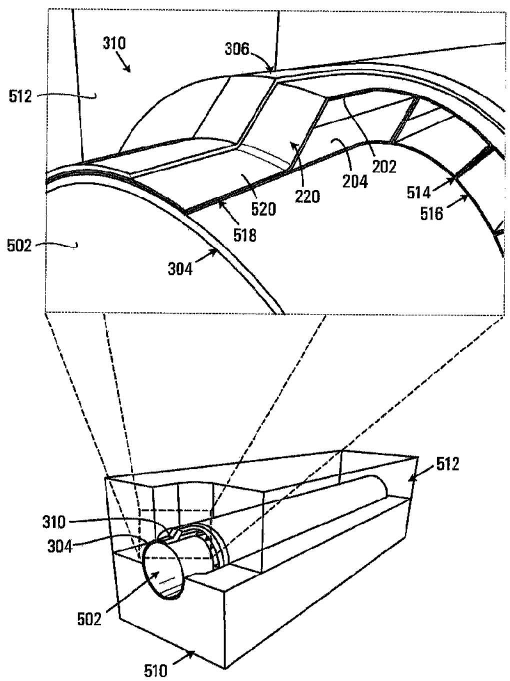
(54) **Titre : TUBAGE EN TITANE A DOUBLE PAROI ET METHODES DE FABRICATION DU TUBAGE**
(54) **Title: DUAL WALLED TITANIUM TUBING AND METHODS OF MANUFACTURING THE TUBING**





(57) **Abrégé/Abstract:**
A double-walled tubing apparatus comprising inner and outer tubes and at least one stiffener extending in a space between the inner and outer tubes and diffusion bonded to the inner and outer tubes. The at least one stiffener is formed by portions of a first tubing portion and a second tubing portion adjacent at least one first stitch line and at least one second stitch line perpendicular to the at least one first stitch line. The first and second tubing portions are stitch welded together with the at least one first and second stitch lines defining a stitch pattern to form a pack assembly, the stitch pattern defining a plurality of cells. The outer tube and the pack assembly are circumferentially seam welded together at at least one end of the inner tube.

ABSTRACT

A double-walled tubing apparatus comprising inner and outer tubes and at least one stiffener extending in a space between the inner and outer tubes and diffusion bonded to the inner and outer tubes. The at least one stiffener is formed by portions of a first tubing portion and a second tubing portion adjacent at least one first stitch line and at least one second stitch line perpendicular to the at least one first stitch line. The first and second tubing portions are stitch welded together with the at least one first and second stitch lines defining a stitch pattern to form a pack assembly, the stitch pattern defining a plurality of cells. The outer tube and the pack assembly are circumferentially seam welded together at at least one end of the inner tube.

Date Reçue/Date Received 2021-02-01

DUAL WALLED TITANIUM TUBING AND METHODS OF MANUFACTURING THE TUBING

FIELD

The present disclosure relates generally to super plastically forming and diffusion bonding dual-walled tubing, and more specifically to a double-walled titanium tube that includes an inner tube and an outer tube with at least one stiffener extending from the inner tube to the outer tube.

BACKGROUND

Tubing and duct systems for conveying fluids are in widespread use in many industries. In the aerospace industry, for example, welded ducts are used in environmental control systems and in wing de-icing systems for conveying heated air from the engine to leading edges and nacelle inlet nose to prevent ice from forming on those surfaces in icing conditions in flight. Tubing, of course, may be utilized in many other industries as well including the oil industry or other industries in which transport elements are required for use in extreme environments at times.

Tubing materials may be manufactured using superplastic forming (SPF) and diffusion bonding (DB) techniques. For many years it has been known that certain metals, such as titanium and many of its alloys, exhibit superplasticity. Superplasticity is the capability of a material to develop unusually high tensile

Date Reçue/Date Received 2021-02-01

elongations with reduced tendency toward necking. This capability is exhibited by a few metals and alloys and within a limited temperature and strain rate range. Titanium and titanium alloys have been observed to exhibit superplastic characteristics equal to or greater than those of any other metals. With suitable titanium alloys, overall increase in surface areas up to **300%** are possible, for example. Advantages of superplastic forming are numerous including abilities to create complex shapes and deep drawn parts, and low deformation stresses are required to form the metal at the superplastic temperature range thereby permitting forming of parts under low pressures that minimize tool deformation and wear.

Diffusion bonding (DB) refers to metallurgical joining of surfaces of similar or dissimilar metals by applying heat and pressure for a time duration so as to cause co-mingling of atoms at the joint interface. Diffusion bonding can be accomplished entirely in the solid-state at or above one-half the base metal melting point (absolute). Actual times, temperatures, and pressures will vary from metal to metal. The joining surfaces are brought within atomic distances by application of pressure. Adequate pressure is provided to cause some plastic flow to fill normal void areas. If pressures are too low, small voids may remain at the joint interface and the joint strength will be less than the maximum obtainable. The application of pressure also breaks up the surface oxides and surface asperities so as to present clean surfaces for bonding. Elevated temperatures used for diffusion bonding serve the functions of accelerating diffusion of atoms at the joint interfaces and providing a metal softening which aids in surface deformation so as to allow more intimate contact for atom bonding and movement across the joint interface. Elevated temperature and

Date Reçue/Date Received 2021-02-01

application of pressure also results in diffusion of the surface contaminants into the base metal during bonding which allows metal atom-to-atom bonding and thereby strengthens the bond. Sufficient time is allowed to ensure the strengthening of the bond by diffusion of atoms across the joint interface.

According to existing processes, tubing sheets are manufactured in a flat form, in which one or more superplastically formable metal sheets are placed in a die cavity defined between cooperable dies, the sheets are heated to an elevated temperature at which the sheets exhibit superplasticity, and then a gas is used to apply differential pressures to the opposite sides of the sheets in order to form the sheets. The pressure is selected to strain the material at a strain rate that is within its superplasticity range at the elevated temperature, stretch the sheets, and cause the sheet to assume the shape of the die surface. In this way, the sheets can be formed to a complex shape defined by the dies.

In other existing processes, SPF and DB can be performed in a combined forming/bonding operation. For instance, in one example combined SPF/DB process, three metal sheets are stacked in a flat form to form a pack. A stop-off material is selectively provided between the sheets to prevent portions of the adjacent surfaces of the sheets from being bonded. The pack is heated and compressed in a die cavity with sufficient gas pressure so that the adjacent portions of the sheets that are not treated with the stop-off material are joined by diffusion bonding. Thereafter, a pressurized gas is injected between the sheets to inflate the pack, and thereby superplastically form the pack to a configuration defined by the

Date Reçue/Date Received 2021-02-01

surface of the die cavity. Such a combined SPF/DB process can be used, e.g., to produce complex honeycomb sandwich structures that are formed and diffusion bonded to define hollow internal cells. Generally, the simplicity of the superplastic forming and/or diffusion bonding processes can result in lighter and less expensive structures with fewer fasteners and higher potential geometric complexity.

However, using existing superplastic forming and diffusion bonding processes results in flat sheets that still require further manufacturing processes to form the sheets into a tubing system, which may alter the bonds created. Using examples described herein, a titanium (or other alloy) double-walled tube can be manufactured using SPF and DB that is corrosion resistant, heat resistant, and structurally reinforced with increased cross section for greater strength than seen in flat sheets to provide a fail safety for a titanium tube.

Date Reçue/Date Received 2021-02-01

SUMMARY

In one embodiment, there is provided a double-walled tubing apparatus comprising inner and outer tubes and at least one stiffener aligned both axially and radially and extending in a space between the inner and outer tubes and diffusion bonded to the inner and outer tubes. The at least one stiffener is formed by portions of intimately concentric first and second tubings adjacent at least one first stitch line and at least one second stitch line perpendicular to the at least one first stitch line. The at least one first and second stitch lines are formed by stitch welding the first and second tubings together to form a stitch pattern on the first and second tubings defining a plurality of cells. At least one end of the inner tube, the outer tube, the first tubing, and the second tubing are circumferentially seam welded together.

In another embodiment, there is provided a double-walled titanium tube structure, comprising an inner wall and an outer wall with a plurality of stiffeners extending between the inner wall and the outer wall. The plurality of stiffeners are aligned both axially and radially. The plurality of stiffeners are diffusion bonded to the inner wall and the outer wall. The plurality of stiffeners are based on stitch welding intimately concentric seamless tubings to create a stitch pattern on the intimately concentric seamless tubings defining individual cells. The double-walled titanium tube structure further comprises a perimeter weld circumferentially enclosing an end of the inner wall and the outer wall.

