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(54) **Title:** METHOD OF MANUFACTURING A COMPOSITE MATERIAL

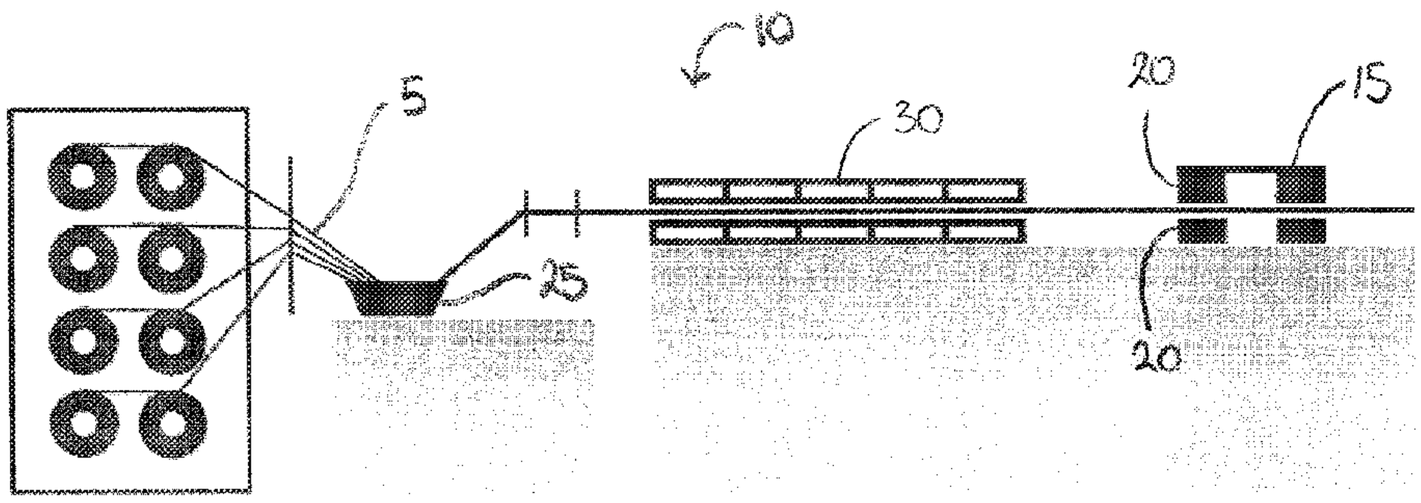


FIG. 1

(57) **Abstract:** A method of manufacturing a structural member includes preheating a plurality of fibers (5) to a first temperature, moving the preheated fibers along an assembly line (10), applying a binder (25) having a viscosity lower than 25 centipoise to at least one of the preheated fibers, providing a die (30) shaped to receive the preheated fibers, wherein the die moves together with the preheated fibers along at least a portion of the assembly line, maintaining a temperature of the plurality of fibers at a temperature substantially similar to the first temperature, and compressing the plurality of fibers within the die while maintaining a temperature.

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METHOD OF MANUFACTURING A COMPOSITE MATERIAL

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority to U.S. Provisional Patent Application No. 62/934,158 filed November 12, 2019, the entire contents of which are herein incorporated by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to a method of manufacturing composite materials, and more particularly to a method of manufacturing fiber reinforced polymer materials.

BACKGROUND

[0003] Fiber reinforced polymers include a fiber material bound by a matrix, typically provided by a binder, such as a resin. Fiber reinforced polymers are conventionally manufactured using a pultrusion process, an example of which is illustrated in FIG. 1.

[0004] In the pultrusion process, incoming fiber 5 is pulled through a production line 10 by a pulling mechanism 15, such as a pair of driven rollers 20. The fiber 5 is drawn into a bath 25 containing one of a variety of binders. Once wetted, the fiber 5 is drawn through a static die 30 that may have one or more heating zones to initiate curing of the binder. In the pultrusion process, the die 30 serves several functions. It creates pressure to promote wetting of the fiber 5, heats the binder and the fiber 5, controls curing of the binder, and controls the final shape of pultruded product.

[0005] Binders have curing profiles that are dictated by chemical reactions (curing, crosslinking, drying, etc.). These curing profiles are functions of the chemical reactivity of the binder, process temperature, and dwell time at the process temperature. As production speeds increase, it becomes increasingly difficult to ensure proper curing of the binder.

[0006] The conventional pultrusion process illustrated in FIG. 1 has inherent constraints that severely hinder the speed of the process. The length of the die 30 is the primary constraint on the

speed of the process, with process temperature, process friction, and process gas removal providing other limiting constraints. The binder bath 25 presents its own drawbacks, including difficulty mixing and maintaining multi-part, reactive binders, undue amounts of waste, and high operating costs due to the typically large volume of binder needed to fill the bath 25. It has previously not been cost-effective to manufacture fiber reinforced products, especially if one or more fast-curing thermosetting polymers and/or a multi-component thermosetting polymer are utilized as a portion of the binder, for at least the reasons listed above.

SUMMARY

[0007] In some embodiments, the invention provides a method of manufacturing a structural member. The method includes preheating a plurality of fibers to a first temperature, moving the preheated fibers along an assembly line and applying a binder to at least one of the preheated fibers, wherein when the binder is applied, the fibers are spaced apart and extend across a first area. The binder has a viscosity below 25 centipoise (cP). The method further includes providing a die having a first portion with a first diameter positioned to receive the preheated fibers and a second portion with a second diameter positioned downstream of the first portion, wherein the first diameter is greater than the second diameter and wherein the die is tapered between the first portion and the second portion. After applying the binder, the method further includes guiding the plurality of fibers along the die. The method further includes decreasing a distance between the plurality of fibers with the die, wherein after decreasing the distance between the plurality of fibers, the fibers extend across a second area that is smaller than the first area, and after decreasing, maintaining the temperature of the plurality of fibers at a temperature substantially similar to the first temperature. The method further includes while maintaining the temperature, shaping the plurality of fibers with a first shaping station, while maintaining the temperature, shaping the plurality of fibers with a second shaping station, spaced from the first shaping station and while maintaining the temperature, shaping the plurality of fibers with a third shaping station, spaced from the first and second shaping stations.

[0008] In some embodiments, the invention provides a method of manufacturing a structural member. The method includes preheating a plurality of fibers to a first temperature, moving the preheated fibers along an assembly line and applying a binder to at least one of the preheated

fibers, wherein when the binder is applied, the fibers are spaced apart and extend across a first area. The binder has a viscosity below 25 centipoise (cP). Applying the binder includes at least one of the following steps: spraying the binder on the at least one of the plurality of fibers, and extruding the binder from a pressurized chamber and dragging the at least one fiber through the extruded binder. After applying the binder, the method further includes guiding the preheated fibers along a die and decreasing a distance between the plurality of fibers with the die, wherein after decreasing the distance between the plurality of fibers, the fibers extend across a second area that is smaller than the first area. After decreasing, the method further includes maintaining the temperature of the plurality of fibers at a temperature substantially similar to the first temperature. The method further includes shaping the plurality of fibers with a first shaping station while maintaining the temperature, shaping the plurality of fibers with a second shaping station, spaced from the first shaping station while maintaining the temperature, and shaping the plurality of fibers with a third shaping station, spaced from the first and second shaping stations while maintaining the temperature.

[0009] In some embodiments, the invention includes a method of manufacturing a continuous structural member. The method includes preheating a plurality of fibers to a first temperature, moving the preheated fibers along an assembly line, applying a binder having a viscosity below 25 centipoise (cP) to at least one of the preheated fibers, providing a die shaped to receive the preheated fibers, wherein the die moves together with the preheated fibers along at least a portion of the assembly line, maintaining a temperature of the plurality of fibers at a temperature substantially similar to the first temperature, and compressing the plurality of fibers within the die while maintaining a temperature.

[0010] Other features and aspects of the invention will become apparent by consideration of the following detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic representation of a typical pultrusion process.

[0012] FIG. 2 is a schematic representation of an assembly line according to some embodiments of the invention.

[0013] FIG. 3 is a perspective view of a portion of the assembly line of FIG. 2.

[0014] FIG. 4 is a perspective view of a portion of the assembly line of FIG. 2.

[0015] FIG. 5 illustrates a binder application assembly according to one embodiment for use in the assembly line of FIG. 2.

[0016] FIGS. 6 and 7 illustrate a binder application assembly according to some embodiments for use in the assembly line of FIG. 2.

[0017] FIG. 8 is a perspective view of another portion of the assembly line of FIG. 2, illustrating a die being curled around a length of wetted fibers.

[0018] FIG. 9 is a perspective representation of the die being curled around the length of wetted fibers.

[0019] FIG. 10 is an end view of a shaping station of the assembly line of FIG. 2.

[0020] FIG. 11 is a schematic representation of a shaping station according to some embodiments.

[0021] FIG. 12 is a schematic representation of a shaping station according to some embodiments.

[0022] FIG. 13 is a schematic representation of a shaping station according to some embodiments.

[0023] FIG. 14 is a schematic representation of a shaping station according to some embodiments.

[0024] FIG. 15 is a schematic representation of a shaping station according to some embodiments.

[0025] FIG. 16 is a schematic representation of a shaping station according to some embodiments.

[0026] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting.

DETAILED DESCRIPTION

[0027] FIGS. 2 and 3 illustrate an assembly line 100 for manufacturing fiber-reinforced polymer (FRP) structural composites (i.e. matrix composites). The structural composites may form a wide variety of structural members, such as rebar, I-beams, C-channels, tubes, structural laminates, and the like. The illustrated assembly line 100 includes a roving station 105, a binder application station 110, and a plurality of shaping stations 115. In some embodiments, additional or alternative stations may be included in the assembly line 100. The assembly line 100 is generally linear and defines a central axis 120 along which the structural composite is produced (FIG. 3). As described in greater detail herein, the assembly line 100 enables FRP structural composites to be continuously manufactured at high speed.

[0028] The roving station 105 includes a plurality of spools or bobbins 125 that support and dispense strands or rovings of fiber 130 to be included in the structural composite. In the illustrated embodiment, the fiber 130 includes basalt; however, the fiber 130 may include glass, aramid, carbon, or any other desired fiber material. The bobbins 125 may be coupled to a power drive system that controls the fiber feed rate. In such embodiments, dancers or other automatic tensioning devices (not shown) may be provided to maintain a consistent tension on the fibers 130.

[0029] After being dispensed from the bobbins 125, the fibers 130 pass through a guide assembly 135 that arranges the fibers 130 for wetting at the binder application station 110 (FIGS. 3 and 4). In some embodiments, the guide assembly 135 may arrange the fibers 130 in a plane to provide a relatively large, rectangular surface area for wetting. Alternatively, the guide assembly 135 may arrange the fibers 130 into other patterns, such as cylindrical, tubular, or spiral patterns.

[0030] In some embodiments, the roving station 105 includes one or more heating elements (not shown) to preheat the fibers 130 to a desired temperature before they are dispensed to the binder application station 110. The heating elements may be located internally within the bobbins 125, or may be external to the bobbins 125. For example, heated air may be directed over the fibers 130 as they leave the roving station 105. Preheating the fibers 130 may reduce the energy input required at the binder application station 110 and may help stabilize the binder curing process, described in greater detail below.

