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(54) **FRICTION-STIR EXTRUDERS AND FRICTION-STIR EXTRUSION PROCESSES**

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B21C 25/02 (2006.01)

B21C 3/02 (2006.01)

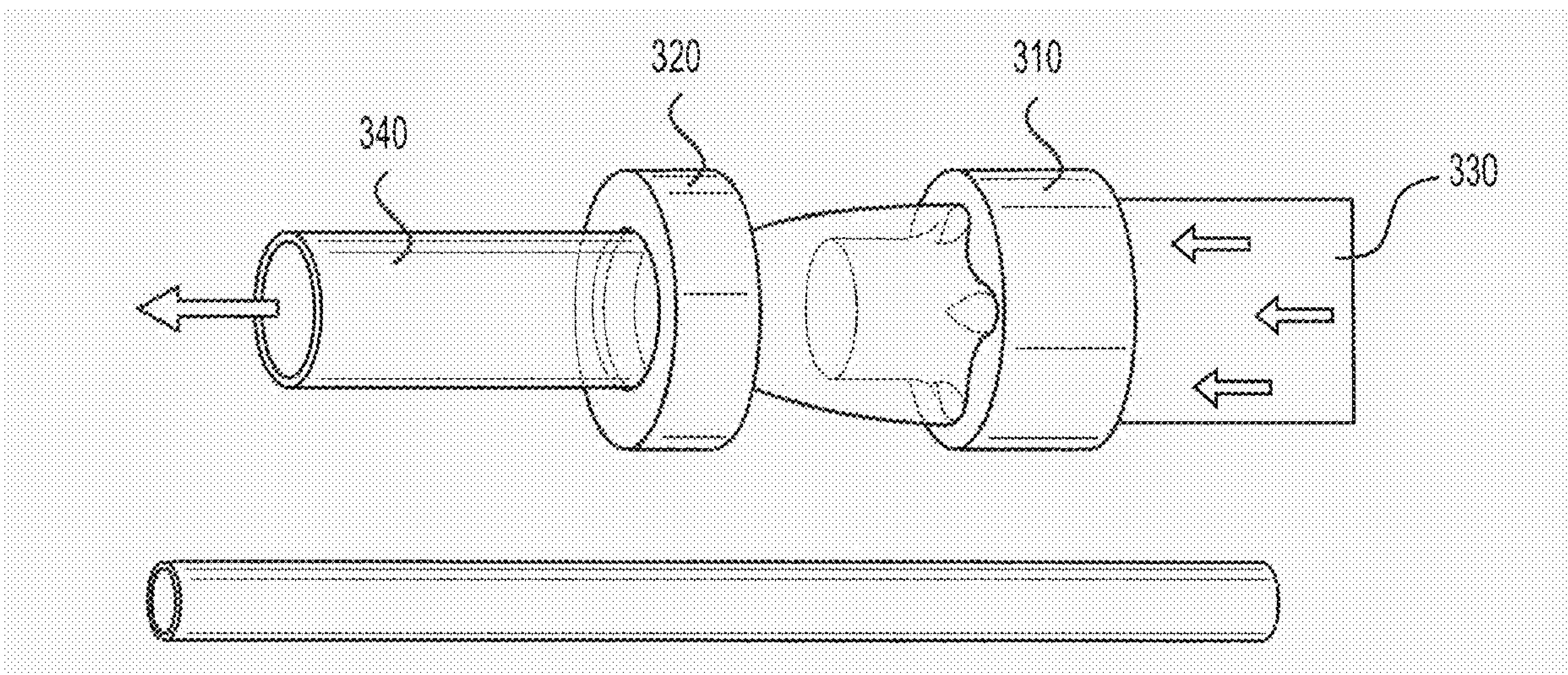
(52) **U.S. Cl.**

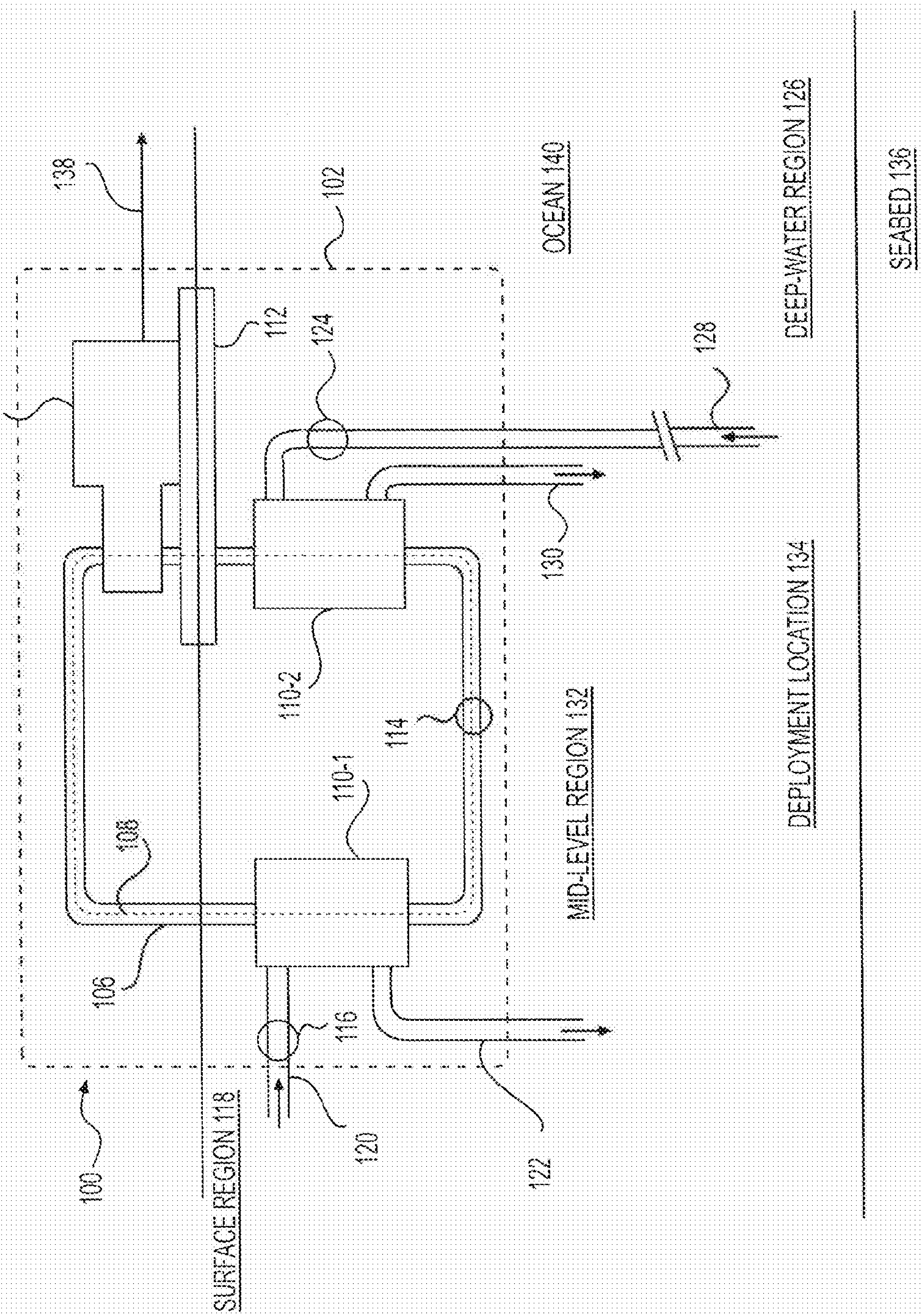
CPC . ***B21C 37/20*** (2013.01); ***B21C 3/02*** (2013.01); ***B21C 25/02*** (2013.01)