In another embodiment, there is provided a double-walled titanium tube structure, comprising an inner wall and an outer wall with a plurality of stiffeners extending between the inner wall and the outer wall. The plurality of stiffeners are aligned both axially and radially. The plurality of stiffeners are diffusion bonded to the inner wall and the outer wall. The plurality of stiffeners are based on stitch welding intimately concentric seamless tubings to create a stitch pattern with a number of parallel lines that run along a length of the intimately concentric seamless tubings and a number of parallel lines that run along a width of the intimately

Date Reçue/Date Received 2022-08-11

concentric seamless tubings resulting in individual cells defined by the stitch pattern on the intimately concentric seamless tubings. The double-walled titanium tube structure further comprises a perimeter weld circumferentially enclosing an end of the inner wall and the outer wall.

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

Date Reçue/Date Received 2022-08-11

BRIEF DESCRIPTION OF THE FIGURES

The illustrative embodiments, as well as a preferred mode of use, further objectives and descriptions thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

Date Reçue/Date Received 2021-02-01

Figure **1** is a flowchart that describes an example method of manufacturing double-walled tubing by super plastically forming and diffusion bonding an outer tube, an inner tube and inner structures of the double-walled tubing.

Figure **2** illustrates a portion of seamless tubing portions with an example stitch pattern welded thereon.

Figure **3** illustrates a portion of an example welded tube assembly.

Figure **4** illustrates a portion of another example welded tube assembly.

Figure **5** illustrates an example tubing and an example die form.

Figures **6**A-**6**D illustrate examples of formation of cells within a pack assembly based on a stitch pattern of the pack assembly.

Figures **7**A-**7**F illustrate another view of examples of formation of cells within a welded tube assembly based on a stitch pattern of a pack assembly.

Figure **8** illustrates an example resulting double-walled tubing.

Figure **9** is a flowchart that describes another example method of manufacturing a double-walled titanium conduit.

DETAILED DESCRIPTION

Disclosed embodiments will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all of the disclosed embodiments are shown. Indeed, several different embodiments may be described and should not be construed as limited to the embodiments set forth herein. Rather,

Date Reçue/Date Received 2021-02-01

these embodiments are described so that this disclosure will be thorough and complete and will fully convey the scope of the disclosure to those skilled in the art.

Within examples, methods and systems for superplastic forming (SPF) and diffusion bonding double-walled tubing are described. SPF generally refers to a process in which a material is superplastically deformed beyond its normal limits of plastic deformation. Superplastic forming can be performed with certain materials that exhibit superplastic properties within limited ranges of temperature and strain rate. For example, workpieces formed of titanium alloys can be superplastically formed in a temperature range between about **1450**° F and about **1850**° F at a strain rate up to about $\mathbf{3 \times 10^{-4}}$ per second. Diffusion bonding (DB) generally refers to a process of joining members using heat and pressure to form a solid-state coalescence between the materials of the joined members. Joining by diffusion bonding can occur at a temperature below a melting point of the materials that are being joined, and the coalescence therebetween may be produced with loads below those that would cause macroscopic deformation of the article.

As an example, super plastically forming and diffusion bonding titanium dual-walled tubing can be achieved by manufacturing a double-walled titanium conduit that has an inner wall defined by an inner tube and an outer wall defined by an outer tube with at least one stiffener extending from the inner wall to the outer wall. The titanium conduit may include a plurality of stiffeners aligned axially, and in other examples, the titanium conduit may include a plurality of stiffeners aligned both axially and radially.

Date Reçue/Date Received 2021-02-01

An example method of super plastically forming and diffusion bonding the double-walled titanium conduit includes arranging substantially intimately concentric seamless tubing portions, cleaning the seamless tubing portions, and stitch welding the seamless tubing portions with a rolled tubing seam welder to form a pack assembly. Following, the method includes circumferentially seam welding an outer tube and an inner tube to the pack assembly to form a welded tube assembly, fusion welding pressure lines, and inserting a cylinder die into the welded tube assembly. The welded tube assembly can be placed into a heated die and brought up to temperature and pressure that is held for a diffusion bond process to occur over a period of time. A resulting tubing can be removed from the die and cooled for use or further processing.

More particularly, the method may involve holding inner and outer concentric tubes within inner and outer die forms while pressurizing a space between the inner and outer tubes to press the inner and outer tubes against the inner and outer die forms and while pressurizing cells defined by stitch weld lines that stitch together first and second tubing portions concentrically located in the space between the inner and outer tubes, to expand the cells within the space such that portions of the first and second tubing portions adjacent the stitch weld lines form radial, longitudinally extending stiffeners and radial, circumferentially extending stiffeners between the inner and outer concentric tubes. The method also involves holding the space and the cells under pressure while heating the inner and outer concentric tubes and the first and second tubing portions sufficiently to cause diffusion bonding between the first tubing portion and the inner tube and between the second tubing portion and the

Date Reçue/Date Received 2021-02-01

outer tube and between the first tubing portion and the second tubing portion in the areas adjacent the stitch weld lines.

Referring now to the figures, Figure **1** is a flowchart that describes an example method **100** of manufacturing double-walled tubing by super plastically forming and diffusion bonding an outer tube, an inner tube and inner pack assembly structures of the double-walled tubing. The outer tube and the inner tube of the tube define interior and exterior layer of the tubing, which may comprise sheets concentrically wound together. The method **100** of super plastically forming and diffusion bonding may include one or more operations, functions, or actions as illustrated by one or more of blocks **102-118**. Although the blocks are illustrated in a sequential order, these blocks may, in some instances, be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

At block **102**, the method **100** includes arranging first and second intimately concentric seamless tubing portions. In some examples, the concentric seamless tubing portions have approximately matching diameters to enable contact during a stitch welding process. The first and second tubing portions can be sandwiched together in a circular manner by using a seamless tubing or rolled tubing. In one example, flat sheets of titanium may be arranged together and wound up to form the concentric titanium seamless tubing portions.

Date Reçue/Date Received 2021-02-01

In some examples, the method **100** may optionally include cleaning the seamless tubing portions to remove oxidation.

At block **104**, the method **100** includes stitch welding the seamless tubing portions with a rolled tubing seam welder to create a pack assembly having a stitch pattern, which later forms inner-to-outer tube stiffeners of the ultimately-formed double-walled tubing. Stitch welding the seamless tubing portions may create the stitch pattern along a length and/or a width of the seamless tubing portions.

Figure **2** illustrates a portion of the seamless tubing portions with an example stitch pattern welded thereon, the portion being shown flattened rather than cylindrical, for ease of reference. In Figure **2**, the portion includes first and second tubing portions **202** and **204** arranged intimately together, and stitch welding has been performed to form a stitch pattern. The stitch pattern in Figure **2** includes a number of parallel stitched lines **206** and **208** extending along a length of the tubing portions **202** and **204**, and other parallel stitch lines **210** and **212** extending along a width of the tubing portions **202** and **204**. The stitch lines **206** and **208** are perpendicular to the stitch lines **210** and **212**. Although the stitch lines **206**, **208**, **210**, and **212** are shown and described as extending along the length and the width of the tubing portions **202** and **204**, stitch welding may be performed in other manners so as to weld stitches, or extend in other areas along the tubing portions **202** and **204** with spaces between the stitch lines, for example.

The stitch pattern creates individual cells, such as cells **214** and **216** for example, along a length of the tubing portions **202** and **204**. A seam welder may be

Date Reçue/Date Received 2021-02-01

used to provide a stitch weld pattern along a length of the tubing portions **202** and **204** such as to provide the stitch lines **206**, and **208**, and a different roll seam welder may be used to form the stitch lines **210** and **212** around a circumference of the tubing portions **202** and **204** to generate a desired cellular structure layout. The first and second tubing portions **202** and **204** stitch welded in the manner described may be referred to as a pack assembly **220**. As mentioned previously, in Figure **2**, the pack assembly **220** is shown flattened for ease of reference. However, the pack assembly **220** generally has a cylindrical shape.

In another embodiment, forming the first and second tubing portions into a cylindrical pack assembly **220** includes arranging first and second flat sheets of titanium into a layer assembly. The first and second flat sheets of the layer assembly are then stitch welded together using stitch lines formed by, for example, a seam welder, to create a stitch pattern. The layer assembly is then wound to cause the first and second flat sheets of titanium to form concentric seamless tubes which are the first and second tubing portions **202** and **204**.

Referring back to Figure **1**, at block **106**, the method **100** includes arranging inner and outer concentric tubes, and at block **108**, the method **100** includes circumferentially seam welding the inner and outer tubes to the cylindrically shaped pack assembly **220** to create a welded tube assembly **310**. In one example, this includes placing the cylindrically shaped pack assembly **220** between an inner tube and an outer tube, and then circumferentially welding together end edges of the

Date Reçue/Date Received 2021-02-01

inner tube, the outer tube, and the pack assembly (i.e., the stitch welded tubing portions).