[0031] Due to the relatively small diameter of the fibers (when compared to the diameter of the grouped fibers in the die and shaping stations), less time and/or energy is required to preheat the individual fibers than would be required to heat the grouped fibers in one or more of the shaping stations. The shaping stations are operable to maintain the elevated temperature of the preheated fibers. In some embodiments, the binder is heated prior to being applied to the fibers 130.

[0032] With reference to FIGS. 2 and 3, the binder application station 110 is located downstream of the roving station 105 such that fibers 130 exiting the guide assembly 135 are drawn into the binder application station 110 to be wetted with a binder, such as a resin. In some embodiments, the binder is an extremely low viscosity short chain length monomer or combination of monomers, such as Dicyclopentadiene (DCPD) or Tricyclopentadiene (TCPD). In some embodiments, the binder includes one or more low viscosity polyurethane polymers and systems, such as a two component mDI-based elastomer. In other embodiments a thermosetting polymer such as a phenolic resin or an epoxy resin. In other embodiments, the binder may include polyester, vinyl ester, Portland cement, or any other suitable binder.

[0033] The binder has a viscosity that is less than 25 centipoise (cP) at temperatures in the range of 20°C to 55°C. In some embodiments, the binder has a viscosity less than 20 centipoise at 20°C to 55°C. In some embodiments, the binder has a viscosity less than 15 centipoise at 20°C to 55°C. In some embodiments, the binder has a viscosity less than 10 centipoise at 20°C to 55°C.

[0034] Extremely low viscosity binders quickly spread between the fibers 130 and move together with the fibers 130 through the assembly line 100 at high speeds without requiring a traction agent. This results in a consistent end product even at very high speeds.

[0035] The binder application station 110 is operable to apply a desired amount of binder to the fibers in a precisely metered manner. Specifically, depending upon the desired ratio of binder to fibers, the appropriate amount of binder can be applied directly to the fibers. This is in direct contrast to the binder bath shown in FIG. 1 which does not control the amount of binder that is applied to the fibers. The excess binder must be removed and thus, more waste is created. Also, the entire binder bath must be maintained at the appropriate temperature which is a waste of energy to heat the extra binder, especially when some of the heated binder is removed from the fibers. Also, the product produced with the binder bath can be inconsistent because the ratio of fibers to binder is not controlled. In the present invention, the quantity of binder applied to the fibers can be controlled to assure the desired quality and consistency of the product produced.

[0036] FIGS. 3-5 illustrate one embodiment of the binder application station 110. In the illustrated embodiment, the binder application station 110 includes a pressurized well 140. The pressurized well 140 receives the binder from a binder source 145, such as a hopper or storage vessel (FIG. 2). The well 140 includes an end plate 150 having an inlet opening 155 through which the binder may be injected (FIG. 5). The binder is then extruded under pressure through a plurality of channels 160 extending radially-outwardly from the inlet opening 155. The channels 160 communicate with wetting regions 165 located at an outer periphery of the end plate 150.

[0037] During operation, the binder is continuously extruded through the channels 160 and into the wetting regions 165. The fibers 130 pass through the wetting regions 165 to be wetted with the binder, beginning the formation of the matrix composite. In the illustrated embodiment, the end plate 150 includes two wetting regions 165 offset from each other by about 180 degrees. Thus, the fibers 130 may be arranged along two paths that are wet simultaneously. The fibers 130 are spaced apart while traveling through the wetting regions 165 to promote thorough coating of the fibers 130 with the binder. In other embodiments, the end plate 150 may include any number of wetting regions. The operating pressure of the well 140 and the number and size of the channels 160 may be variable to provide a desired wetting rate.

[0038] FIGS. 6 and 7 illustrate portions of a binder application station 110a according to another embodiment. The binder application station 110a can be utilized with any of the embodiments described herein. In some embodiments, the binder application station 110a is utilized in addition to the binder application station illustrated and described in other embodiments, whereas in other embodiments, the binder application station 110a is utilized in the place of the binder application station illustrated and described in other embodiments. In the illustrated embodiment, the binder application station 110a includes a die 170 that guides the incoming fibers 130 into a generally tapered or conical arrangement. The die 170 can be capable of moving in a longitudinal direction (i.e. along the central axis 120). This movement may facilitate formation of the incoming fibers 130 into a generally continuous wall or sheet. The binder application station 110a includes a spray nozzle 175 that receives binder from the binder source 145 (FIG. 2) and is operable to spray a stream of binder against the incoming fibers 130. The position of the nozzle 175 may be modified in the longitudinal direction to adjust the binder spray characteristics.

[0039] In yet another alternative embodiment, the binder application station may include a binder bath. After passing through the bath, the fibers 130 may be routed through a series of parallel rollers to mechanically agitate and physically force the binder into the passing fibers. The binder content of the impregnated fibers may be controlled using wipers and/or rollers. In addition, the binder content may be controlled by directing some of the fibers 130 to bypass the binder bath.

[0040] In this alternative embodiment, the assembly line 100 may further include an oven buncher station between the binder application station and the one or more shaping stations 115 to heat the binder impregnated fiber 130, finish the wetting process, begin the curing process, and roughly form the wetted fibers. In addition, the oven buncher station may include one or more drive rollers to pull the fibers from the roving station 105 and through the binder application station.

[0041] With reference to FIGS. 2, 4, 8, and 9, the assembly line 100 further includes a continuously-conformable translating die 180 that is wrapped around the wetted fibers 130 as they exit the binder application station 110. The illustrated die 180 is a strip of paper fed from a

roll 185 (FIG. 4). The paper die 180 travels along the central axis 120 adjacent the wetted fibers 130, and a series of Teflon guide plates 190 gradually curls the die 180 around the wetted fibers 130 until the die completely surrounds and encases the wetted fibers 130 (FIGS. 8 and 9). As the wetted fibers 130 enter a first portion or entrance 195 of the die 180, the fibers 130 are compressed from the relatively large, rectangular area into a smaller generally circular area corresponding with the diameter of the die at the entrance 195.

[0042] The die 180 travels with the wetted fibers 130 through the remainder of the assembly line 100. As described in greater detail below, the die 180 facilitates travel of the wetted fibers 130 through the shaping stations 115 by inhibiting the wetted fibers 130 from sticking to the shaping stations 115. In addition, the die 180 constrains the wetted fibers 130 during curing, facilitates mixing of the binder and the fibers 130 to ensure thorough wetting, and helps to maintain a consistent curing pressure and temperature.

[0043] The process speed or product output rate of the assembly line 100 and any other continuous FRP manufacturing process is governed by the following equation:

$$Process\ Speed = \frac{Die\ Length}{Resin\ Curing\ Time}$$

[0044] Because the continuously-conformable translating die 180 moves with the wetted fibers 130, it can be many times longer than the static die 30 employed in the typical pultrusion process (FIG. 1). Accordingly, the assembly line 100 may operate at a process speed many times greater than that of the typical pultrusion process. For example, if the translating die has a length of 2,000 feet, and the binder requires 2 minutes to cure, the assembly line 100 will have a potential process speed of 1,000 feet per minute. In some embodiments, the assembly line 100 is configured to have a process speed greater than about 20 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 20 feet per minute and about 50 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 50 feet per minute and about 100 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 100 feet per minute and about 250 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 100 feet per minute and about 500 feet per

minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 100 feet per minute and about 1000 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 20 feet per minute and about 100 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 20 feet per minute and about 1,000 feet per minute. In other embodiments, the assembly line 100 is configured to have a process speed between about 100 feet per minute and about 1,000 feet per minute.

[0045] The paper die 180 may be coated with a release agent, such as silicone, to facilitate removal of the die 180 from the finished structural composite. In addition, the paper die 180 may be relatively porous to permit gas and vapor to be released through the die 180. Alternatively, the die 180 may be substantially air tight.

[0046] The die 180 may include other substrate materials or combinations of materials applied to the wetted fibers 130 in various ways. For example, in some embodiments the die 180 may include a powder or a liquid (e.g., molten wax) that is applied to the wetted fibers 130 and subsequently hardened or cured using UV light, temperature, a chemical reactant, or other suitable means. In other embodiments, the die 180 may include a vapor releasing micro-porous membrane such as GORE-TEX. In other embodiments, the die 180 may include a macro-porous material such as a woven fabric or fiber mat. In yet other embodiments, the die 180 may include one or more metal films, such as non-sacrificial stainless steel, carbon steel cover, or copper etc.

[0047] In some embodiments the die 180 may be wetted by the binder to bind the die 180 to the matrix composite, thereby creating an integrated construction that includes all or a portion of the die 180. Thus, the die material may be chosen to provide the produced structural composite with additional desired properties. For example, the die 180 may include an electrically-conductive material to provide electrical conductivity to an otherwise non-conducting composite. The die material may have an affinity to an external binding compound (e.g., Portland cement) to facilitate integration of the structural composite (e.g., rebar) into its particular application (e.g., reinforced concrete).

[0048] Now referring to FIGS. 2-4, the shaping stations 115 are located downstream of the binder application station 110. In the illustrated embodiment, the assembly line 100 includes

first, second, and third shaping stations 115 that are spaced from one another along the central axis 120 (FIG. 2). In other embodiments, the assembly line 100 may include any number of shaping stations 115.

[0049] The shaping stations 115 each include at least one guide that contacts and shapes the fibers 130. In some embodiments, the guide can include one or more rollers with one or more slots sized to receive and shape the fibers 130. In some embodiments, the guide can include one or more stationary or rotating dies that have one or more openings sized to receive and shape the fibers 130. The slots in the rollers and the openings in the stationary dies can each have different shapes and sizes to mold the fibers 130 into different shapes and sizes.

[0050] Each of the illustrated shaping stations 115 includes a plurality of rollers 200. The rollers 200 are arranged in pairs, and each includes a groove 205 through which the die-wrapped fibers 130 are rolled and shaped (FIG. 10). In some embodiments, pairs of rollers 200 may be positioned in different orientations. For example, pairs of rollers 200 may alternate between horizontal and vertical orientations. Some or all of the rollers 200 may be driven using variable speed drive motors to draw the die 180 and fibers 130 through the assembly line 100.

[0051] Referring again to FIGS. 2 and 3, each shaping station 115 can further include thermal transfer panels (not shown) to allow precise control of the process temperature. For example, each shaping station 115 may be controlled to maintain the wetted fibers 130 at a stable, controlled temperature that cures the binder at a rate of speed that corresponds to the process speed. The specific temperature is dependent upon the type of binder used and the process speed of the assembly line. In some embodiments, a phenolic resin is used as the binder and the fibers are maintained at a temperature of about 160 degrees Celsius. In some embodiments, an epoxy resin is used as the binder and the fibers are maintained at a temperature of between about 50 and about 90 degrees Celsius. Accordingly, the binder curing process may be completed while the shaped, wetted fibers 130 are traveling through the shaping stations 115.

[0052] Process temperature can be controlled in multiple zones along the length of each shaping station 115 to promote or reduce the speed of curing along the length of the die 180. The rollers 200 exert pressure on the die 180 to provide the required curing pressure. As the die 180 and fibers 130 pass between adjacent shaping stations 115, the product may be cooled if

desired (either by exposure to the ambient environment between the adjacent shaping stations 115 or through controlled cooling zones), and gas or vapor byproducts may be vented through the die 180. This is not possible in a typical pultrusion process, as the static dies 30 (FIG. 1) are typically impermeable. In some embodiments, one or more of the shaping stations 115 cool the die 180 and the fibers 130 to a temperature below the glass transition temperature of the binder. Therefore, the die 180 and fibers 130 dispensed from the shaping stations 115 can maintain its shape. In other embodiments, the die 180 and fibers 130 are not cooled below the glass transition temperature until after the die 180 and fibers 130 have exited the shaping stations 115 to permit final manipulation of the die 180 and fibers 130 into the desired final shape and/or formation of any surface configurations (such as, for example, ribs, protrusions, recesses and/or other suitable surface configurations).