USPC **72/68**; 72/256; 72/283

(57) **ABSTRACT**

A friction-stir mandrel includes a textured end portion integral with a body portion. The textured end portion is configured to friction-stir process a starting material forced across the textured end portion and through a die in a plasticized state to form a pipe. A pipe can be formed by forcing a starting material across a textured end of the mandrel and through a die in a plasticized state, so that the textured end of the mandrel breaks up existing grains of the starting material. The pipe is formed from material that is forced through the die. The friction-stir mandrel can be used with porthole die friction-stir extrusion, seamless tube friction-stir extrusion, and tube friction-stir drawing processes to provide tubing in which the grains are broken up by the textured portion of the friction-stir mandrel. The textured portion can include features, such as threads, ridges, studs, protrusions, and the like.

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MID-LEVEL REGION 132
DEPLOYMENT LOCATION 134
DEEP-WATER REGION 126
SEABED 136
OCEAN 140

FIG. 1

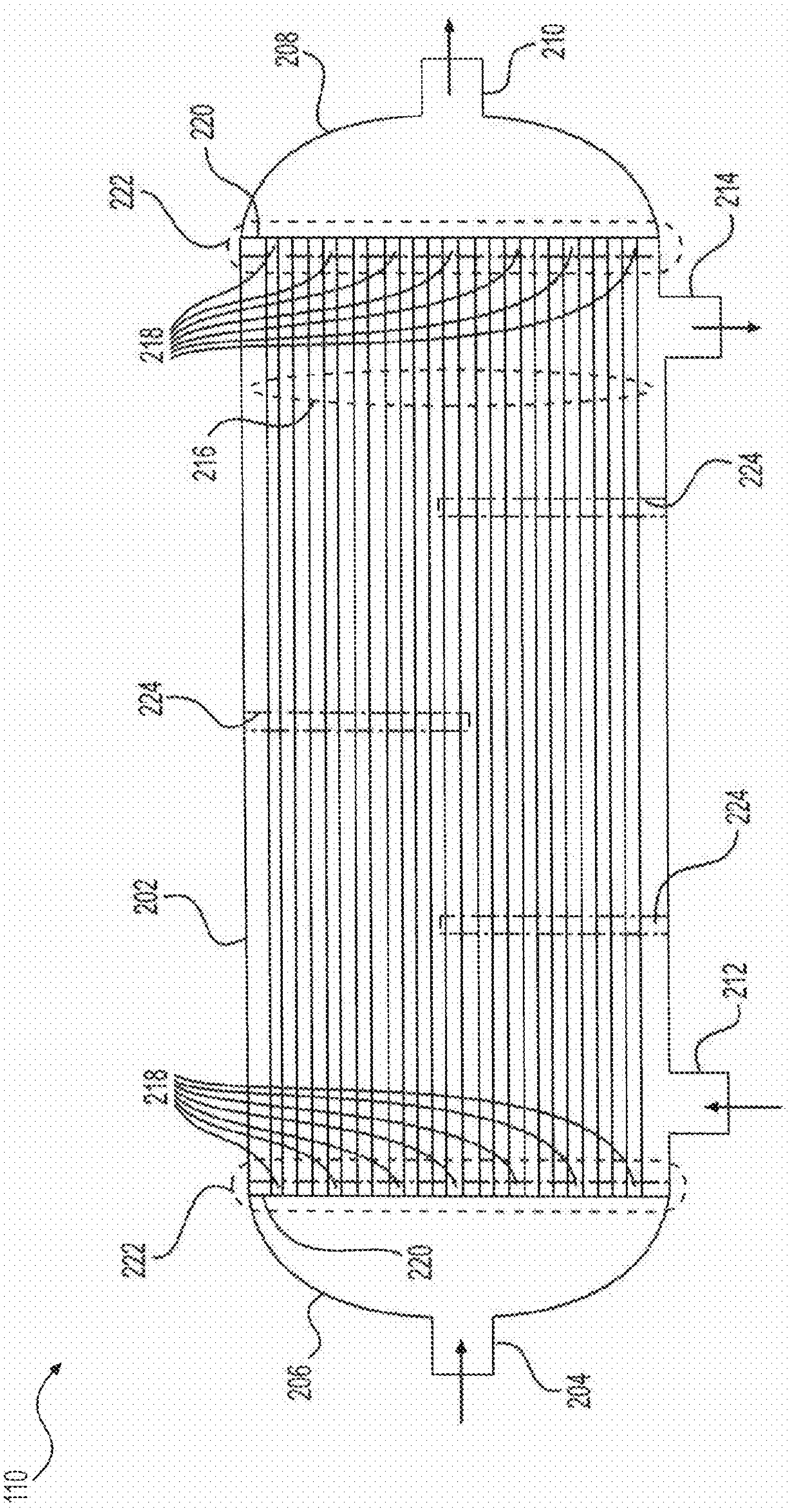
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FIG. 2