Figure **3** illustrates a portion of an example welded tube assembly **310**. In Figure **3**, a seam welder has been used to provide a perimeter weld **302** enclosing the first and second tubing portions **202** and **204** of the pack assembly shown in Figure **2** between inner and outer tubes **304** and **306**. The perimeter weld **302** may be a circumferential seam weld on the end edges of the ends of the first and second tubing portions **202** and **204** and the end edges of the ends of the inner and outer tubes **304** and **306**. In Figure **3**, the portion of the welded tube assembly **310** is tubular or cylindrical in cross-section.

Figure **4** illustrates a portion of another example welded tube assembly **311**. In Figure **4**, the welded tube assembly is shown to be more elliptical in cross-section. The welded tube assembly may be configured to have other cross-sectional shapes as well.

Referring back to Figure **1**, at block **110**, the method **100** includes inserting a cylinder die into the inner tube **304** of the welded tube assembly **310**, and at block **112**, the method **100** includes placing the welded tube assembly **310** into a heated die. An example die is a three piece die including cylindrical die to hold a shape on an inside of the ultimately formed tubing and two outer die halves to hold a shape on the outside of the ultimately formed tubing.

Figure **5** illustrates the example welded tube assembly **310** and an example die arrangement. In Figure **5**, a cylinder die **502** is inserted into the inner tube **304** of

Date Reçue/Date Received 2021-02-01

the welded tube assembly **310**. The welded tube assembly **310** is then inserted into a lower die **510** and an upper die **512** is placed on top to form a three piece die arrangement including the cylinder die **502**, the lower die **510**, and the upper die **512**. This die arrangement is used to hold the shape of the tubing during a bonding process. While Figure **5** shows a substantially linear length of tubing with substantially constant cross section, it will be readily understood that the curvature tubing may be non-linear or curved, and may have any other cross-section.

Referring back to Figure **1**, at block **114**, the method **100** includes heating the welded tube assembly. As one example, the welded tube assembly within the die is heated to a temperature in a range of about **1450**^{0} F to about **1850**^{0} F, or in a range of about **1500**^{0} F to about **1700**^{0} F degrees depending on an alloy of the materials.

At block **116**, the method **100** includes pressurizing the space between the inner and outer tubes **304** and **306** to fill the upper and lower dies **510** and **512**, and at block **118**, the method **100** includes pressurizing the cells formed in the pack assembly **220** to form the inner structures according to a stitch pattern of the pack assembly. A pressure may be applied by supplying an inert gas at a pressure of about **300** psi, or at any other pressure suitable to facilitate a diffusion bond process to occur. As an example, as shown in Figure **5**, diffusion bonds may be created within the pack assembly **220**, such as diffusion bond **514**. Diffusion bonds may also occur between the inner and outer tubes **304** and **306**, respectively, and the first and second tubing portions **204** and **206** of the pack assembly **220**, such as diffusion bonds **516**, **518**, and **520**.

Date Reçue/Date Received 2021-02-01

The pressurizing causes the inner and outer tubes **304** and **306** of the welded tube assembly **310** to fill contours of the heated lower die **510** and upper die **512**. Pressurizing also causes the cells of the pack assembly **220**, such as shown at **214** and **216** in Figure **2,** to expand to contact the inner and outer tubes **304** and **306** and form webs between the inner and outer tubes, the webs being based on the stitch pattern of the pack assembly. For example, the stitch pattern provides boundaries to enable the cells to expand. In embodiments wherein the tubing portions **202** and **204**, the inner tube **304** and the outer tube **306** are formed from the sheets of titanium, for example, heating and pressurizing allows the sheets of titanium to be bonded together.

Figures **6**A-**6**D illustrate examples of formation of cells within a stitch welded pack assembly based on a stitch pattern. Figure **6**A illustrates the pack assembly **220** before pressurization. During the heating and pressurizing process, with the tubing portions **202** and **204** stitched together in a quilt-like pattern, bubbles form over time. Figure **6**B shows an initial stage of bubbles forming, such as bubble **218**. Figure **6**C shows a subsequent stage with the bubbles more fully formed and expanding. Figure **6**D shows an example final formation of the cells, which may be rectangles, squares, or any other shapes (depending on the stitch pattern of the pack assembly), and diffusion bonds have formed between the tubing portions **204** and **206**, such as diffusion bonds **222** and **224** in areas adjacent the stitch weld lines **206**, **208**, **210** and **212** (shown in Figure **6**A).

Date Reçue/Date Received 2021-02-01

Referring back to Figure **1**, at block **120**, the method **100** includes holding pressure for a diffusion bond process to occur between the first tubing portion **202** and the outer tube **306** and between the second tubing portion **204** and the inner tube **304** and between the first and second tubing portions **202** and **204** in areas adjacent the stitch lines such as shown at **222** and **224** in Figure **6**D. The pressure is held to enable the first tubing portion **202** to diffusion bond to the outer tube **306**, the second tubing portion **204** to diffusion bond to the inner tube **304** and the first tubing portion **202** to diffusion bond to the second tubing portion **204**. The pressure can be held for a time period, such as about three hours, to enable the diffusion bond process such that the first and second tubing portions **202** and **204** the outer tube **306** and the inner tube **304** become an integral piece. The pressure also enables full forming of the cells, or inner structures of the ultimately formed double-walled tubing, to form.

At block **122**, the method **100** includes removing the resulting double-walled tubing from the heated die and cooling it.

Figures **7**A-**7**F illustrate another view of examples of formation of cells within a tubular structure based on a stitch pattern. In Figure **7**A, an example of pack assembly is shown generally at **220**. The pack assembly **220** includes first and second stitch welded tubing portions **202** and **204**. The first and second tubing portions **202** and **204** are welded with stitch welds **210** (also shown in Figure **6**A).

In Figure **7**B, the inner tube **304** and the outer tube **306** are assembled around and welded to the pack assembly **220** to form the welded tube assembly

Date Reçue/Date Received 2021-02-01

310. Specifically, circumferential welds may be used to join the end edges of the inner tube **304**, the pack assembly **220** and the outer tube **306** at the stitch welds **210** of the pack assembly **220**. The circumferential welds seal edges of the inner tube **306**, the pack assembly **220**, and the outer rube **306** together, causing them to be air tight.

In Figure **7**C, with pressurization and elevated temperature, further bonding takes place within the pack assembly **220** stars initial formation, of cells **214**. In Figure **7**D, with further pressurization and elevated temperature, bonding takes place within the pack assembly **220**, and the stitch welded areas begin to define stiffeners **806** (walls) between the cells **214**. The thickness of the inner and outer tubes **304** and **306** and the first and second tubing portions **202** and **204** is shown exaggerated for ease of understanding. In Figure **7**E, with sustained pressurization and elevated temperatures, the stiffeners 806 extend radially between the inner and outer tubes **304** and **306**, and cell formation is complete. In Figure **7**F, diffusion bonding occurs between the inner tube **304** and the second tubing portion **204**, between the outer tube **306** and between the first tubing potion **202**, and the first and second tubing portions **202** and **204**, by holding at pressure and temperature, resulting in diffusion bonds (e.g., bond **710**).

Figure **8** illustrates an example resulting double-walled tubing. As shown, the double-walled tubing may be a double-walled titanium tube structure that includes an inner surface **802** of the inner tube **304** and an outer surface **804** of the outer tube **306** with a plurality of stiffeners, such as the stiffener **806**, extending between the

Date Reçue/Date Received 2021-02-01

inner tube **304** to outer tube **306**. The plurality of stiffeners (**806**) are aligned both axially and radially, and the plurality of stiffeners are diffusion bonded to the inner tube **304** and the outer tube **306**. As previously described, the plurality of stiffeners **806** may be formed from the pack assembly **220** according to the stitch pattern of the pack assembly **220**.

The double-walled titanium tube structure shown in Figure **8** may be a unitary tube with no fasteners resulting from multiple concentric tubes of titanium resistance welded prior to die forming at temperature and pressure. The plurality of stiffeners provide a continuous internal load path for the tube for greater strength. The annulus of the tube can be used for insulative purposes for corrosion resistant or heat resistant applications. The annulus with a specific stitch pattern can also accommodate a parallel or counter flow in any configuration of air or fluids.