[0053] In a typical process, gaps between any stations must be minimized so that proper support is offered to the fibers along an entire length of the assembly line. In contrast, the illustrated shaping stations 115 are spaced apart a distance in the die flow direction, because the die 180 provides sufficient supports to the fibers 130 between the shaping stations 115. The space between the shaping stations 115 permits air and water to vent from the die 180 and fibers 130. Further, the spaced apart shaping stations 115 extend across a longer distance than if the shaping stations 115 were directly adjacent. The increase in the overall distance of the shaping stations 115 permits the die 180 to move through the shaping stations 115 at a faster speed while still partially or fully curing in the shaping stations 115. Therefore, by using more shaping stations 115 and spaced apart shaping stations 115, the process speed can be increased, thereby increasing productivity and profitability. The distance between the shaping stations 115 also decreases the capital cost of building and installing the assembly, when compared to an arrangement in which shaping stations are adjacent for an entire length of the shaping assembly. The shaping stations 115 can be modular, such that one or more shaping stations 115 can be added, removed or repaired without a substantial loss of production. Instead of shutting down production of the entire assembly line (as would be required for units that utilized a single, stationary die), the production would be shut down for a brief period to permit addition, removal or replacement of one or more of the shaping stations 115. The removed shaping station 115 can be repaired or stored while the assembly line is in operation.

[0054] With reference to FIGS. 11-16, one or more of the shaping stations 115 may also dynamically manipulate the die 180 and the fibers 130 to promote thorough wetting and homogeneous curing. Wetting is improved through shear viscosity changes that are induced by dynamically modifying the cross-sectional area of the matrix composite. Further shear mixing of the matrix composite can be induced by selectively increasing and decreasing the mechanical pressure applied by the shaping station 115. In some embodiments, the shaping station 115 can be configured to have incomplete wet-out of the fibers 130 to improve the flexibility of the fibers 130 upon curing.

[0055] In some embodiments, the guides may be configured to progressively increase the applied mechanical pressure over the length of the die 180. In some embodiments, the increase in pressure is created by moving the fibers 130 through a tapered stationary die that has an opening with a decreasing diameter along the length. In other embodiments, the increase in mechanical pressure can be created by moving the fibers 130 through a series of stationary dies, each of which has progressively smaller openings. In some embodiments, the holes in the stationary dies can have different shapes and sizes of openings to dynamically alter the cross-sectional shape of the die 180 and the fibers 130.

[0056] In the embodiment illustrated in in FIG. 11, the rollers 200 are configured to progressively increase the applied mechanical pressure over the length of the die 180. As such, the cross-sectional area of the die 180 may decrease through each successive pair of rollers 200. This promotes thorough wetting and compacting of the fibers 130. In other embodiments, the rollers 200 may be configured to dynamically alter the cross-sectional shape of the die 180 and the fibers 130 (FIGS. 12-15). For example, the die 180 may be rolled into an oval shape that assumes different orientations at alternating roller pairs 200 to promote further shear mixing (FIG. 12). Alternatively, die 180 may be rolled into a variety of other shapes, such as oval, circle, rectangle, square, triangle, etc. (see, for example, FIG. 13). In other embodiments, one or more of the shaping stations 115 may twist the die 180 and the fibers 130 about the central axis 120 (FIG. 14). In yet other embodiments, one or more of the shaping stations 115 may alternatingly increase and decrease the cross-sectional area of the die 180 (FIG. 15). In still other embodiments, the rollers 200 may be offset to create undulations in the die 180 and the fibers

130 (FIG. 16). Each of the shaping stations 115 can have different arrangements and configurations of rollers 200 and/or stationary dies.

[0057] In some embodiments, the assembly line 100 may further include a burn-off station 210 to thermally abrade the cured surface of the composite structure (FIG. 2). The burn-off station 210 may be employed to remove the die, to expose portions of the fiber, and/or to provide a carbonaceous char that may have an affinity for an external binding compound like Portland cement.

[0058] In some embodiments, the assembly line 100 may further include a post-cure station 215. The post-cure station 215 may include one or more heating elements to provide any necessary secondary curing time and temperature controls. In addition, the post-cure station 215 may include one or more machining devices operable to shape the structural composite into a desired final shape. For example, the structural composite may be bent or cut and folded into a C-channel shape, a spiral shape or other desirable shape.

[0059] In some embodiments, the assembly line 100 may further include a packaging station 220. The packaging station 220 may include one or more cutting devices operable to cut the structural composite into a desired length for sale and shipping. The structural composite may be marked with product information, branding information, or other indicia, and then packaged for shipping.

[0060] In operation, a plurality of fibers 130 is dispensed from the roving station 105 and moved along the assembly line 100 to the binder application station 110. The fibers 130 are generally spaced apart as they enter the binder application station 110 such that the fibers 130 extend across a first, relatively large surface area. After being wetted with binder, the wetted fibers 130 are guided into the first portion 195 of the die 180 proximate the binder application station 110, and the die 180 is curved to wrap around the wetted fibers 130. As the die 180 is wrapped around the wetted fibers 130, the fibers 130 are compressed together. The wetted fibers 130, encased by the die 180, are then fed into the shaping stations 115.

[0061] In the shaping stations 115, the die 180 and the wetted fibers 130 are compressed between the guides, such as the sets of rollers 200 or the stationary dies to mix the binder and the

fibers 130, to form the product shape. The die 180 separates the wetted fibers 130 from the rollers 200 and/or the stationary dies in order to prevent the binder from sticking to the rollers 200 and/or the stationary dies. Heat is applied throughout the shaping stations 115 to promote curing of the binder. As the die 180 travels between adjacent shaping stations, the matrix may cool and/or expel gas and vapor byproducts.

[0062] In some embodiments, sand may be applied to the die 180 and/or the fibers 130 before or after curing has been completed. The sand may be chosen to improve physical bond characteristics between the final composite of the fibers 130 and the binder and the material the final composite will be connected to, such as, for example, concrete.

[0063] Various features of the invention are set forth in the following claims.

CLAIMS

What is claimed is:

1. A method of manufacturing a structural member, the method comprising:

applying a binder having a viscosity below 25 centipoise (cP) at 30°C to at least one of a plurality of fibers, wherein when the binder is applied, the fibers are spaced apart and extend across a first area;

providing a die having a first portion with a first diameter positioned to receive the fibers and a second portion with a second diameter positioned downstream of the first portion, wherein the first diameter is greater than the second diameter and wherein the die is tapered between the first portion and the second portion;

after applying the binder, guiding the plurality of fibers along the die;

decreasing a distance between the plurality of fibers with the die, wherein after decreasing the distance between the plurality of fibers, the fibers extend across a second area that is smaller than the first area; and

after decreasing the distance, shaping the plurality of fibers with a shaping station.

2. The method of claim 1, wherein the shaping station is a first shaping station, the method further comprising

after shaping the fibers with the first shaping station, shaping the plurality of fibers with a second shaping station, spaced from the first shaping station; and

after shaping the plurality of fibers with the second shaping station, shaping the plurality of fibers with a third shaping station, spaced from the first and second shaping stations.

3. The method of claim 1, further comprising

preheating the plurality of fibers to a first temperature;

moving the preheated fibers along an assembly line;

after decreasing, maintaining the temperature of the plurality of fibers at a temperature substantially similar to the first temperature;

maintaining the temperature while shaping the plurality of fibers with the shaping station.

4. The method of claim 3, wherein the resin includes at least one short chain length monomer.

5. The method of claim 1, wherein the die includes a porous material to thereby permit air to escape through the die.

6. The method of claim 1, further comprising moving the plurality of fibers out of the shaping station; and

curing the plurality of fibers after moving the plurality of fibers out of the shaping station.

7. The method of claim 1, further comprising applying the binder to the die prior to decreasing the distance between the plurality of fibers with the die,

8. A method of manufacturing a structural member, the method comprising:

preheating a plurality of fibers to a first temperature;

moving the preheated fibers along an assembly line;

applying a binder having a viscosity below 25 centipoise (cP) at 30°C to at least one of the preheated fibers; wherein when the binder is applied, the fibers are spaced apart and extend across a first area;

after applying the binder, guiding the preheated fibers along a die;

decreasing a distance between the plurality of fibers with the die, wherein after decreasing the distance between the plurality of fibers, the fibers extend across a second area that is smaller than the first area;

after decreasing, maintaining the temperature of the plurality of fibers at a second temperature substantially similar to the first temperature; and

shaping the plurality of fibers with a shaping station while maintaining the temperature.

9. The method of claim 8, wherein the resin includes at least one short chain length monomer.

10. The method of claim 8, wherein the die includes a porous material to thereby permit air to escape through the die.

11. The method of claim 8, further comprising applying the binder to the die prior to decreasing the distance between the plurality of fibers with the die.

12. The method of claim 8, wherein applying the binder includes spraying the binder on the at least one of the plurality of fibers.

13. The method of claim 8, wherein applying the binder includes extruding the binder from a pressurized chamber and dragging the at least one fiber through the extruded binder.

14. The method of claim 8, wherein applying the binder includes spraying the binder on the at least one of the plurality of fibers, and extruding the binder from a pressurized chamber and dragging the at least one fiber through the extruded binder.

15. A method of manufacturing a continuous structural member, the method comprising:

preheating a plurality of fibers to a first temperature;

moving the preheated fibers along an assembly line;

applying a binder having a viscosity below 25 centipoise (cP) at 30°C to at least one of the preheated fibers;

providing a die shaped to receive the preheated fibers, wherein the die moves together with the preheated fibers along at least a portion of the assembly line;

maintaining a temperature of the plurality of fibers at a temperature substantially similar to the first temperature; and

compressing the plurality of fibers within the die while maintaining a temperature.

16. The method of claim 15, further comprising applying the binder to the die prior to decreasing the distance between the plurality of fibers with the die.

17. The method of claim 15, wherein applying the binder includes spraying the binder on the at least one of the plurality of fibers.

18. The method of claim 15, wherein applying the binder includes extruding the binder from a pressurized chamber and dragging the at least one fiber through the extruded binder.