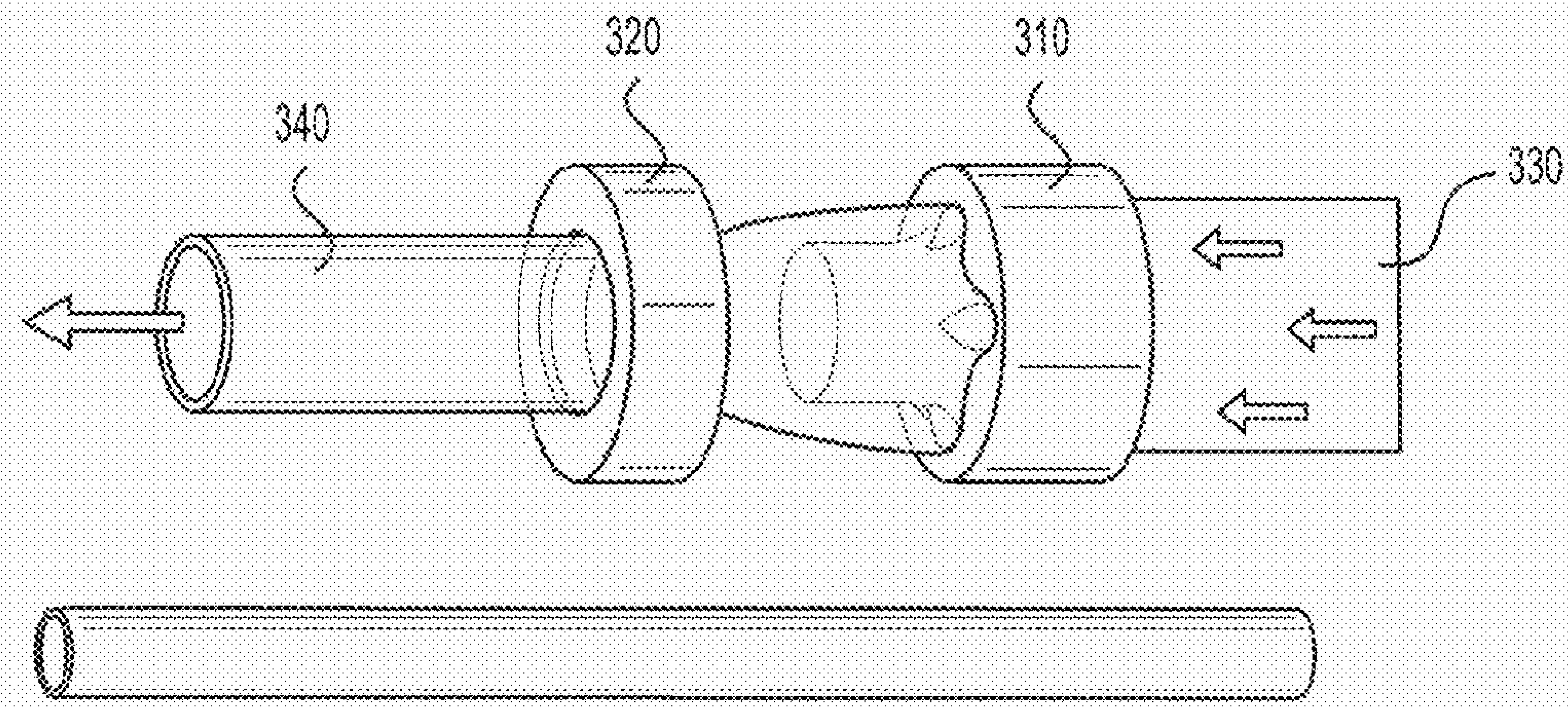


FIG. 3A

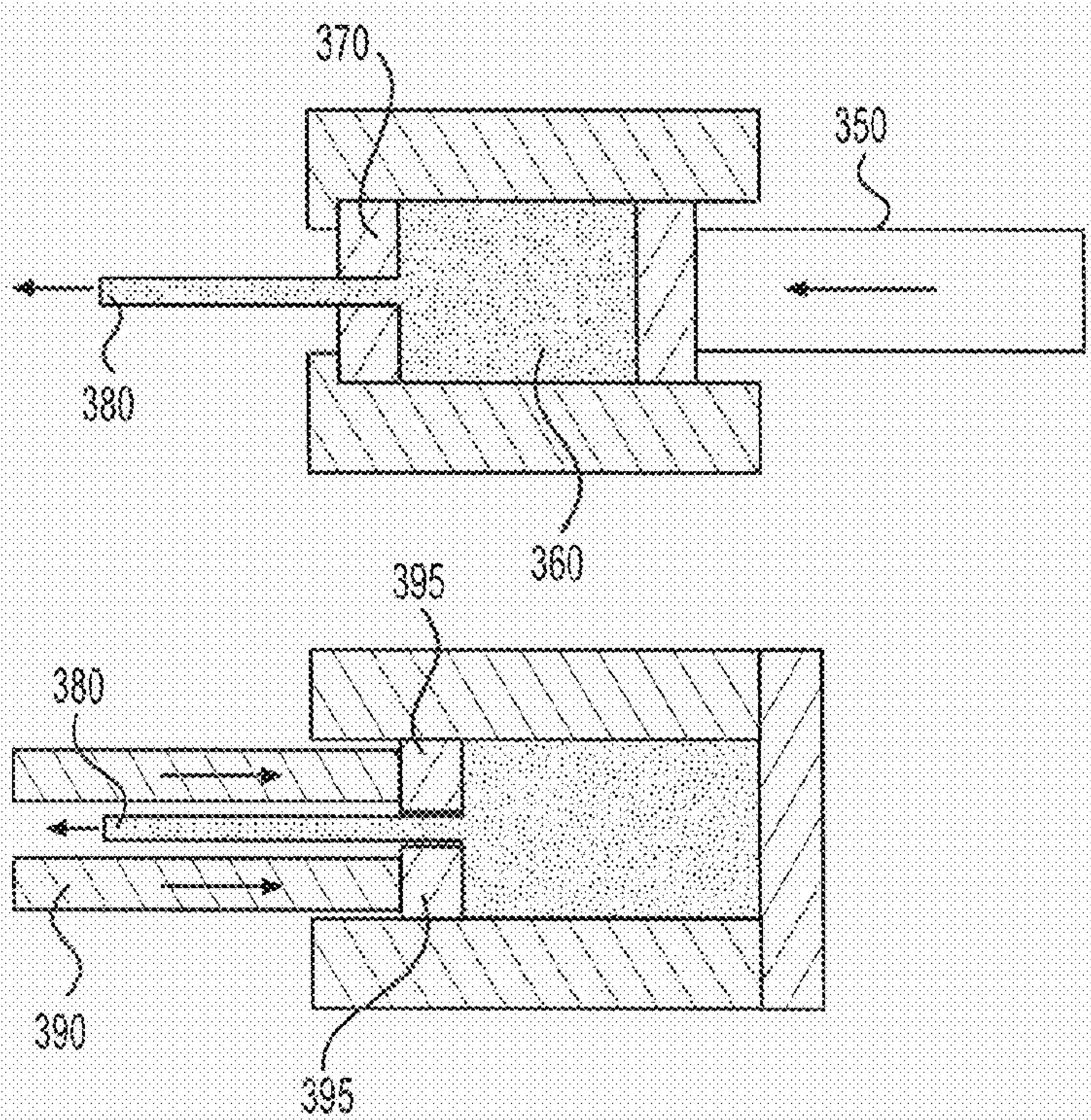


FIG. 3B