The method **100** shown in Figure **1** may be performed to manufacture a number or variety of types of double-walled conduits or tube structures. One example includes a seamless, open annulus, heated press process, as shown and described. Another example includes a seamless, closed annulus, heated press process following stitch welding, spot or circumferential welding that can be performed for radial spacing. Yet another example includes a rolled tube, open annulus, heated press process, in which the sheets are rolled into tubing, and friction stir welded to ensure SPF properties. Still another example includes a rolled tube, closed annulus, heated press process in which both spot or circumferential welding and friction stir welding are performed.

Date Reçue/Date Received 2021-02-01

Figure **9** is a flowchart that describes another example method **900** of manufacturing a double-walled titanium conduit. The method **900** may include one or more operations, functions, or actions as illustrated by one or more of blocks **902**-**910**. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

At block **902**, the method **900** includes stitch welding multiple concentric sheets to form a pack assembly. In some examples, stitch welding creates a pattern on the multiple concentric sheets that will define a size and shape of inner structures to be formed later in the method.

At block **904**, the method **900** includes providing the pack assembly between inner and outer tubes that will ultimately provide an inner wall and an outer wall respectively of the double-walled titanium conduit. A specific stitch welding pattern for the pack assembly may be chosen based on an application of the conduit for creation of a pathway or creation of cells between the inner wall and the outer wall and to form the above-mentioned inner structures which can include at least one stiffener extending between the inner and outer wall of the ultimately formed double-walled titanium conduit, for example.

Date Reçue/Date Received 2021-02-01

At block **906**, the method **900** includes circumferentially seam welding edges of the inner and the outer tubes to the pack assembly to create a welded assembly. The welded assembly is in a tubular shape and configuration.

At block **908**, the method **900** includes die forming the welded assembly at temperature and pressure to form the above-mentioned inner structures between the inner and outer tubes according to stitch welding lines on the pack assembly and to enable a diffusion bond process among the inner tube, the pack assembly, and the outer tube. A shape and configuration of dies can be chosen based on an application of the conduit. Pressure and temperature are applied for the diffusion bonding process to occur such as at **300** psi and **1450**^{0} F for about **3** hours.

At block **910**, the method **900** includes removing the double-walled titanium conduit from the die. In one example, the double-walled titanium conduit may have a circular cross-section. In other examples, the double-walled titanium conduit may have a non-circular cross-section.

Using examples described herein, a titanium (or other alloy) double-walled tube can be manufactured that is corrosion resistant, heat resistant, and structurally reinforced with increased cross section for greater strength to provide a fail safety for a titanium tube. Example uses include tubing for transport elements or structural applications in extreme environments, such as in the oil industry or aerospace industry, for example.

The description of the different arrangements has been presented for purposes of illustration and description, and is not intended to be exhaustive or

Date Reçue/Date Received 2021-02-01

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 advantageous embodiments may describe different advantages as compared to other advantageous 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 various embodiments with various modifications as are suited to the particular use contemplated.

Date Reçue/Date Received 2021-02-01

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

1. A double-walled tubing apparatus comprising:

inner and outer tubes; and

at least one stiffener aligned both axially and radially and extending in a space between the inner and outer tubes and diffusion bonded to the inner and outer tubes,

wherein the at least one stiffener is formed by portions of intimately concentric first and second tubings adjacent at least one first stitch line and at least one second stitch line perpendicular to the at least one first stitch line,

wherein the at least one first and second stitch lines are formed by stitch welding the first and second tubings together to form a stitch pattern on the first and second tubings defining a plurality of cells, and

wherein at least one end of the inner tube, the outer tube, the first tubing, and the second tubing are circumferentially seam welded together.

2. The apparatus of claim **1** wherein at least one of the inner tube, the outer tube, the first tubing and the second tubing are made of an alloy of titanium.

3. The apparatus of claim **1** or **2** wherein the inner tube, the outer tube, the first tubing and the second tubing are an integral unit.

4. The apparatus of any one of claims **1** to **3** wherein the first tubing and the outer tube are diffusion bonded.

Date Reçue/Date Received 2022-08-11

5. The apparatus of any one of claims **1** to **4** wherein the second tubing and the inner tube are diffusion bonded.

6. The apparatus of any one of claims **1** to **5** wherein portions of the first tubing adjacent the at least one first and second stitch lines are diffusion bonded to form the at least one stiffener.

7. The apparatus of any one of claims **1** to **6** wherein portions of the second tubing adjacent the at least one first and second stitch lines are diffusion bonded to form the at least one stiffener.

8. The apparatus of any one of claims **1** to **7** wherein at least one of the inner tube and outer tube comprise a unitary tube with no fasteners.

9. The apparatus of any one of claims **1** to **8** wherein the at least one stiffener provides a continuous internal load path.

10. The apparatus of any one of claims **1** to **9** wherein said at least one first stitch line comprises a plurality of first stitch lines extending along a longitudinal length of the first and second tubings.

11. The apparatus of claim **10** wherein said at least one stiffener comprises a plurality of stiffeners extending radially along a longitudinal length of the inner and outer tubes formed by portions of said first and second tubings adjacent said plurality of first stitch lines.

12. The apparatus of any one of claims **1** to **11** wherein the at least one second stitch line comprises a plurality of second stitch lines extending along a circumferential width of the first and second tubings.

13. The apparatus of claim **12** wherein said at least one stiffener comprises a plurality of stiffeners extending radially along a circumference of the inner and outer tubes

Date Reçue/Date Received 2022-08-11

formed by portions of said first and second tubings adjacent said plurality of second stitch lines.

14. A double-walled titanium tube structure, comprising:

an inner wall and an outer wall with a plurality of stiffeners extending between the inner wall and the outer wall, wherein the plurality of stiffeners are aligned both axially and radially, the plurality of stiffeners are diffusion bonded to the inner wall and the outer wall, and the plurality of stiffeners are based on stitch welding intimately concentric seamless tubings to create a stitch pattern on the intimately concentric seamless tubings defining individual cells; and

a perimeter weld circumferentially enclosing an end of the inner wall and the outer wall.

15. The double-walled titanium tube structure of claim **14** wherein the inner wall and the outer wall comprise a unitary tube with no fasteners resulting from multiple concentric tubes of titanium resistance welded prior to die forming at temperature and pressure.

16. The double-walled titanium tube structure of claim **14** or **15** wherein the plurality of stiffeners provide a continuous internal load path.

17. The double-walled titanium tube structure of any one of claims **14** to **16** wherein stitch welding the intimately concentric seamless tubings comprises stitch welding the intimately concentric seamless tubings with a rolled tubing seam welder to create the stitch pattern and pressurizing the stitch welded intimately concentric seamless tubings to form the plurality of stiffners according to the stitch pattern.

Date Reçue/Date Received 2022-08-11

18. The double-walled titanium tube structure of any one of claims **14** to **17** wherein the stitch pattern comprises a number of parallel lines that run along a length of the intimately concentric seamless tubings.

19. The double-walled titanium tube structure of any one of claims **14** to **17** wherein the stitch pattern is created along a length of the intimately concentric seamless tubings.

20. The double-walled titanium tube structure of any one of claims **14** to **19** wherein the stitch pattern comprises a number of parallel lines that run along a width of the intimately concentric seamless tubings.

21. The double-walled titanium tube structure of any one of claims **14** to **20** wherein the stitch pattern forms a size and shape of the plurality of stiffeners.

22. The double-walled titanium tube structure of any one of claims **14** to **21** wherein the intimately concentric seamless tubings have approximately matching diameters to enable intimate contact during the stitch welding.

23. The double-walled titanium tube structure of any one of claims **14** to **22** wherein the inner wall and the outer wall are diffusion bonded.

24. The double-walled titanium tube structure of any one of claims **14** to **23** wherein the double-walled titanium tube structure has an elliptical shape.

25. The double-walled titanium tube structure of any one of claims **14** to **23** wherein the double-walled titanium tube structure has a cylindrical shape.

26. The double-walled titanium tube structure of any one of claims **14** to **25** wherein the double-walled titanium tube structure has a curved cross section.

Date Reçue/Date Received 2022-08-11

27. A double-walled titanium tube structure, comprising:

an inner wall and an outer wall with a plurality of stiffeners extending between the inner wall and the outer wall, wherein the plurality of stiffeners are aligned both axially and radially, the plurality of stiffeners are diffusion bonded to the inner wall and the outer wall, and the plurality of stiffeners are based on stitch welding intimately concentric seamless tubings to create a stitch pattern with a number of parallel lines that run along a length of the intimately concentric seamless tubings and a number of parallel lines that run along a width of the intimately concentric seamless tubings resulting in individual cells defined by the stitch pattern on the intimately concentric seamless tubings; and

a perimeter weld circumferentially enclosing an end of the inner wall and the outer wall.

28. The double-walled titanium tube structure of claim **27** wherein the inner wall and the outer wall comprise a unitary tube with no fasteners resulting from multiple concentric tubes of titanium resistance welded prior to die forming at temperature and pressure.