19. The method of claim 15, wherein the binder includes at least one short chain length monomer.

20. The method of claim 15, wherein the die includes a porous material to thereby permit air to escape through the die.

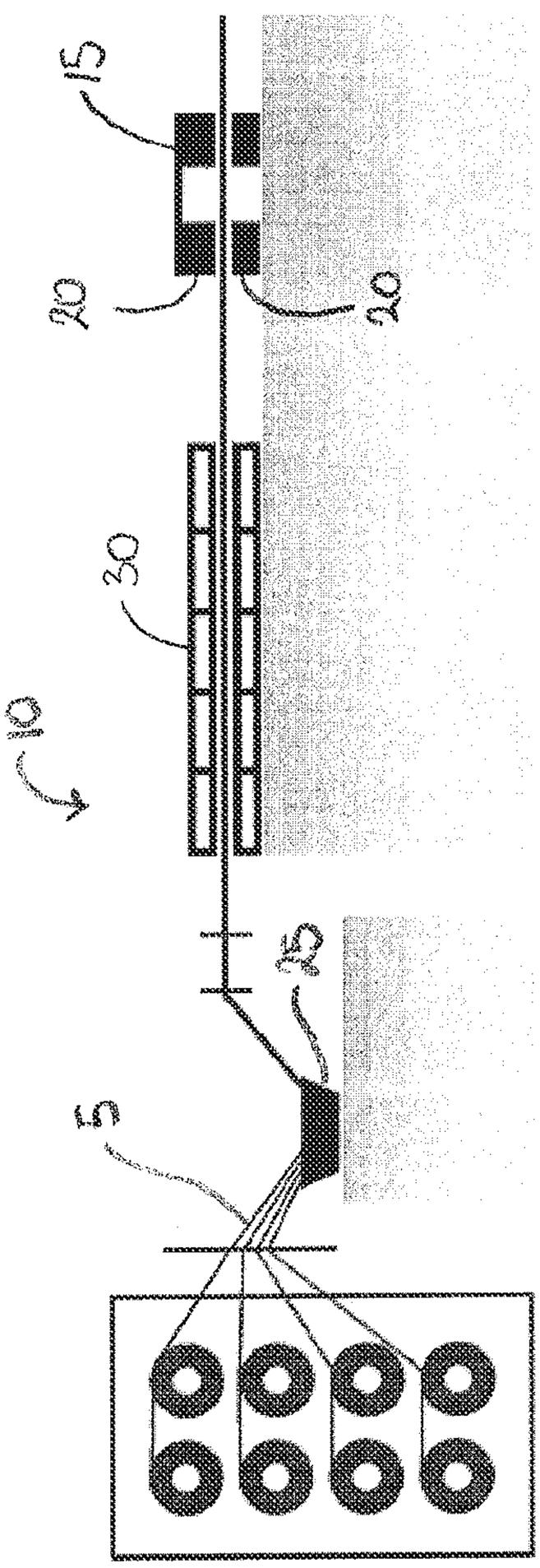

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FIG. 1

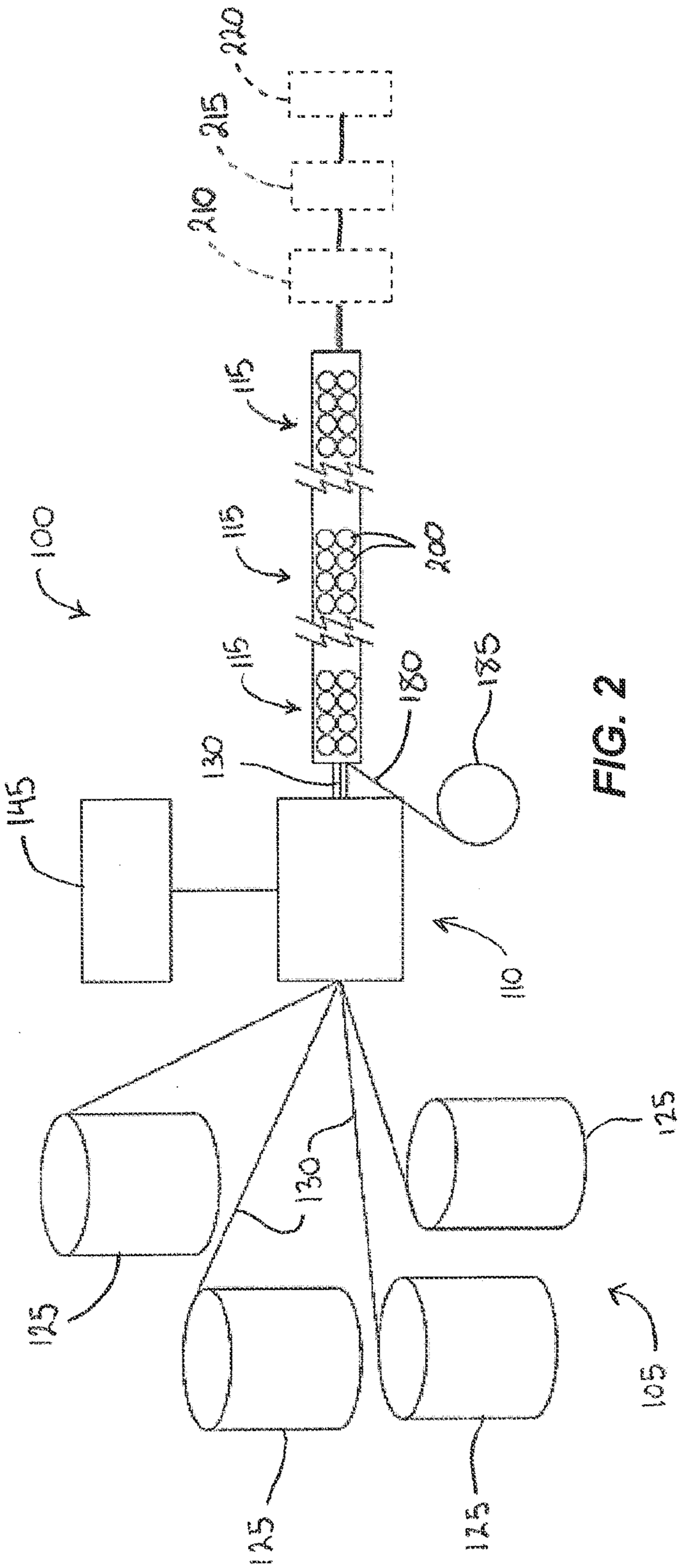

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FIG. 2

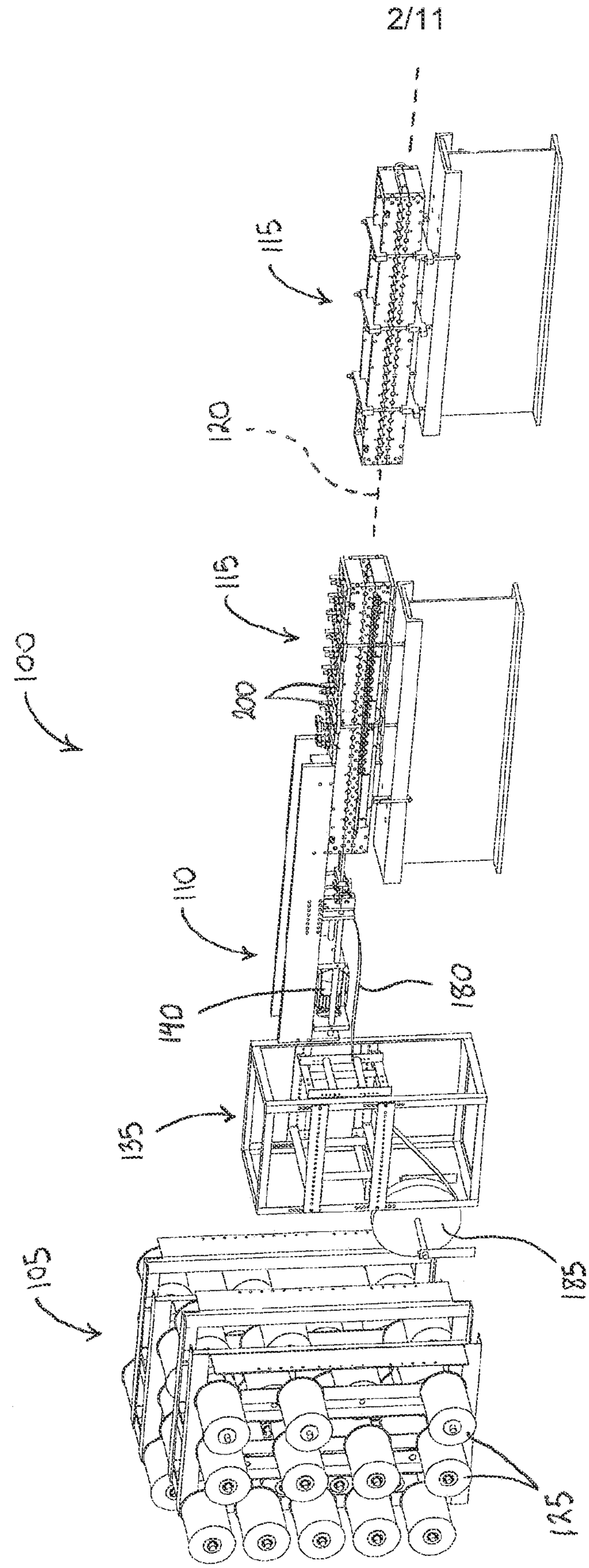


FIG. 3