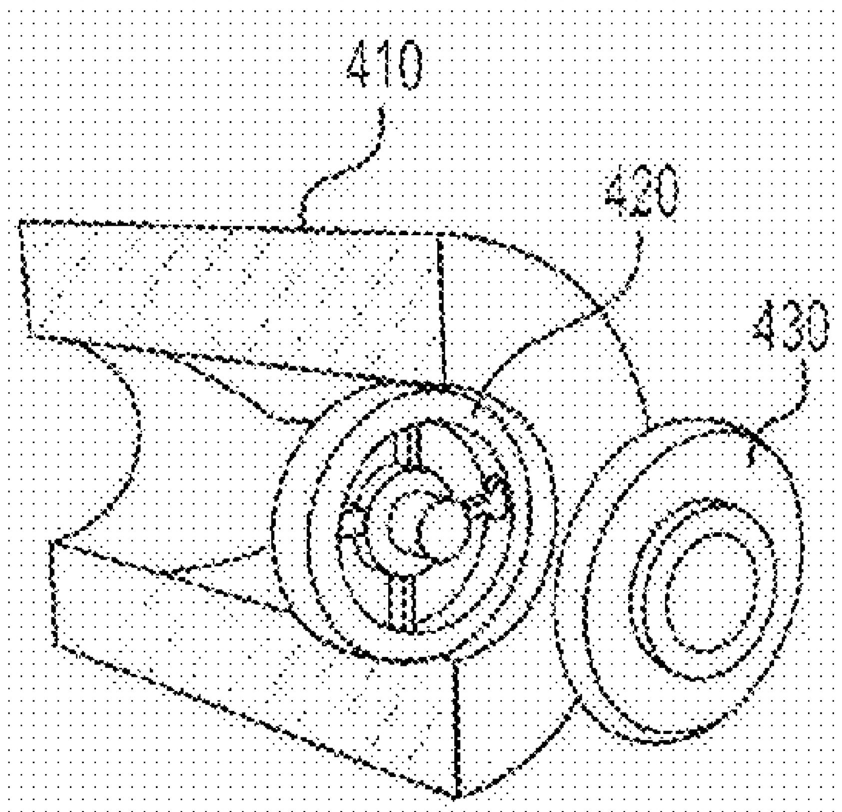


FIG. 4A

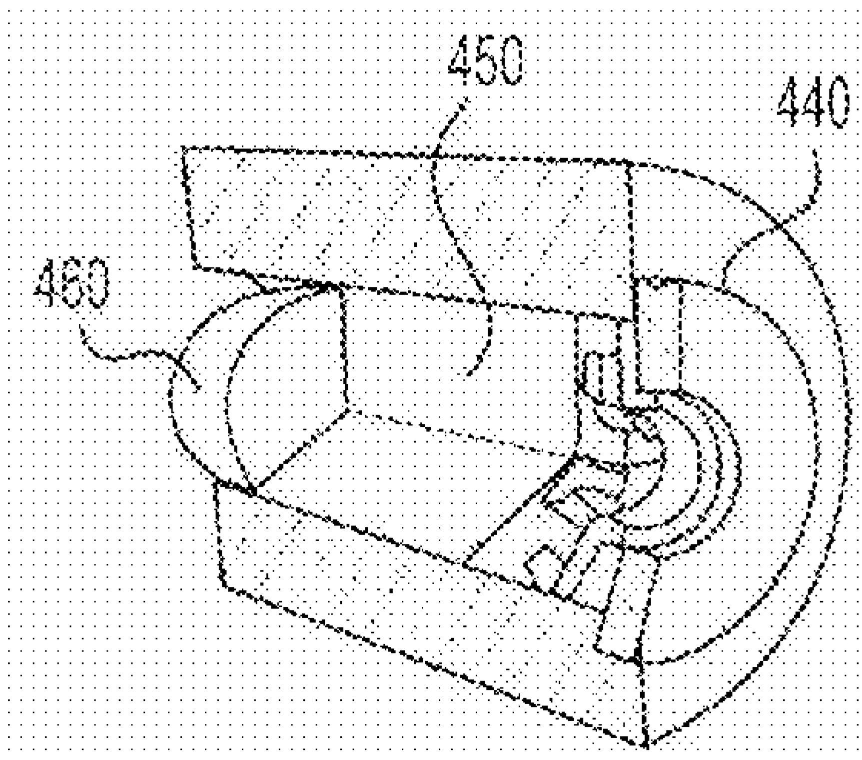


FIG. 4B

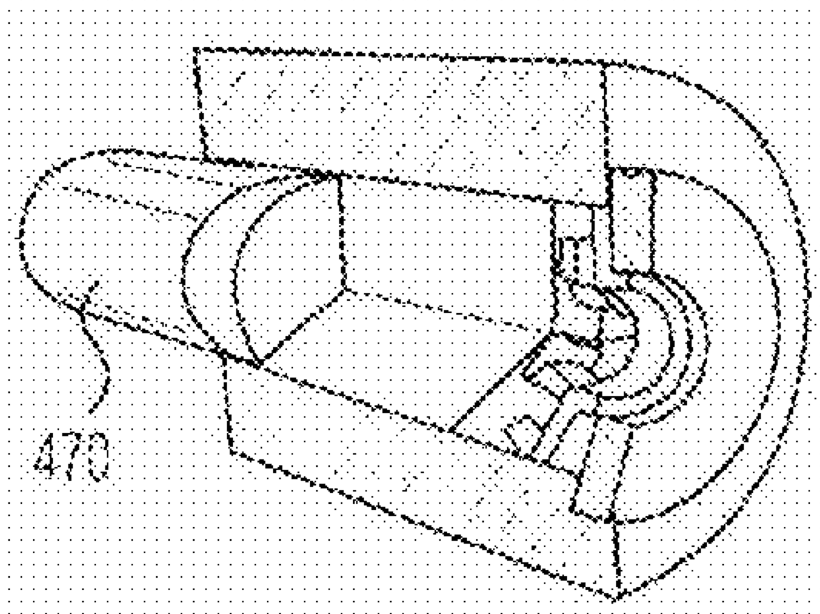