29. The double-walled titanium tube structure of claim **27** or **28** wherein the stitch pattern forms a size and shape of the plurality of stiffeners.

30. The double-walled titanium tube structure of any one of claims **27** to **29** wherein the intimately concentric seamless tubings have approximately matching diameters to enable intimate contact during the stitch welding.

Date Reçue/Date Received 2022-08-11

31. The double-walled titanium tube structure of any one of claims **27** to **30** wherein the inner wall and the outer wall are diffusion bonded.

Date Reçue/Date Received 2022-08-11

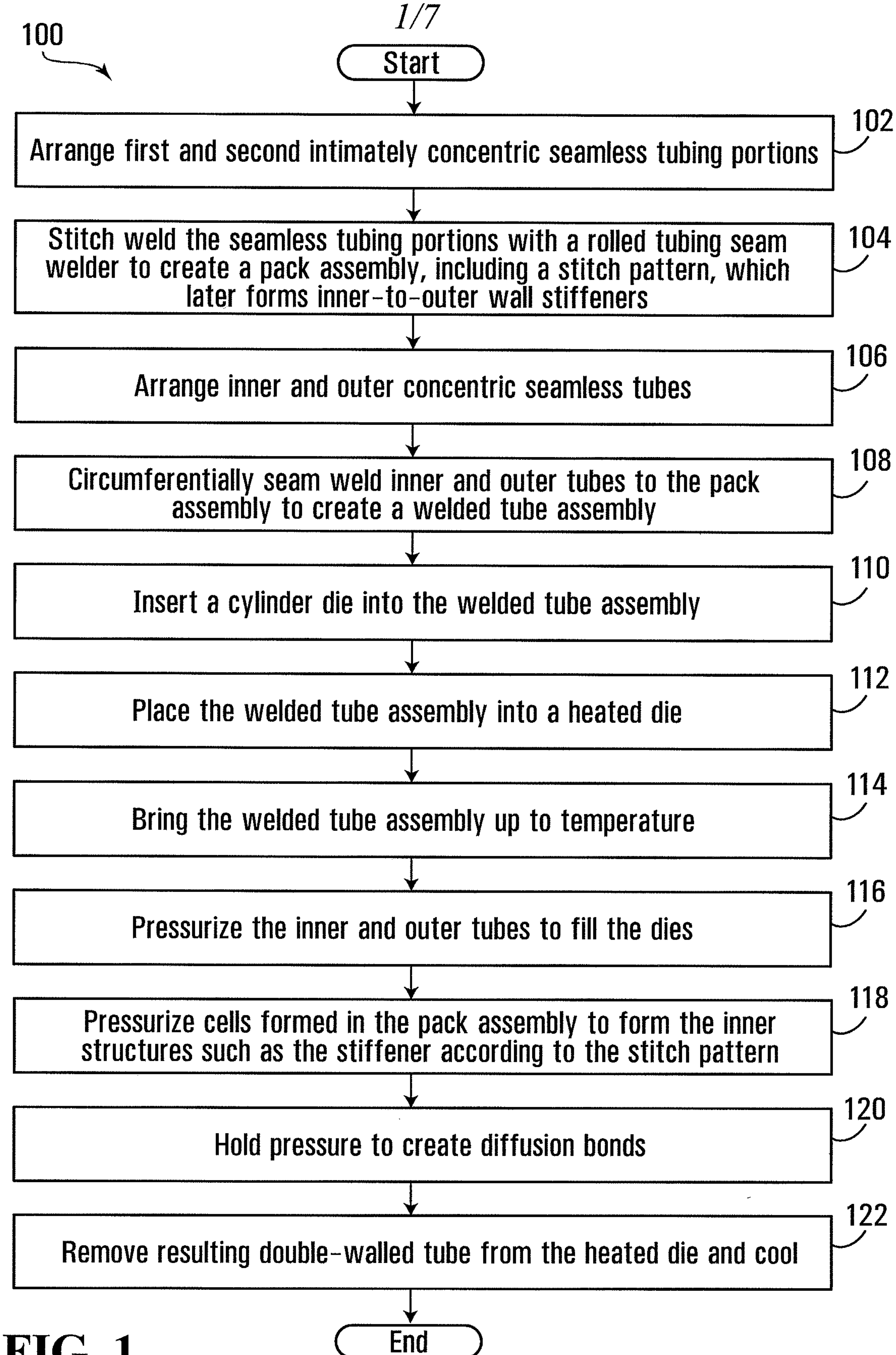

100
Start
Arrange first and second intimately concentric seamless tubing portions
102
Stitch weld the seamless tubing portions with a rolled tubing seam welder to create a pack assembly, including a stitch pattern, which later forms inner-to-outer wall stiffeners
104
Arrange inner and outer concentric seamless tubes
106
Circumferentially seam weld inner and outer tubes to the pack assembly to create a welded tube assembly
108
Insert a cylinder die into the welded tube assembly
110
Place the welded tube assembly into a heated die
112
Bring the welded tube assembly up to temperature
114
Pressurize the inner and outer tubes to fill the dies
116
Pressurize cells formed in the pack assembly to form the inner structures such as the stiffener according to the stitch pattern
118
Hold pressure to create diffusion bonds
120
Remove resulting double-walled tube from the heated die and cool
122
End