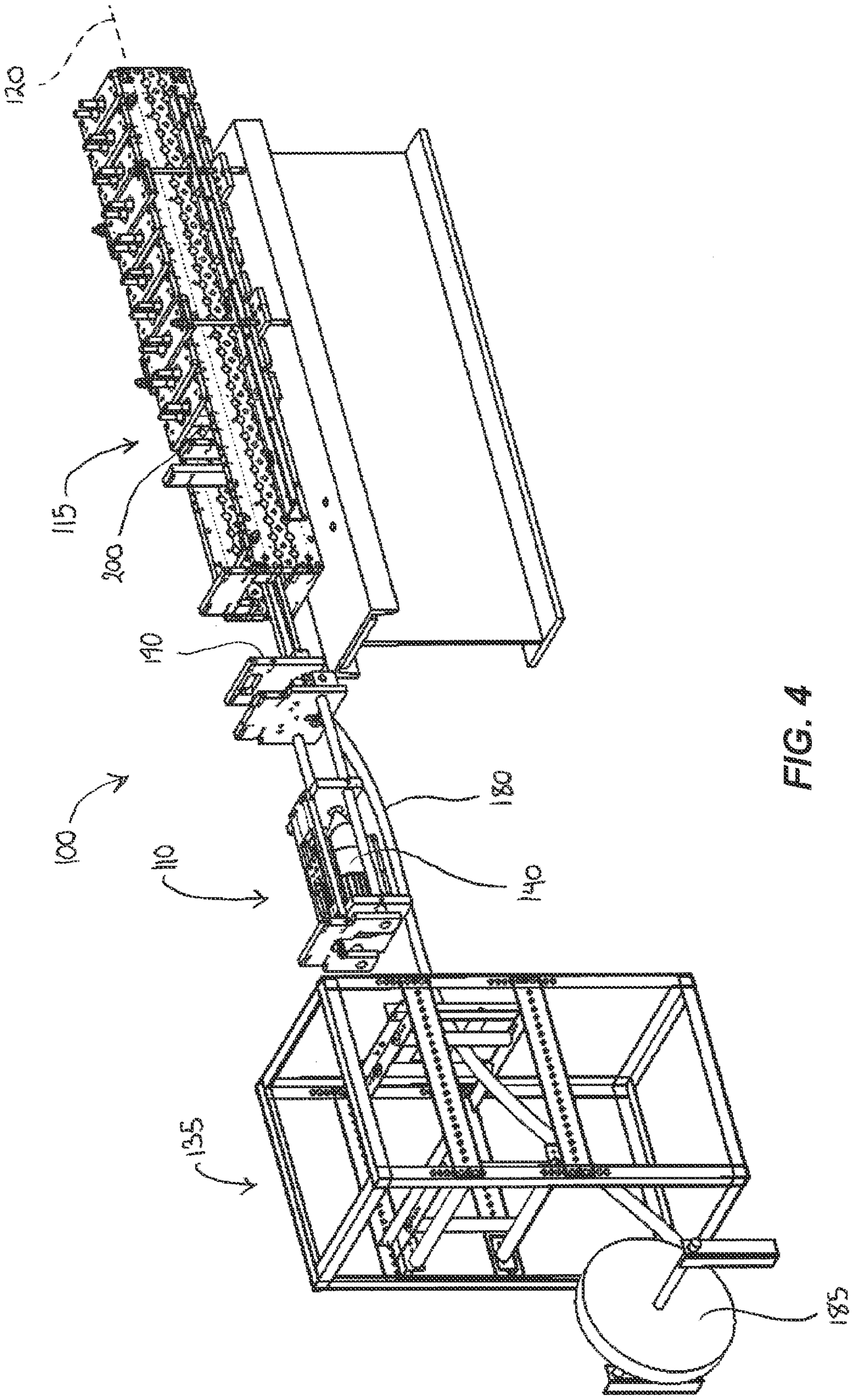


FIG. 4

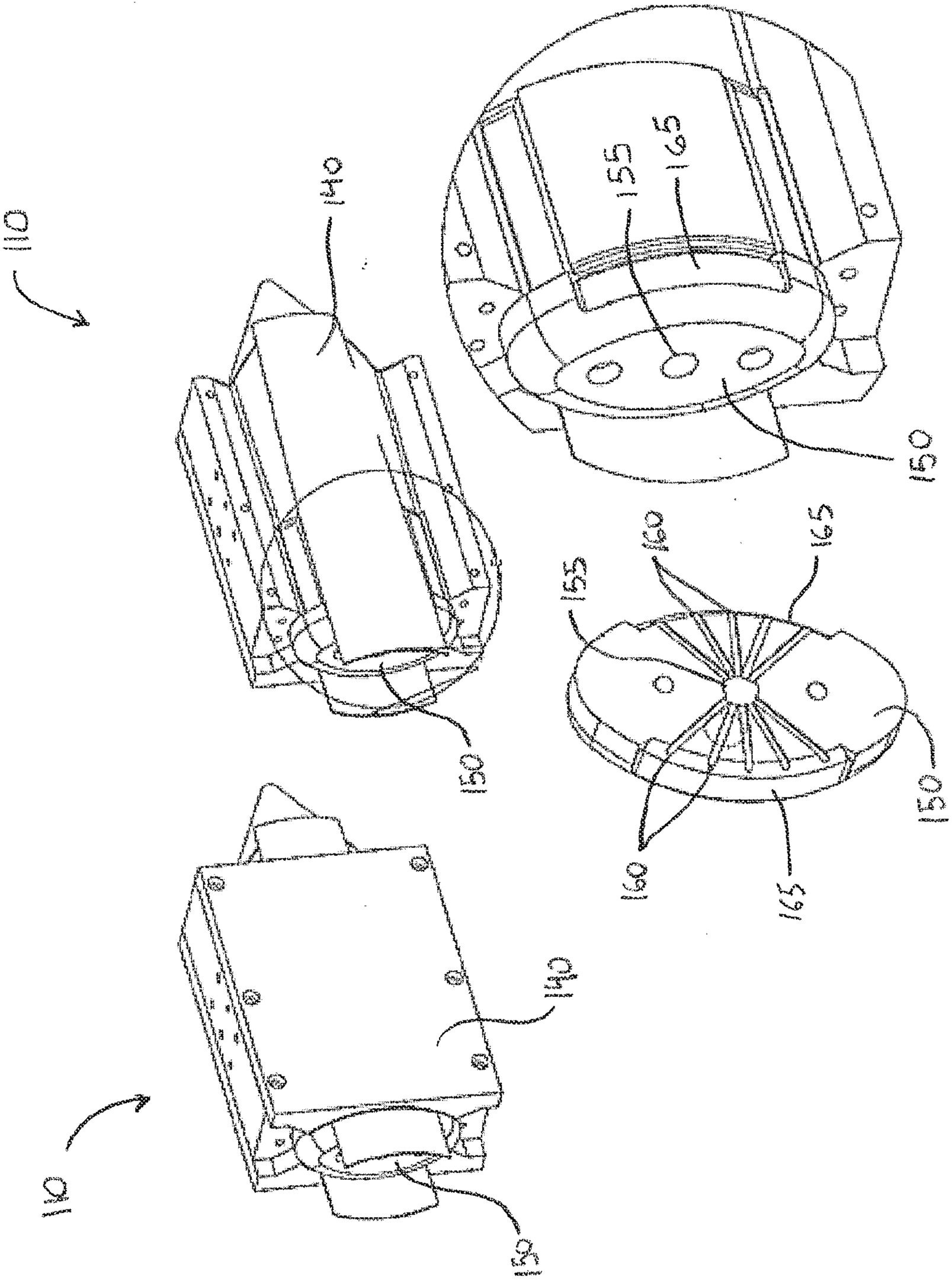


FIG. 5

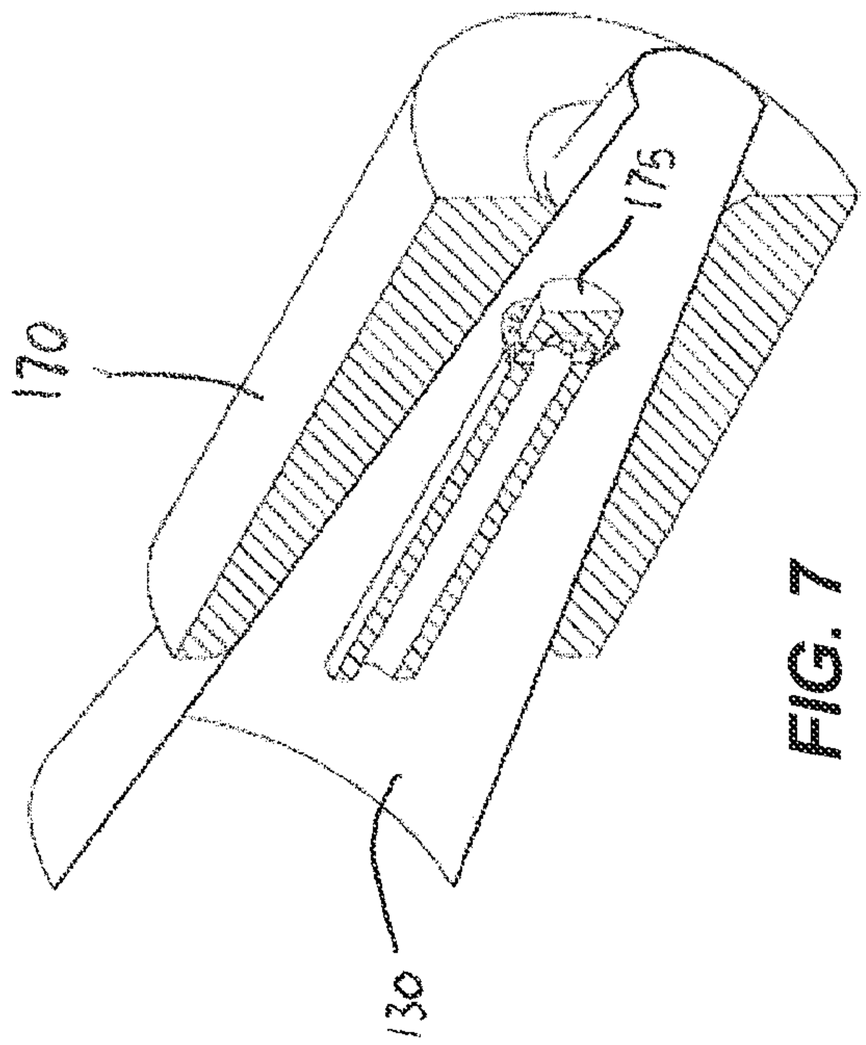


FIG. 7

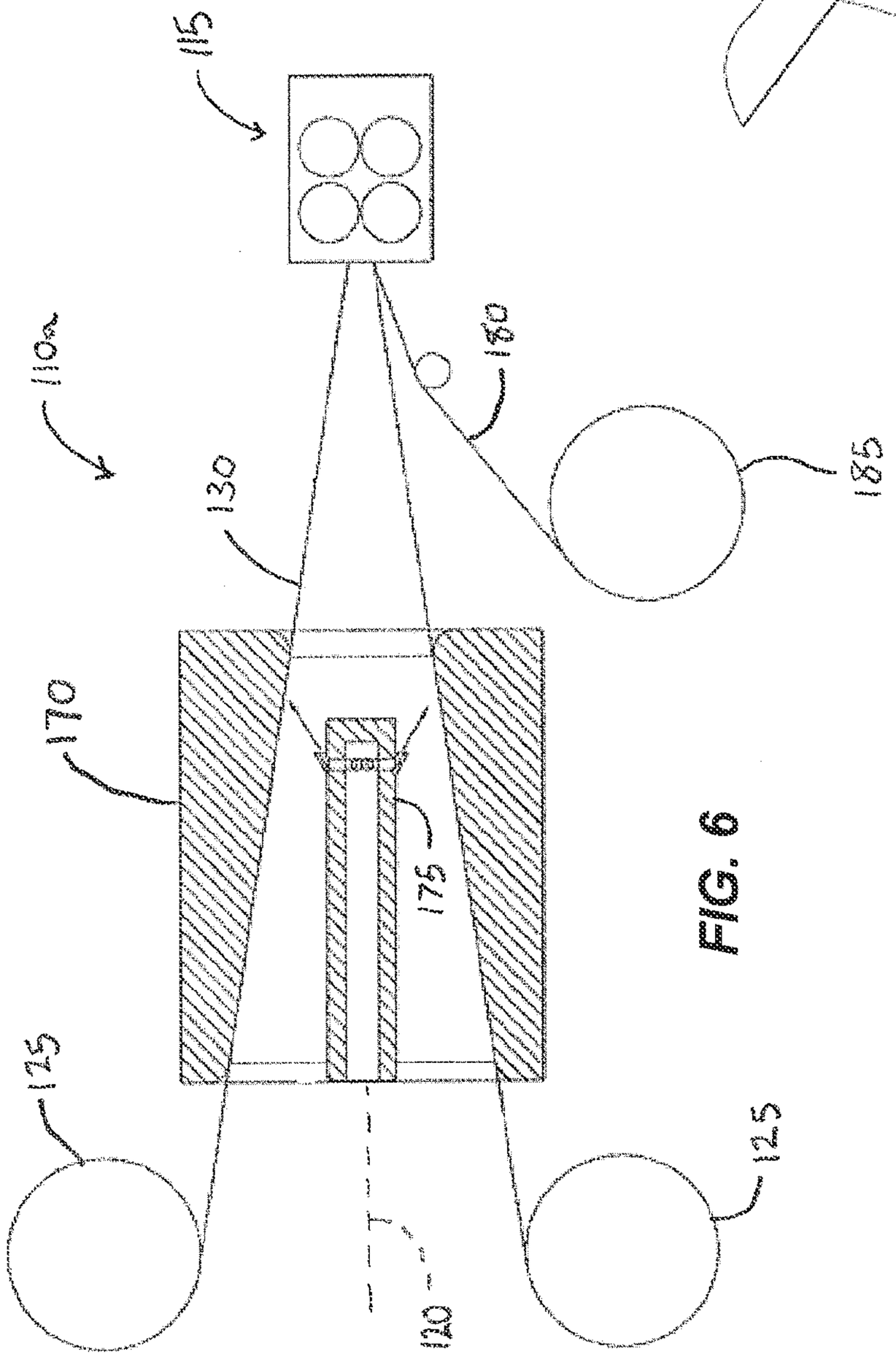


FIG. 6

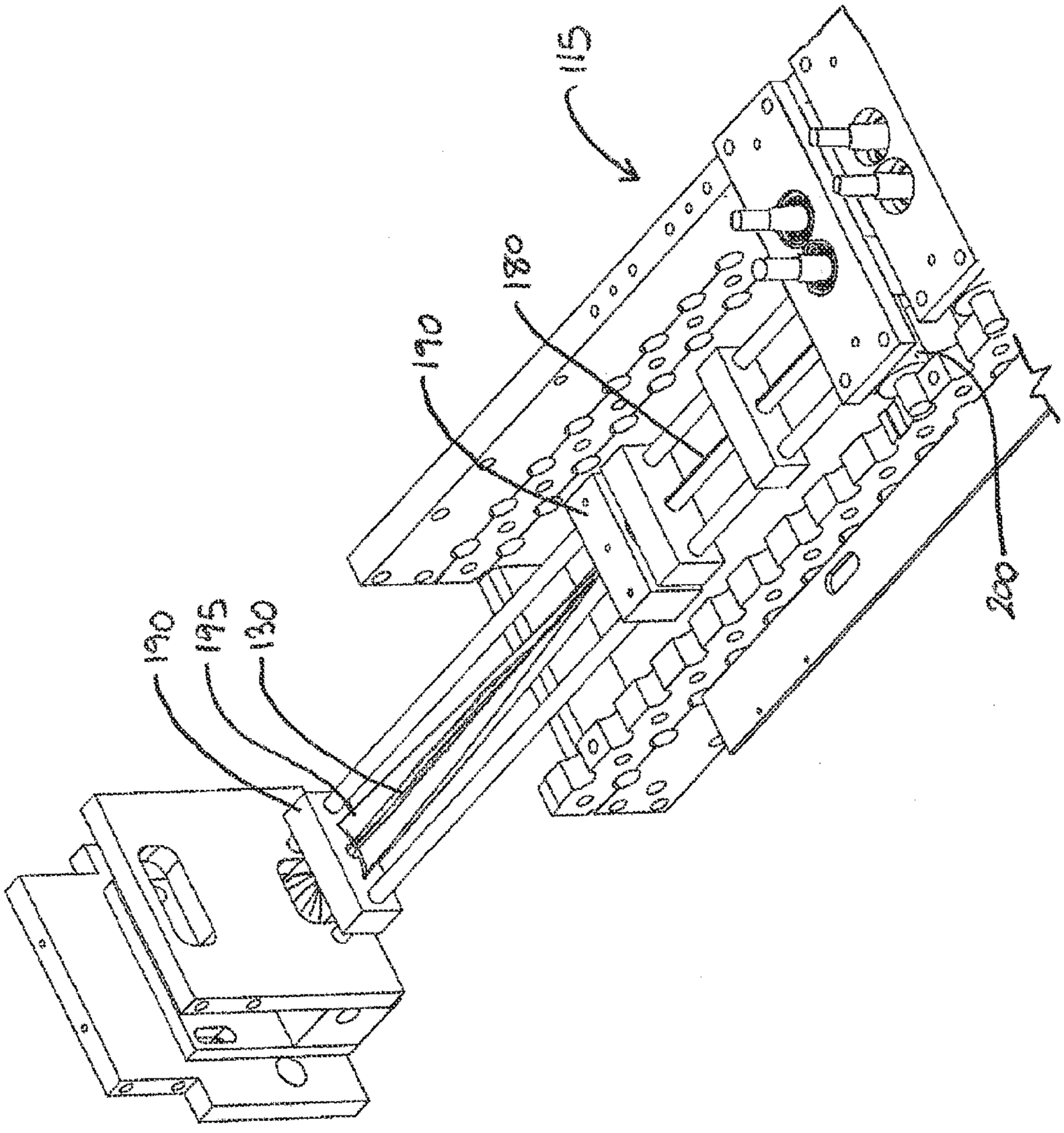


FIG. 8

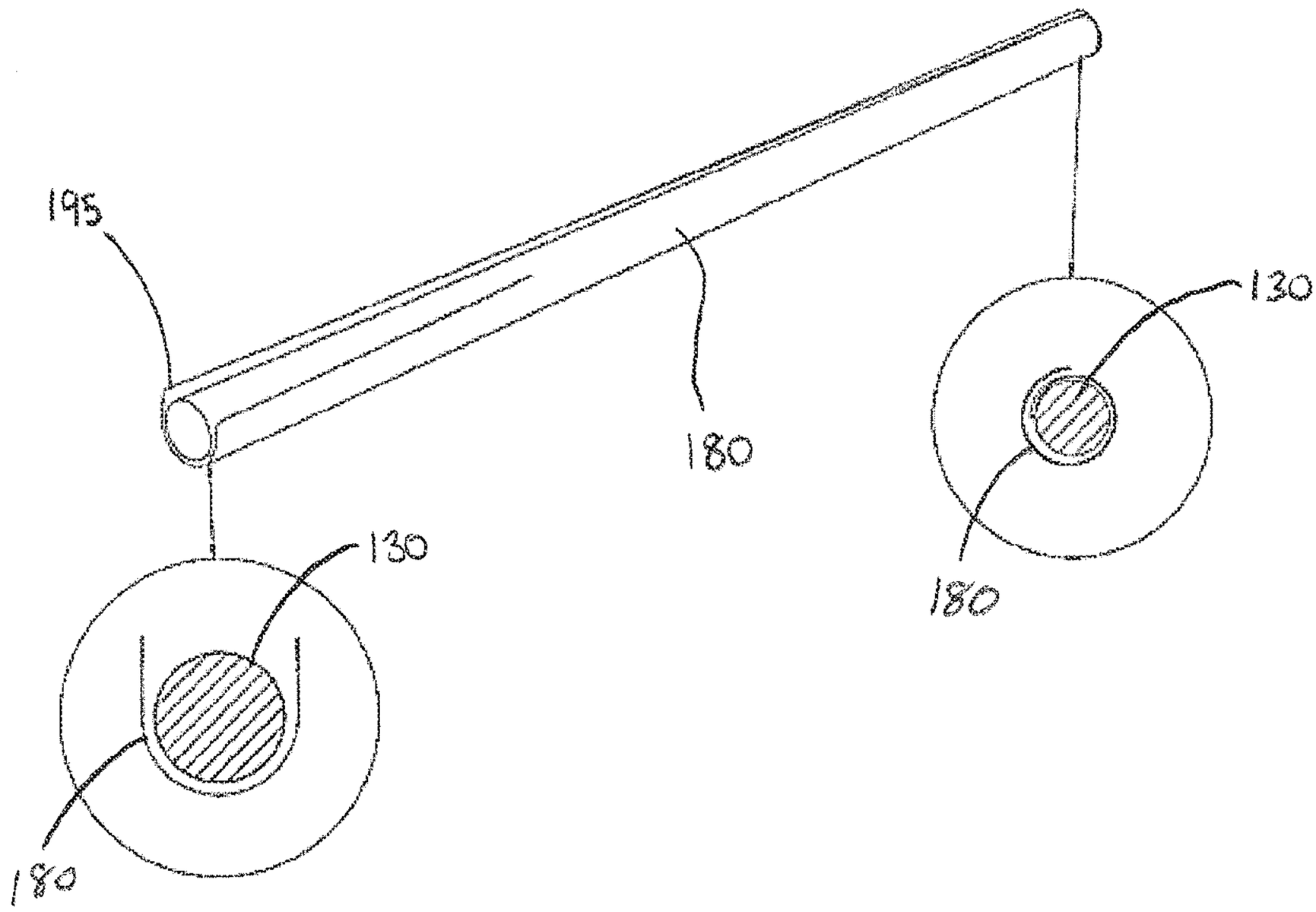


FIG. 9

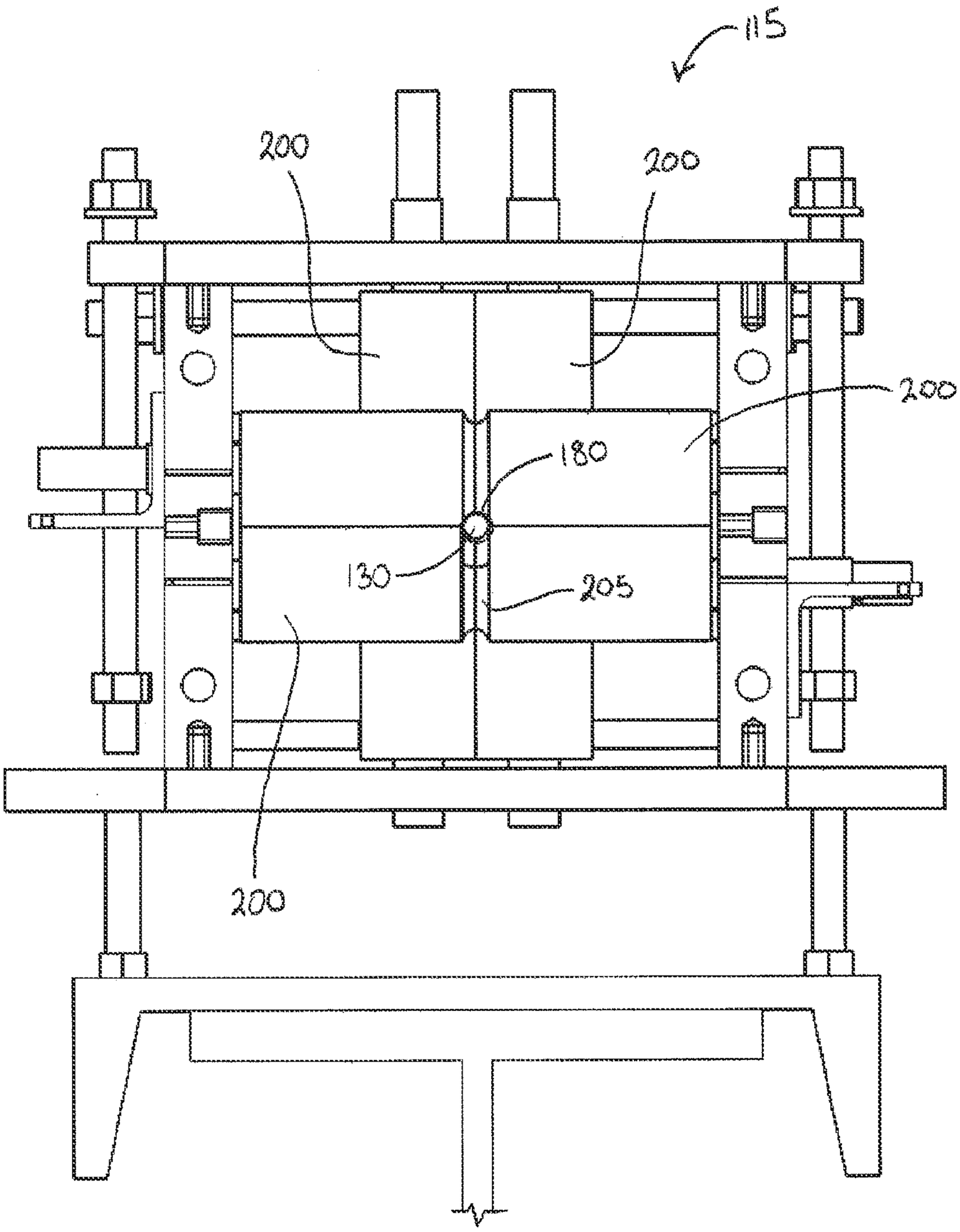


FIG. 10

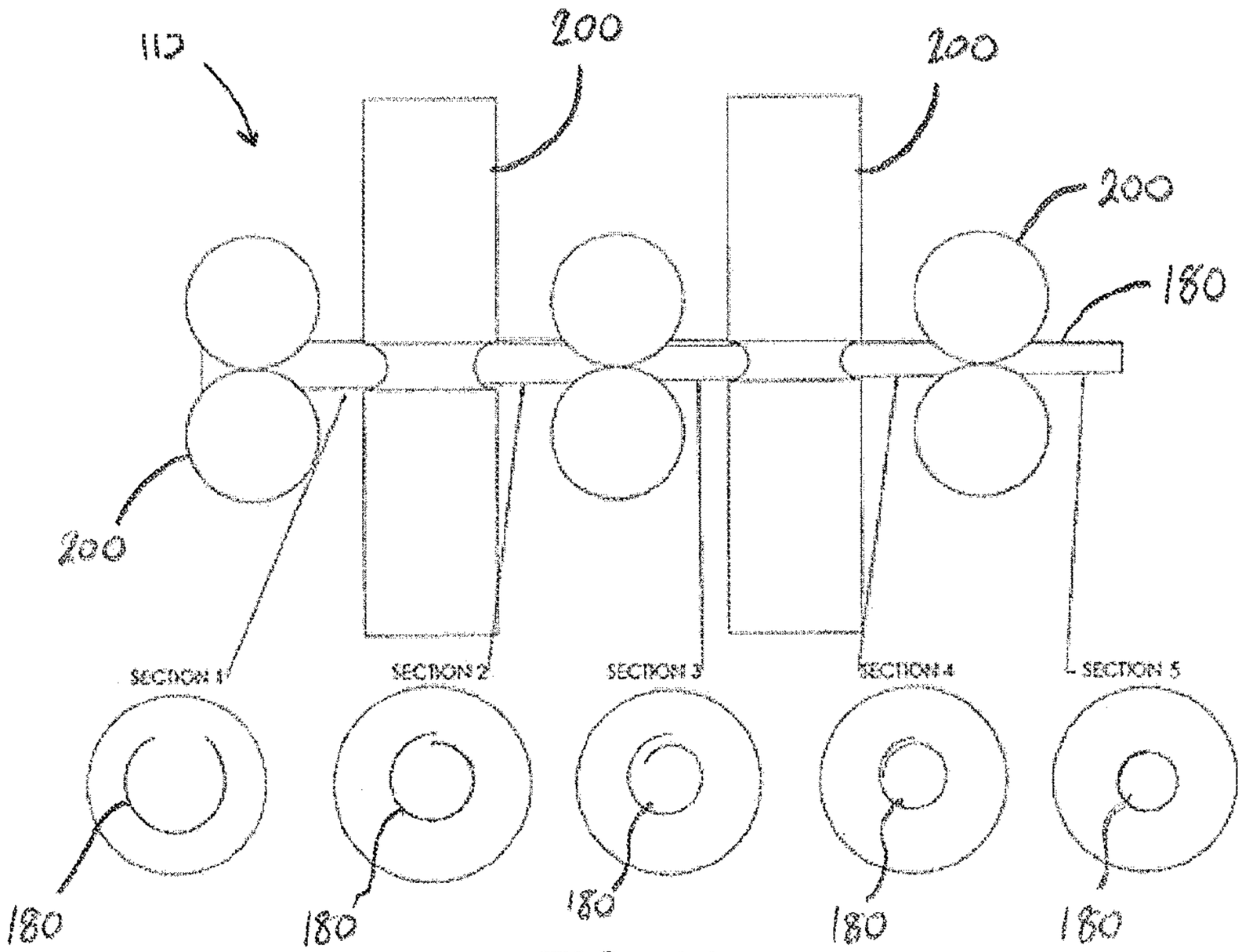

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FIG. 11

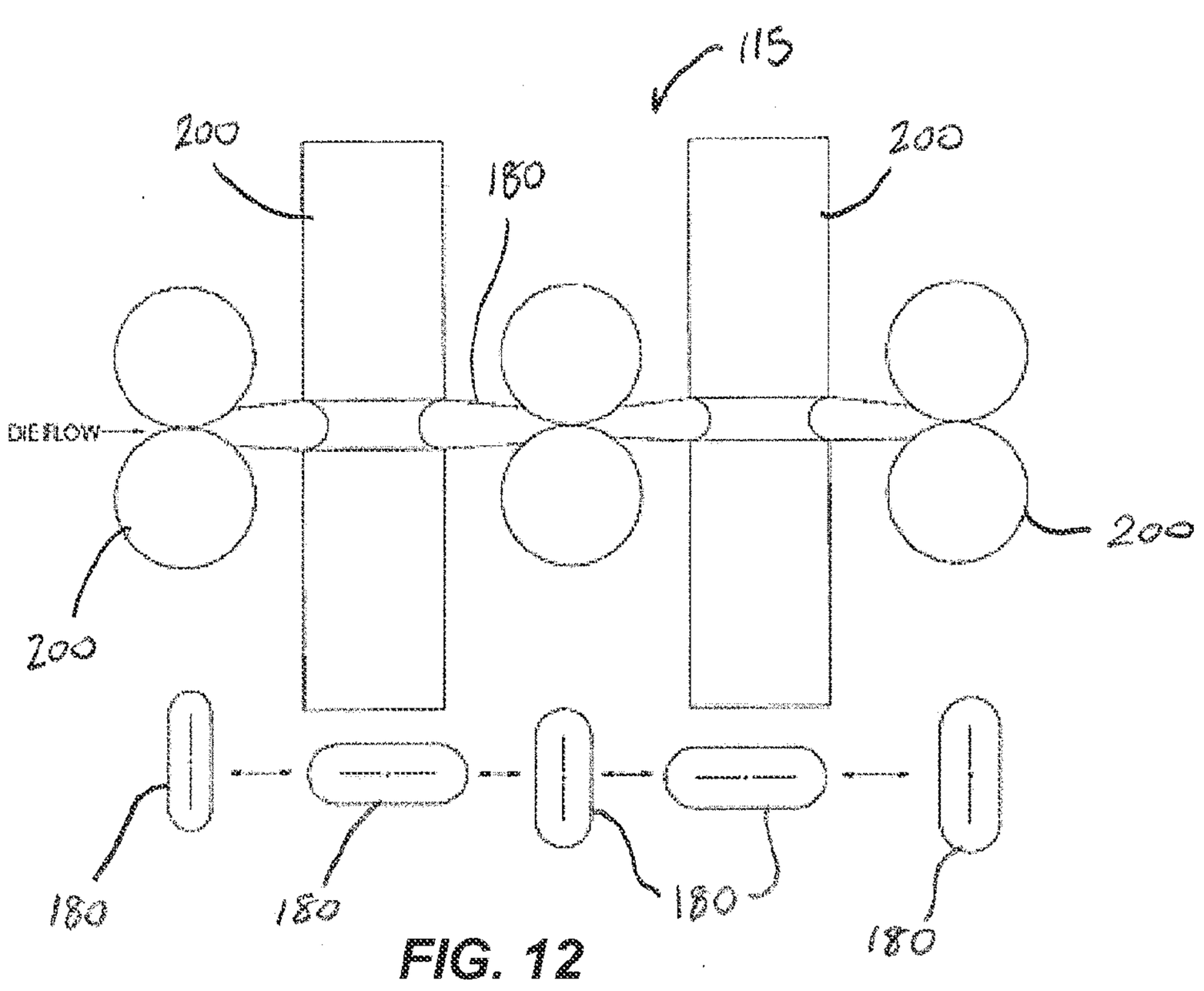