FIG. 4C

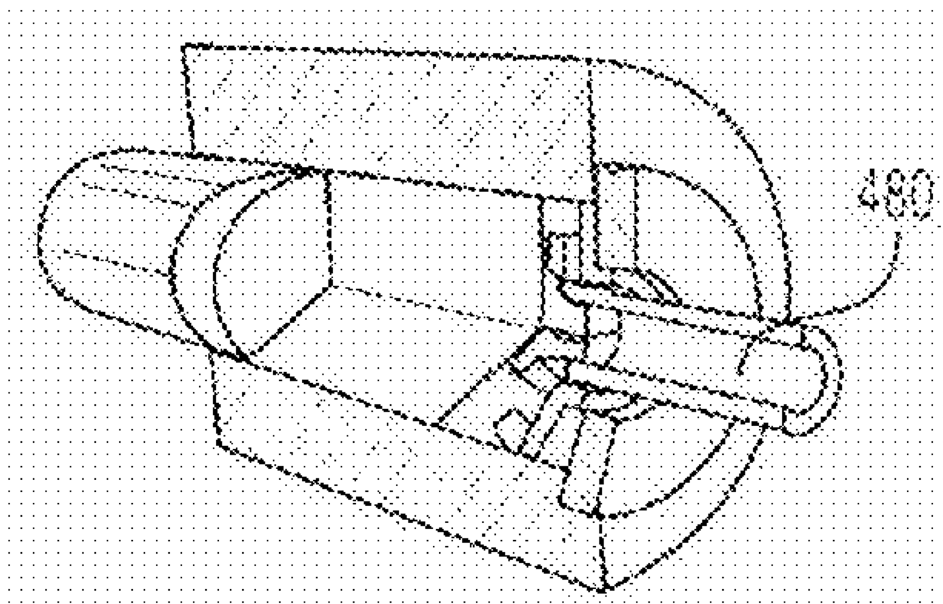


FIG. 4D

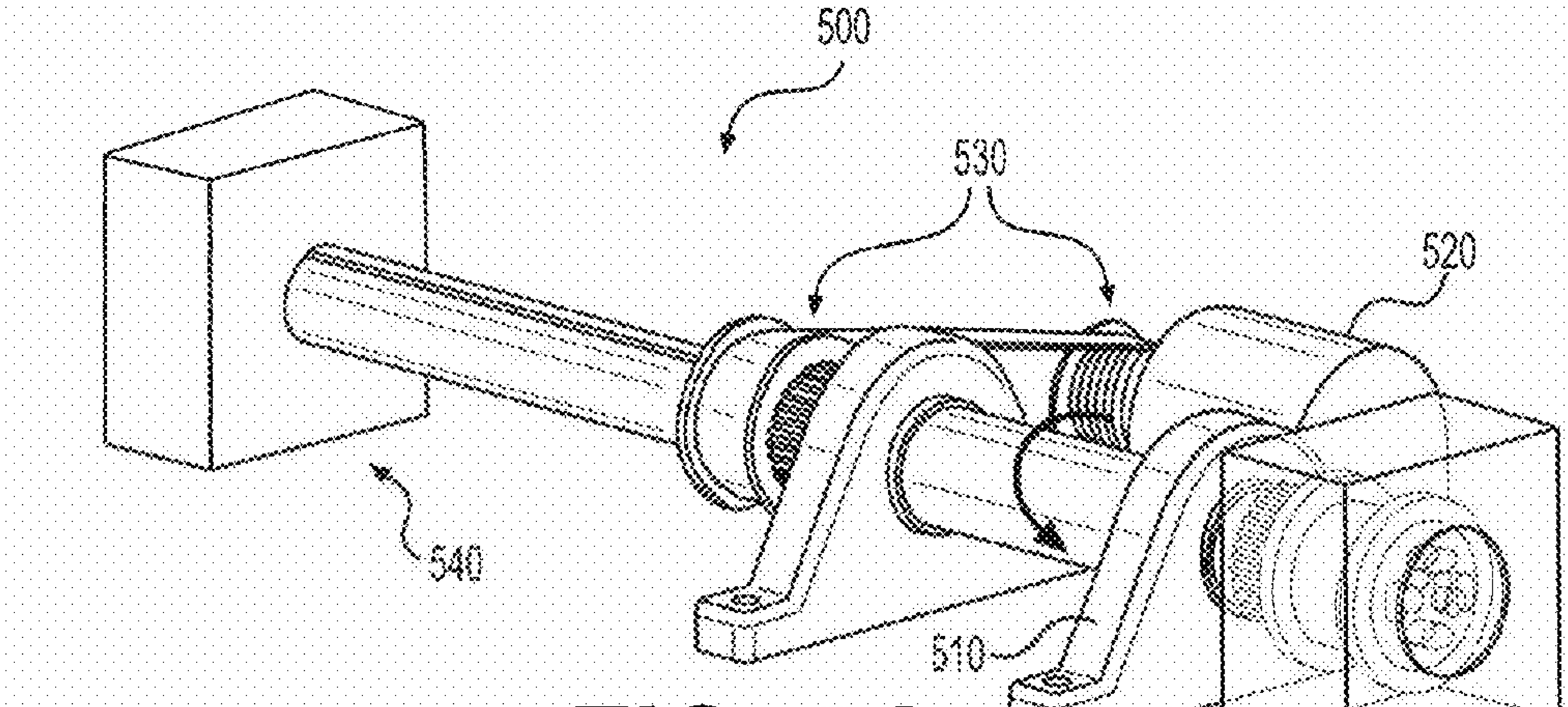


FIG. 5A