FIG. 1

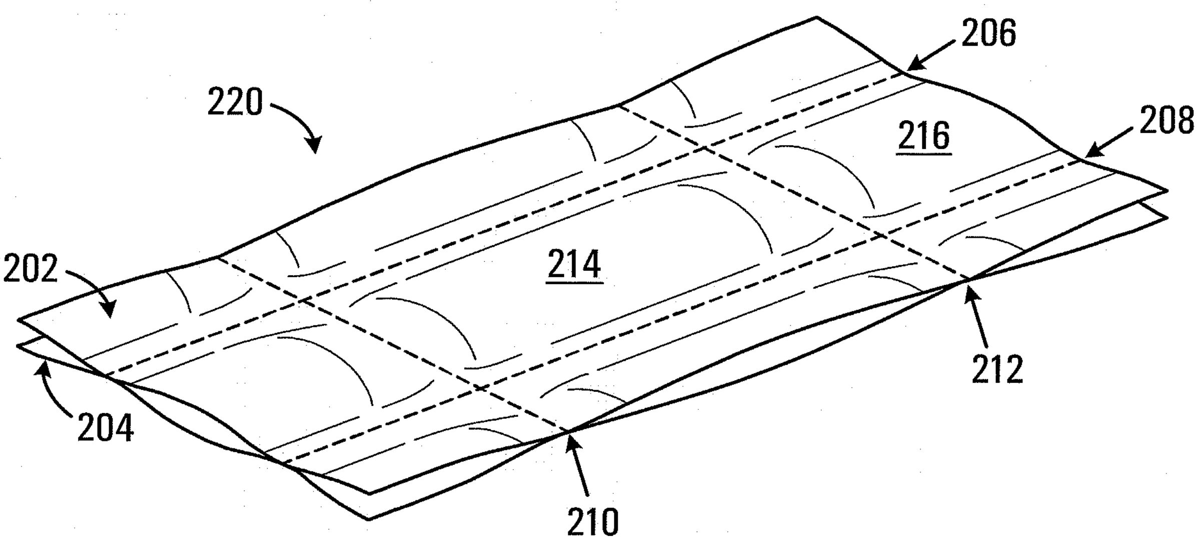


FIG. 2

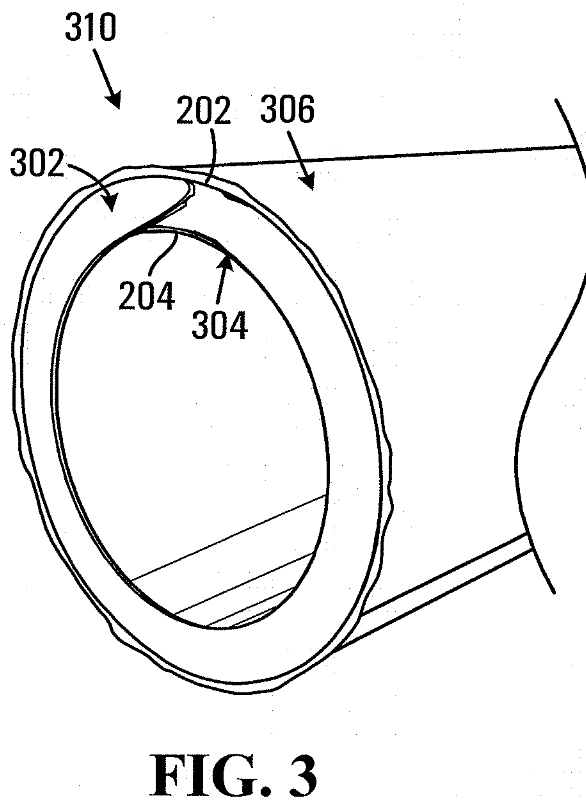


FIG. 3

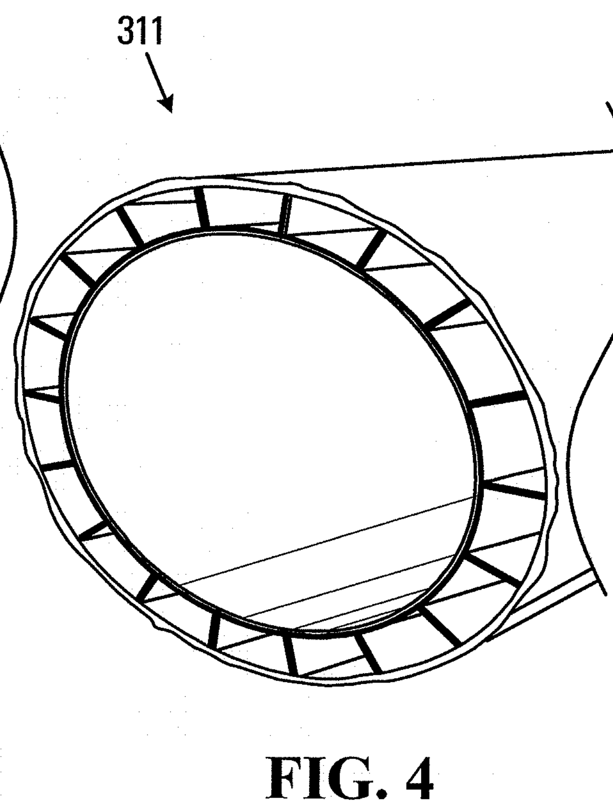


FIG. 4

Date Reçue/Date Received 2021-02-01

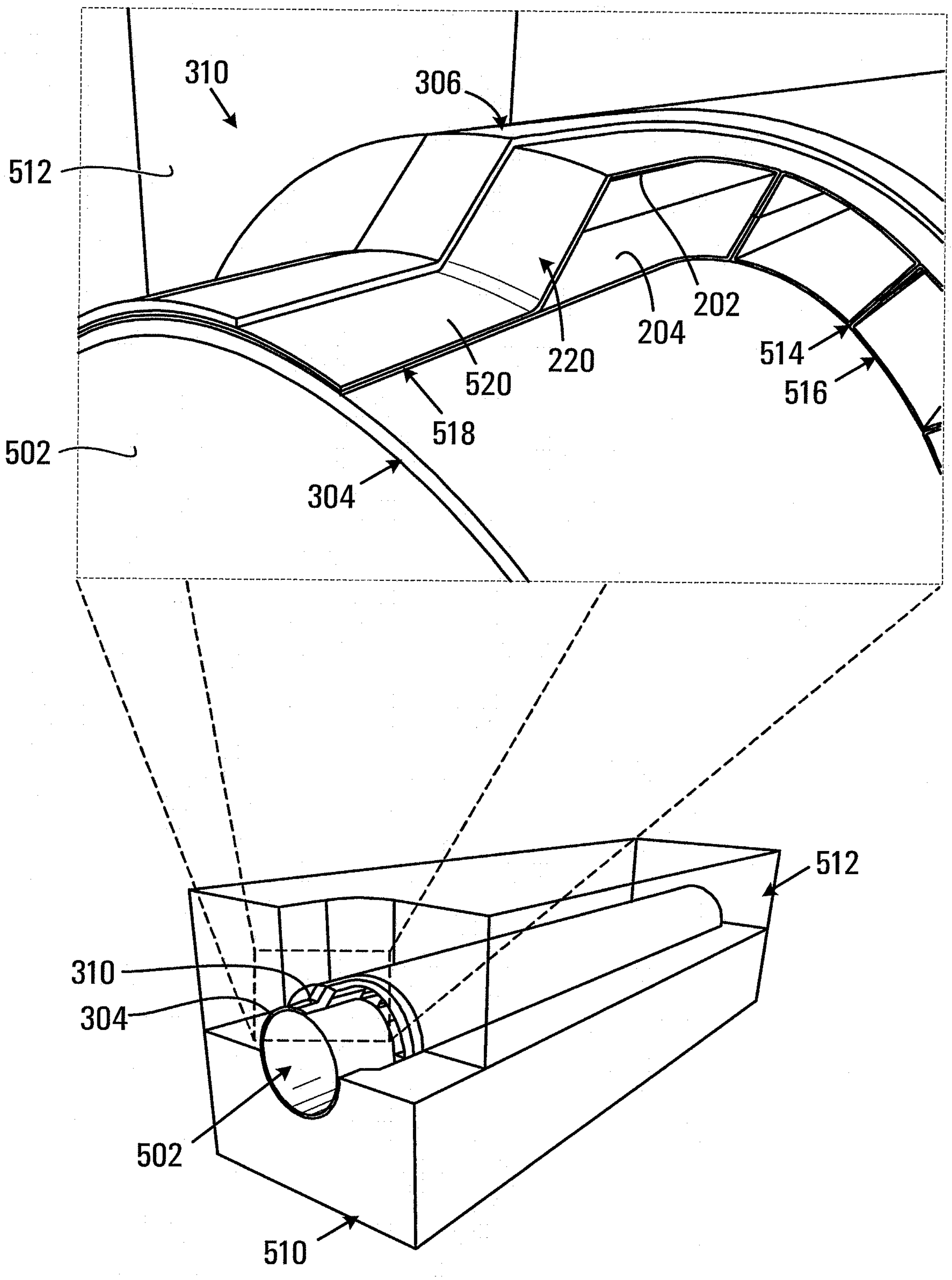


FIG. 5

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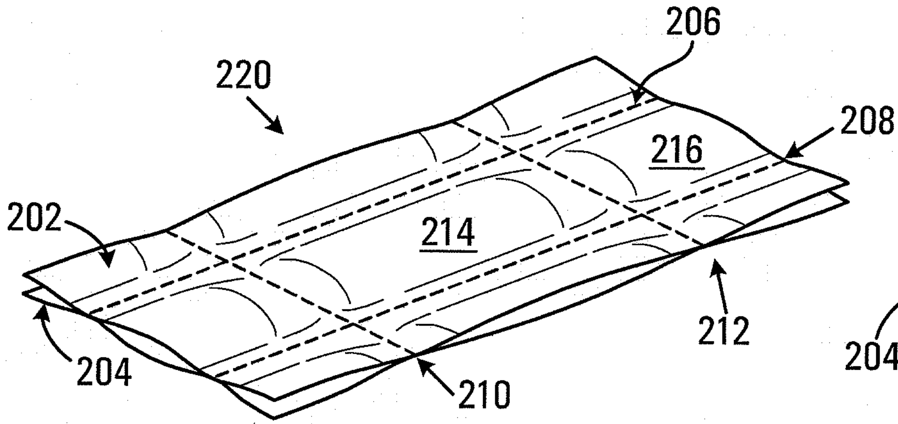