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FIG. 12

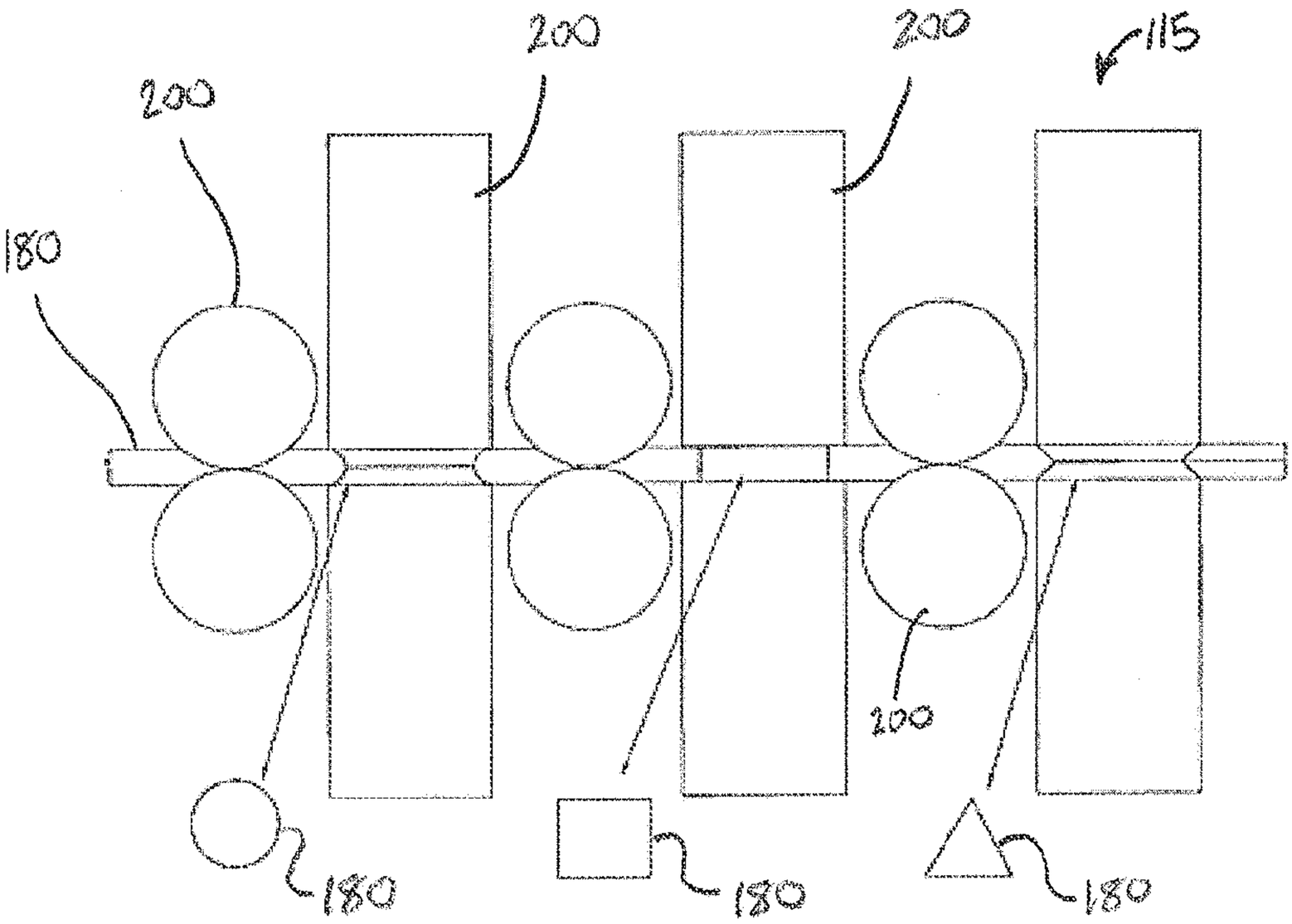


FIG. 13

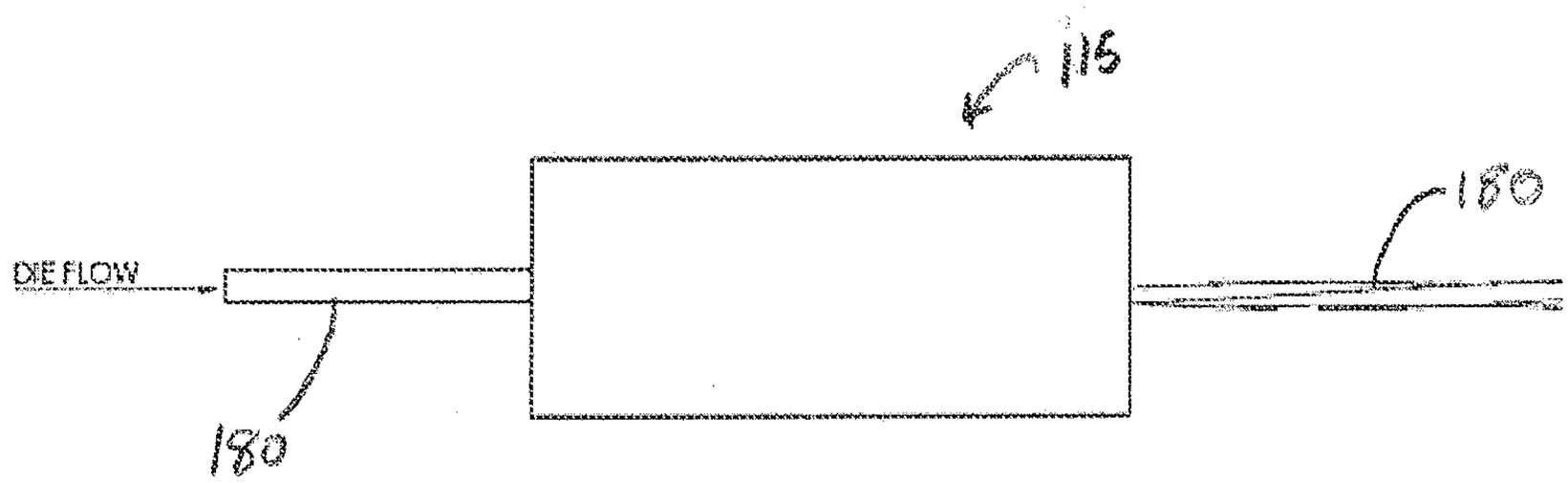


FIG. 14

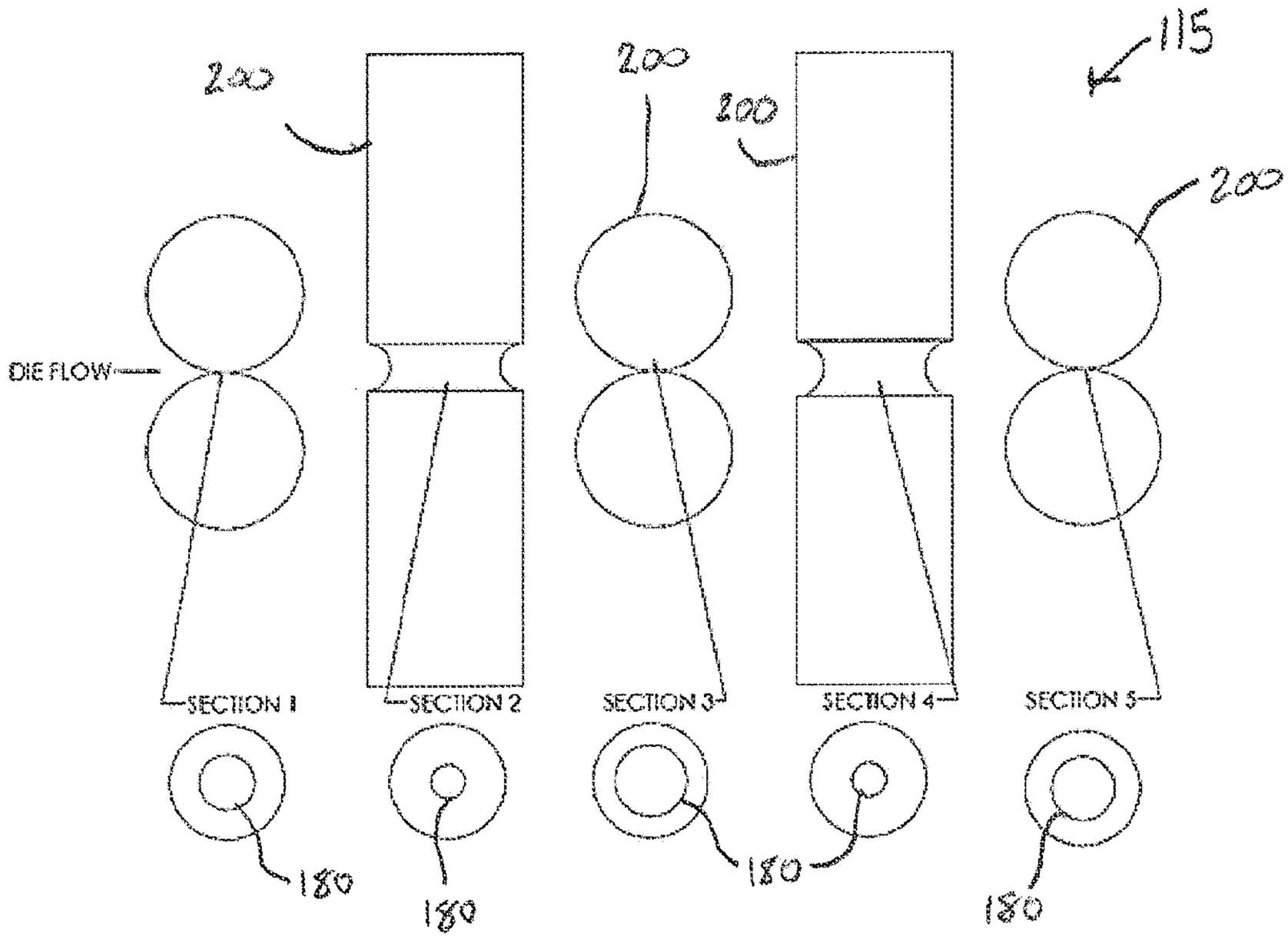

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FIG. 15

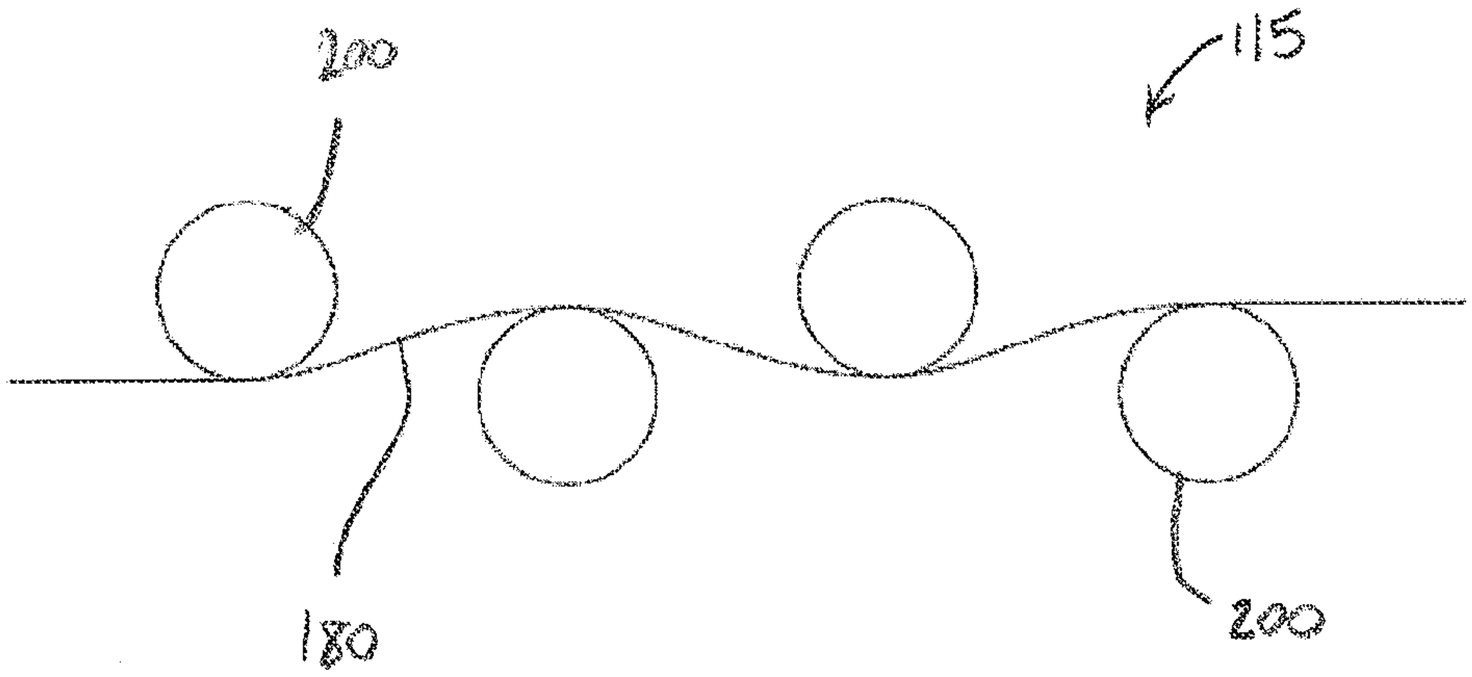

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FIG. 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2020/060182

A. CLASSIFICATION OF SUBJECT MATTER
INV. B29C70/52 B29C70/54 B29B15/12
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B29C B29B

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2014/332996 A1 (KIILUNEN ERIK JOHN [US] ET AL) 13 November 2014 (2014-11-13) claim 1 -----	1-3,5-8, 10-18,20 4,9,19
Y	SHAKYA N ET AL: "Effect of Resin Viscosity in Fiber Reinforcement Compaction in Resin Injection Pultrusion Process", APPLIED COMPOSITE MATERIALS, KLUWER ACADEMIC PUBLISHERS, LONDON, NL, vol. 20, no. 6, 5 June 2013 (2013-06-05), pages 1173-1193, XP035362798, ISSN: 0929-189X, DOI: 10.1007/S10443-013-9320-0 [retrieved on 2013-06-05] Conclusions -----	1-3,5-8, 10-18,20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 February 2021	09/03/2021
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Van Wallene, Allard

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2020/060182

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		CN 105307843 A	03-02-2016
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