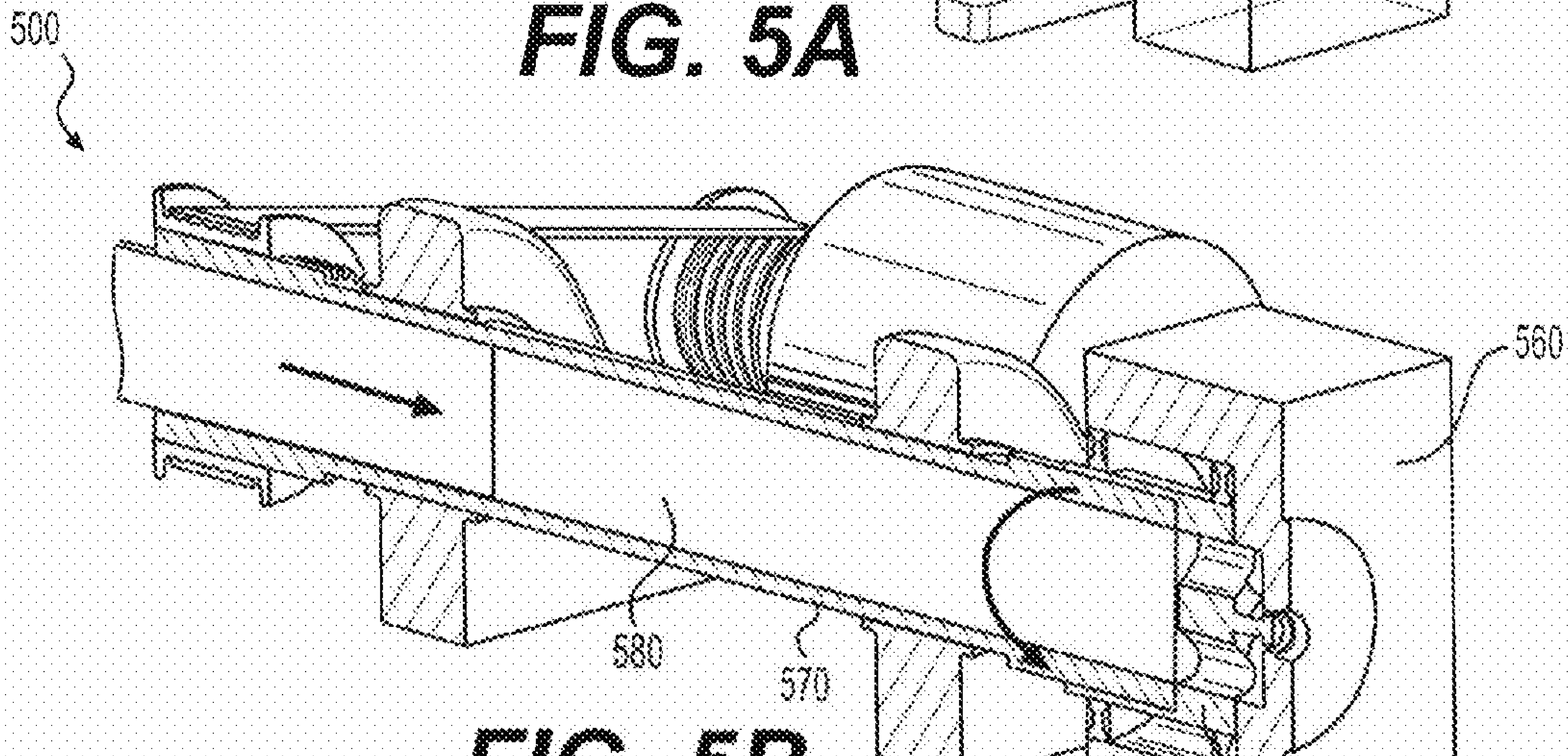


FIG. 5B

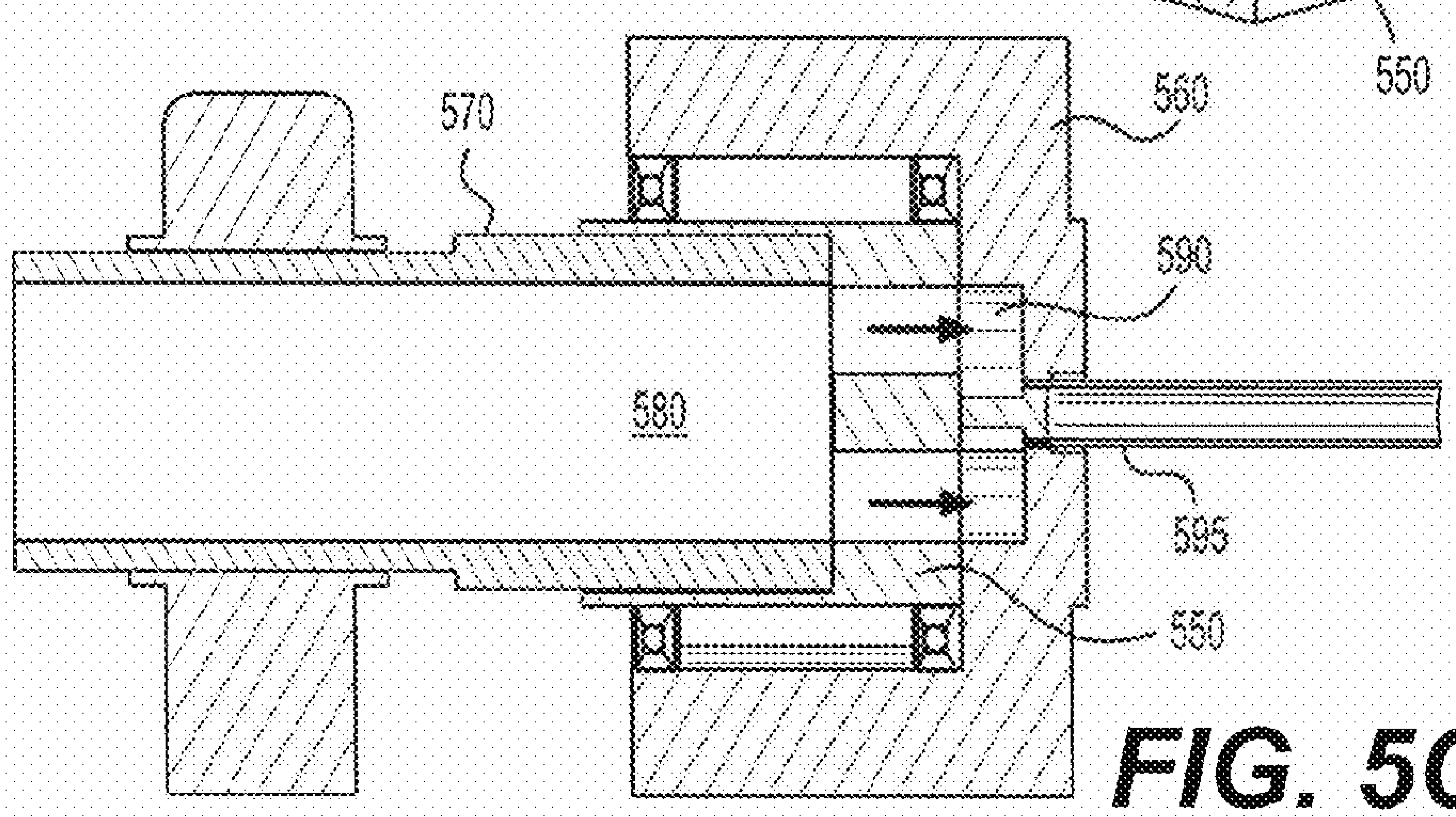


FIG. 5C