FIG. 6A

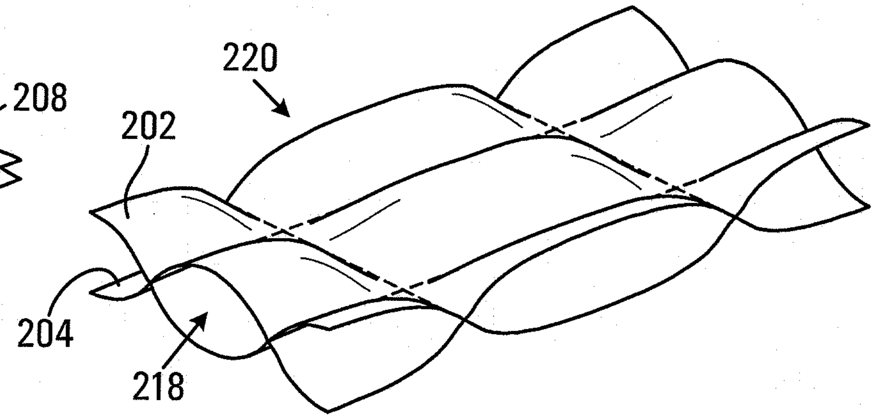


FIG. 6B

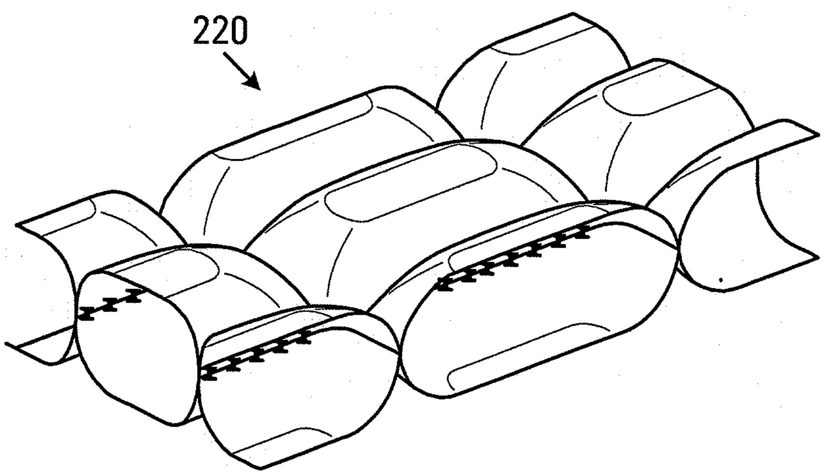


FIG. 6C

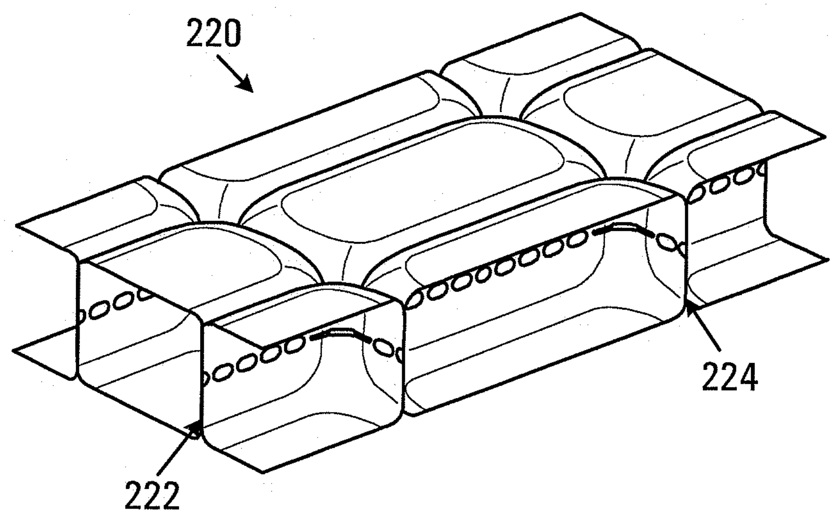


FIG. 6D

Date Reçue/Date Received 2021-02-01

FIG. 7A

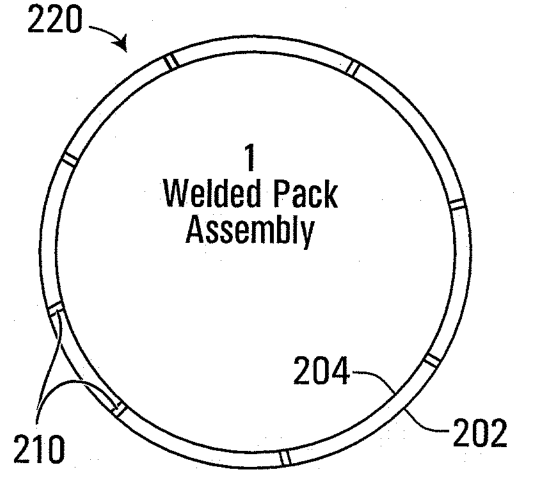


FIG. 7B

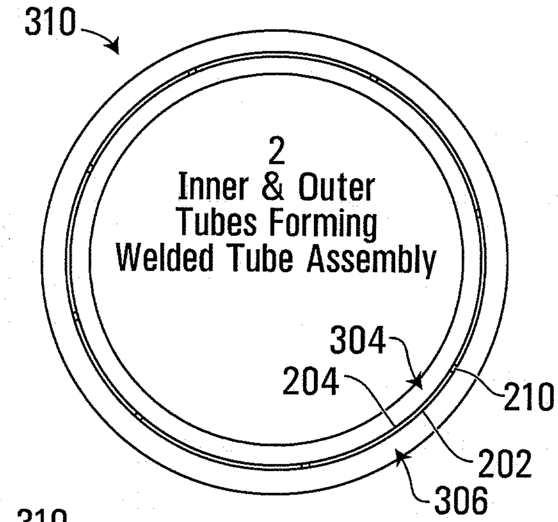
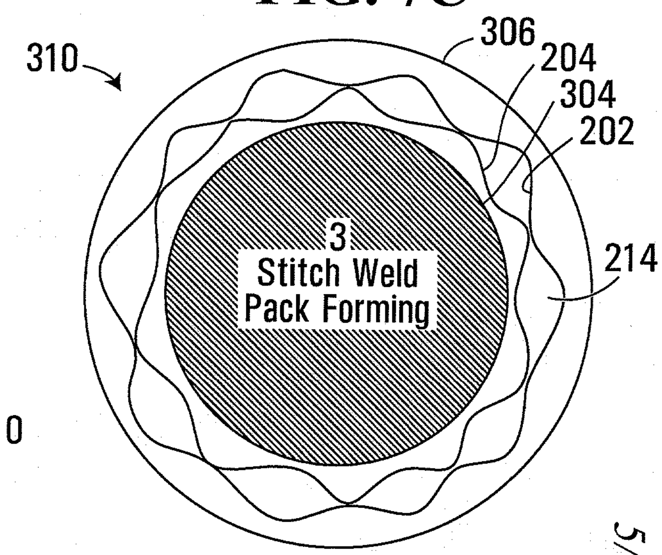