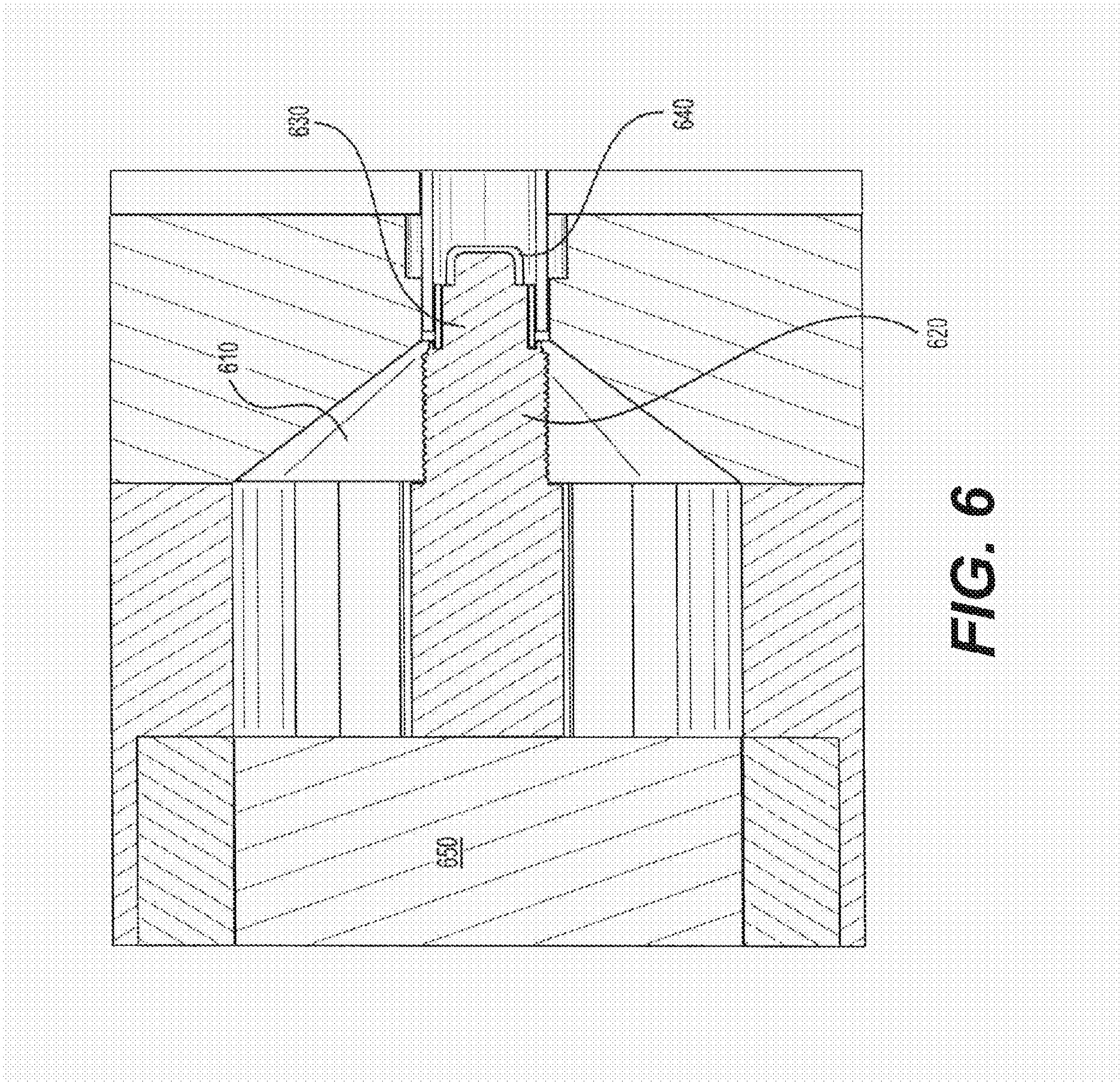


FIG. 6

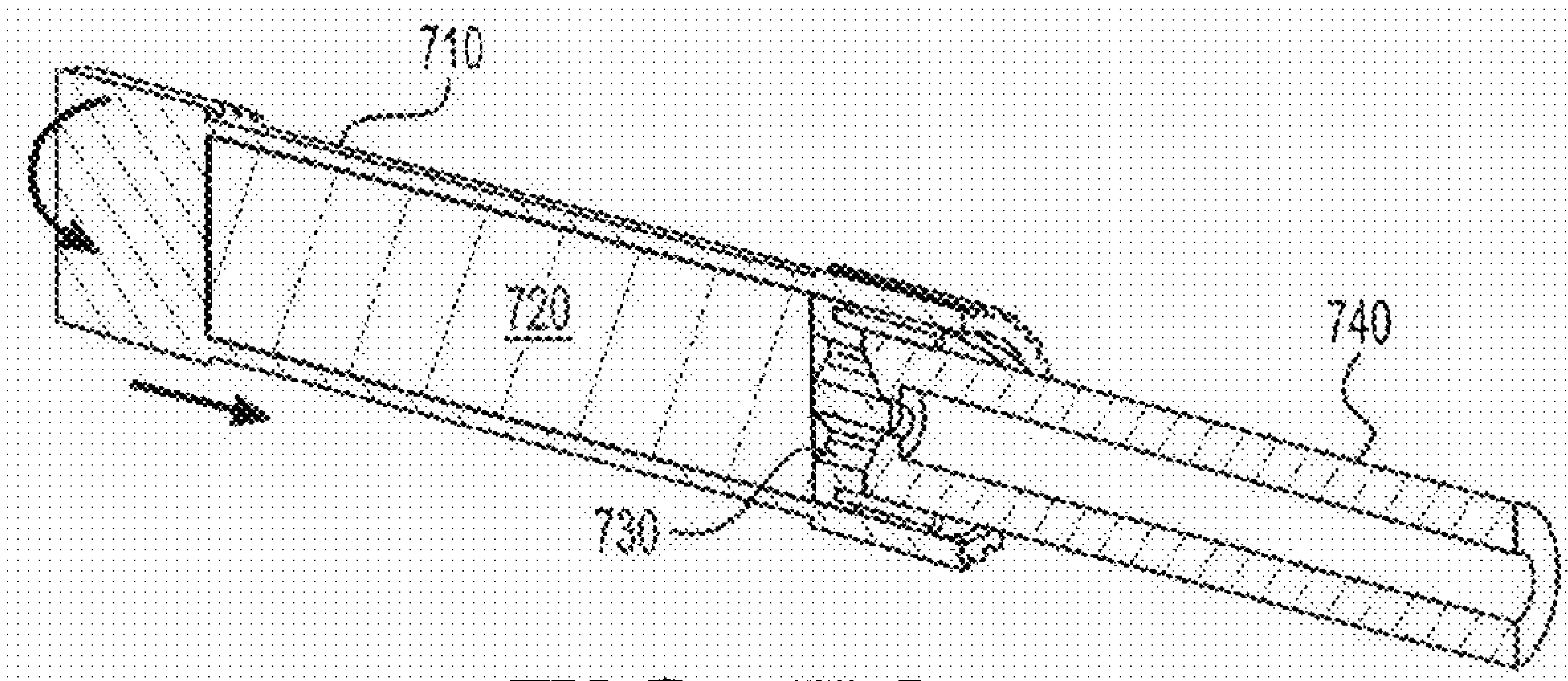
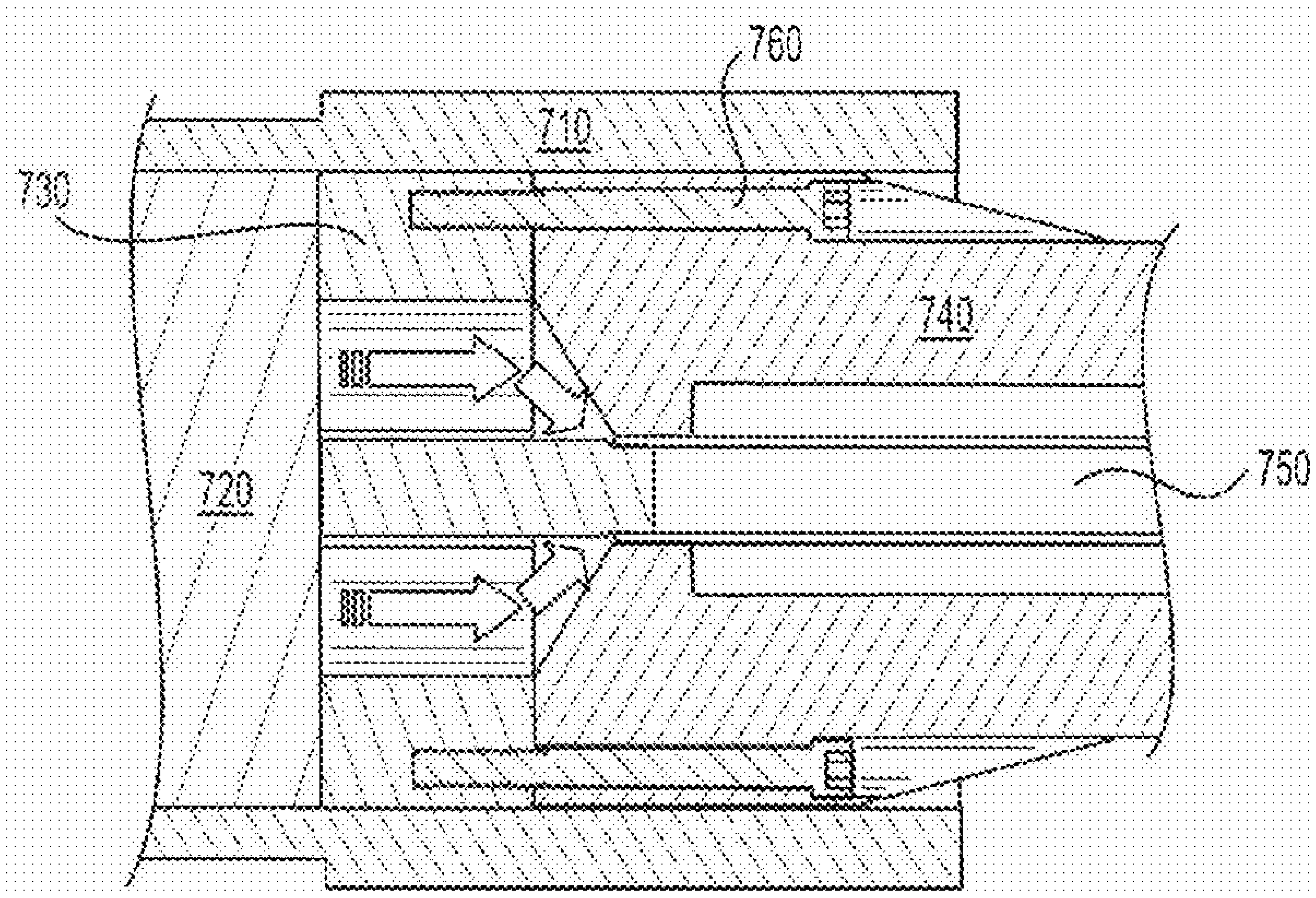