FIG. 7C



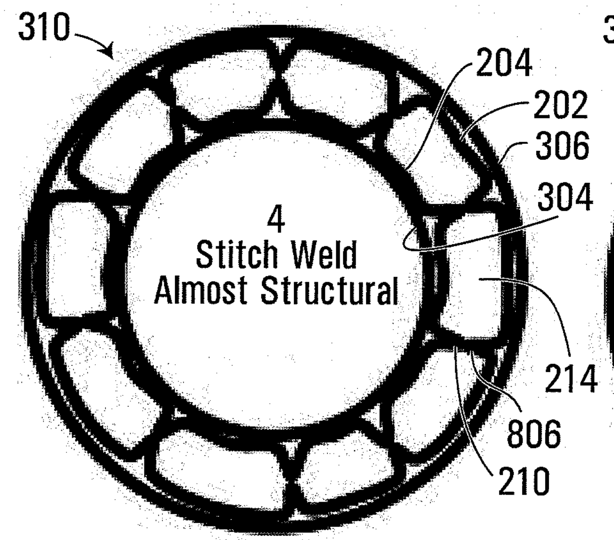


FIG. 7D

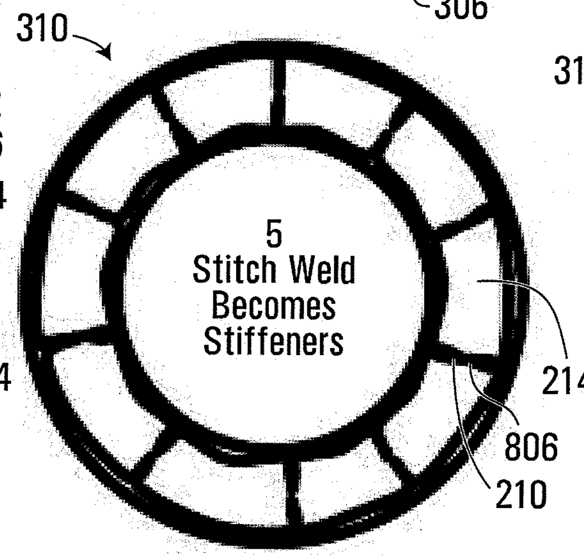


FIG. 7E

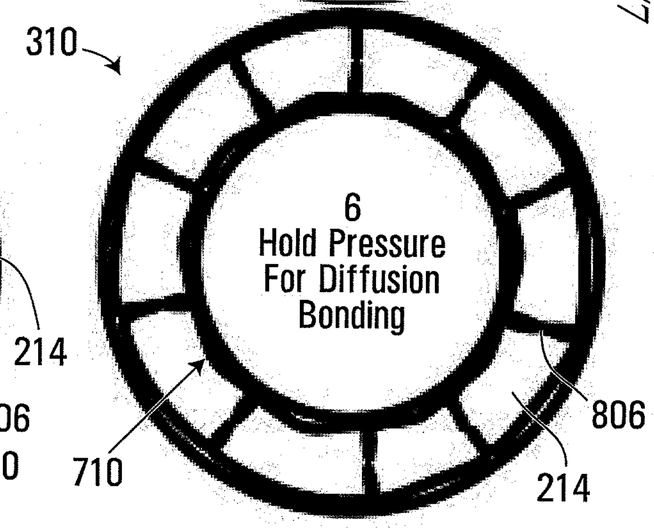


FIG. 7F

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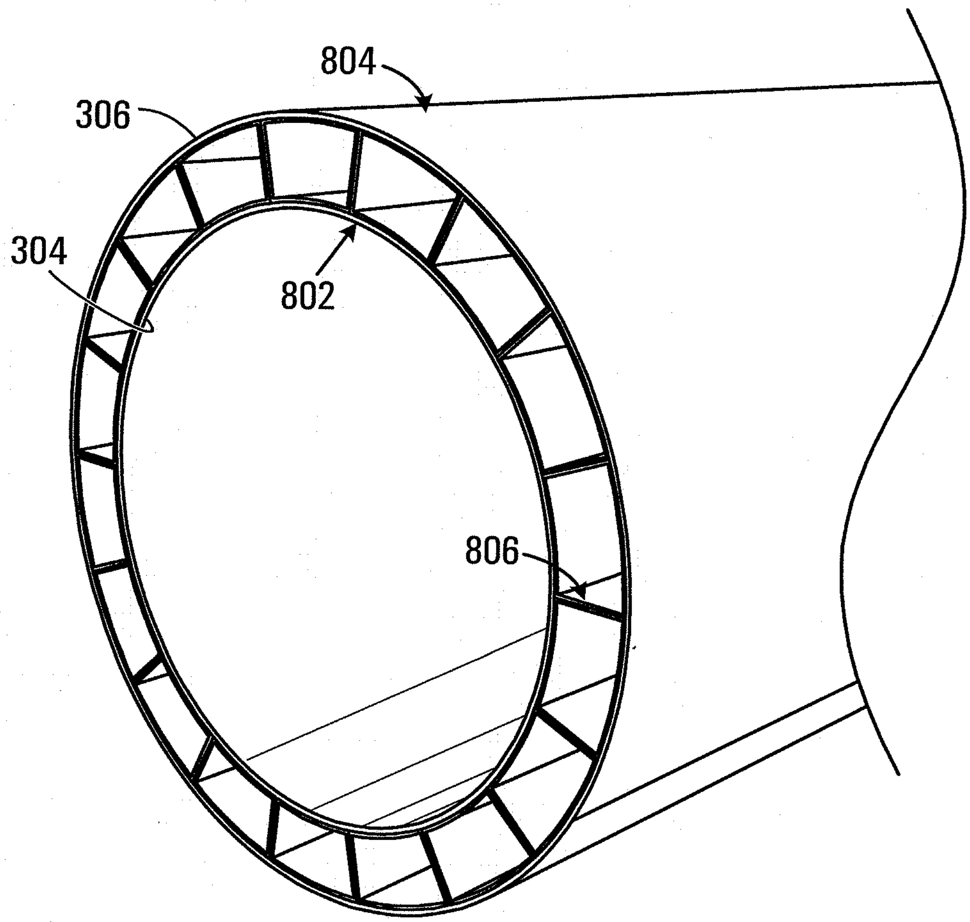


FIG. 8

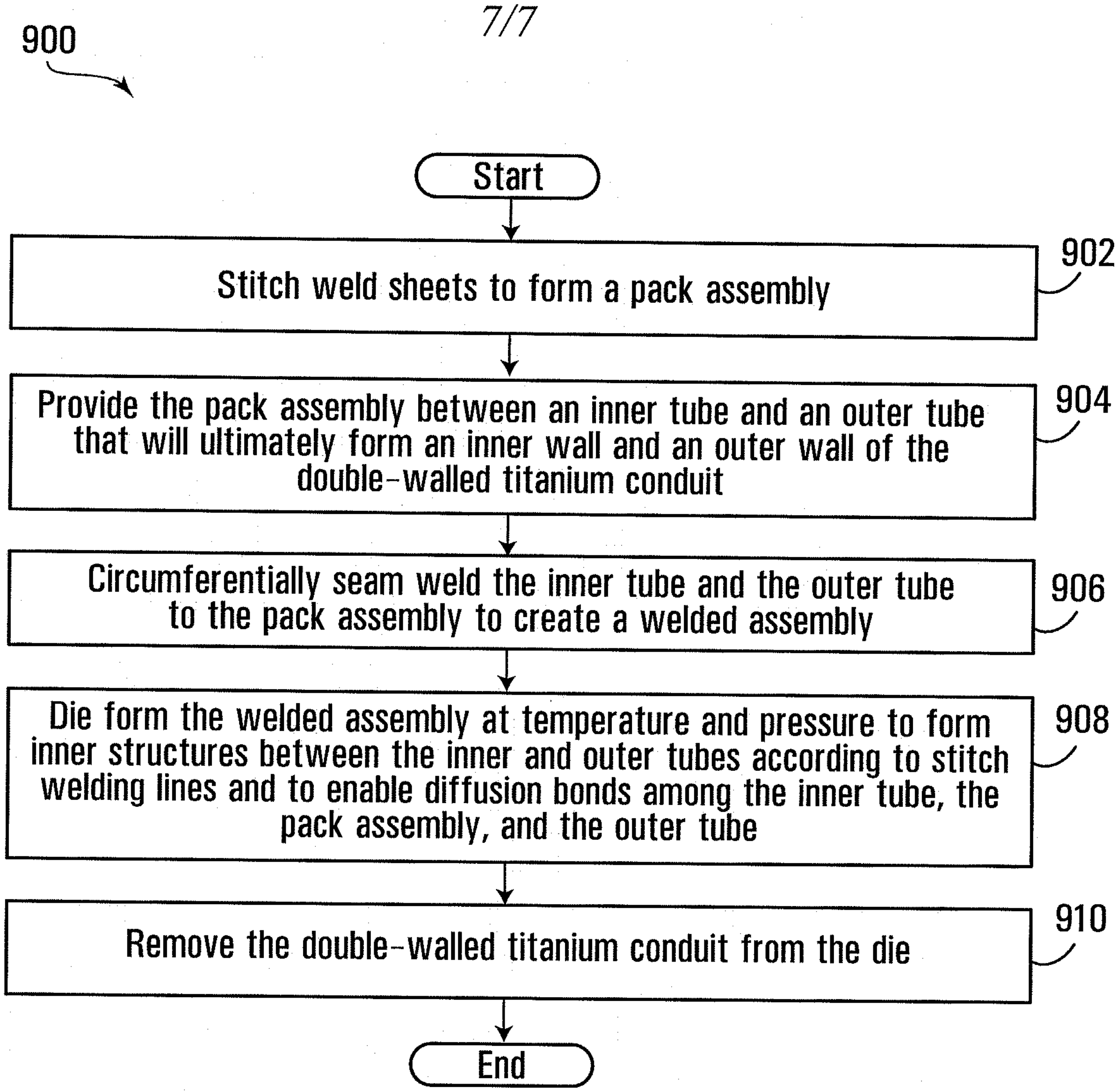
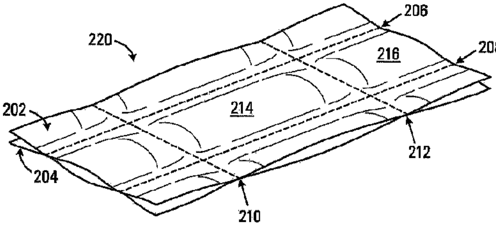


FIG. 9

Date Reçue/Date Received 2021-02-01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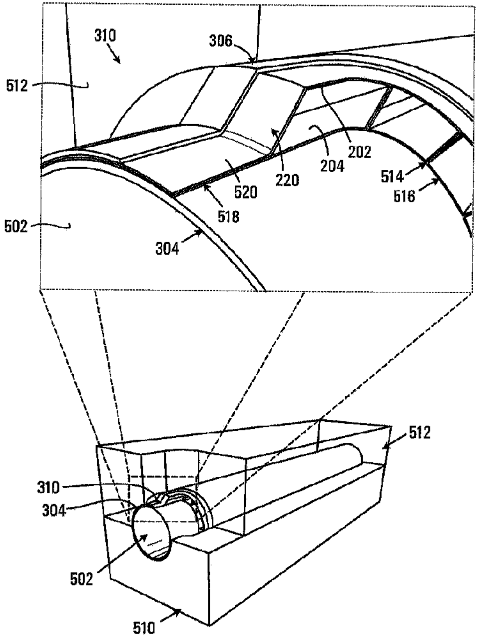
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