FIG. 7A



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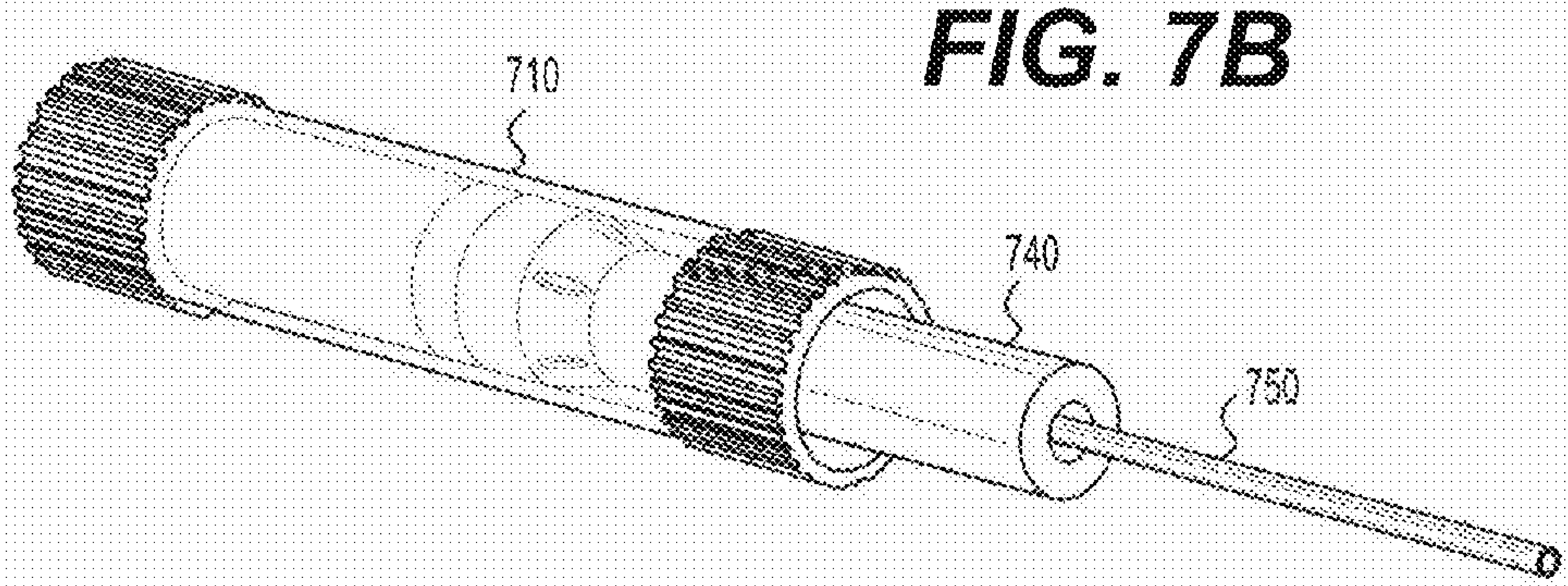

FIG. 7C

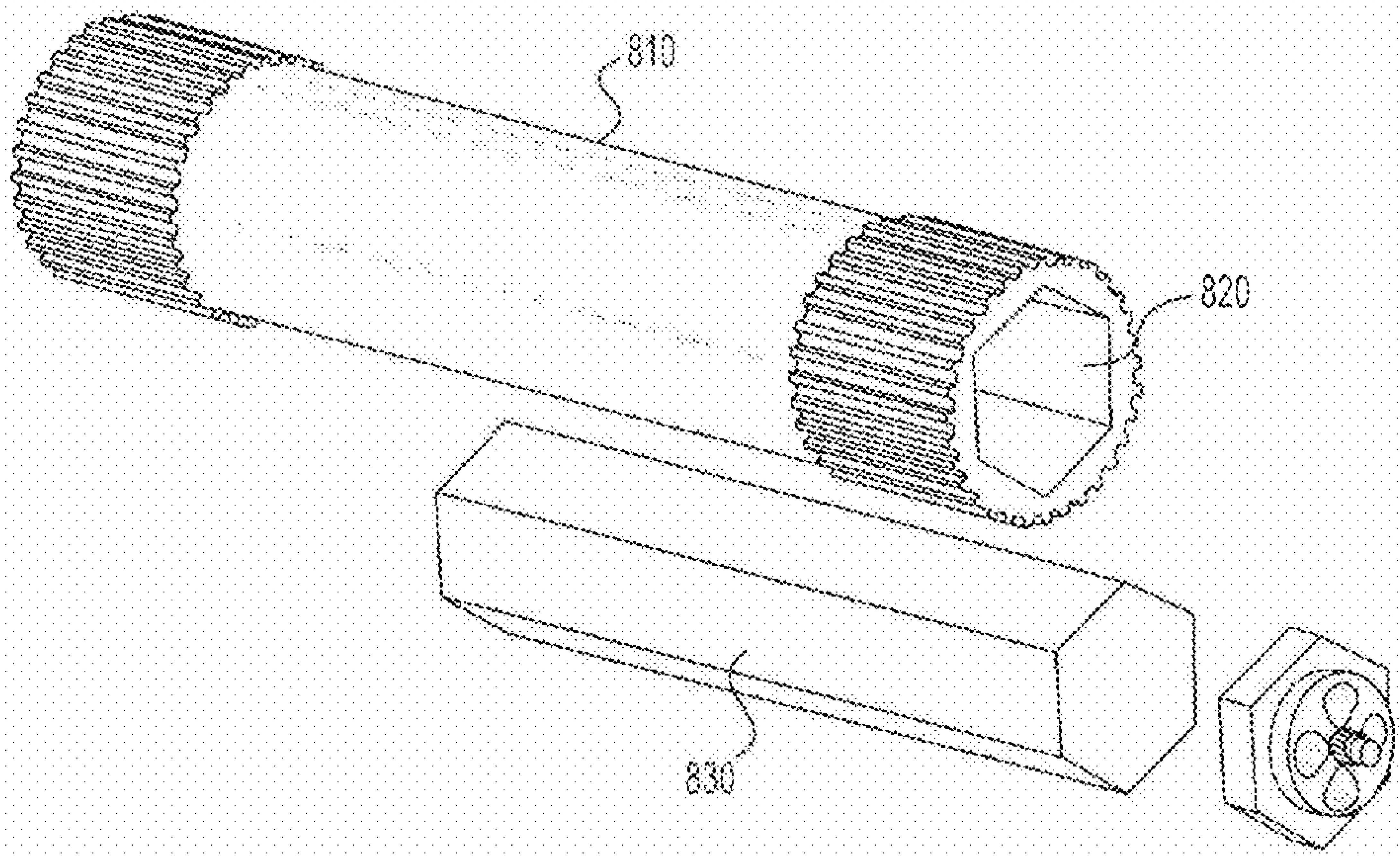

FIG. 8A

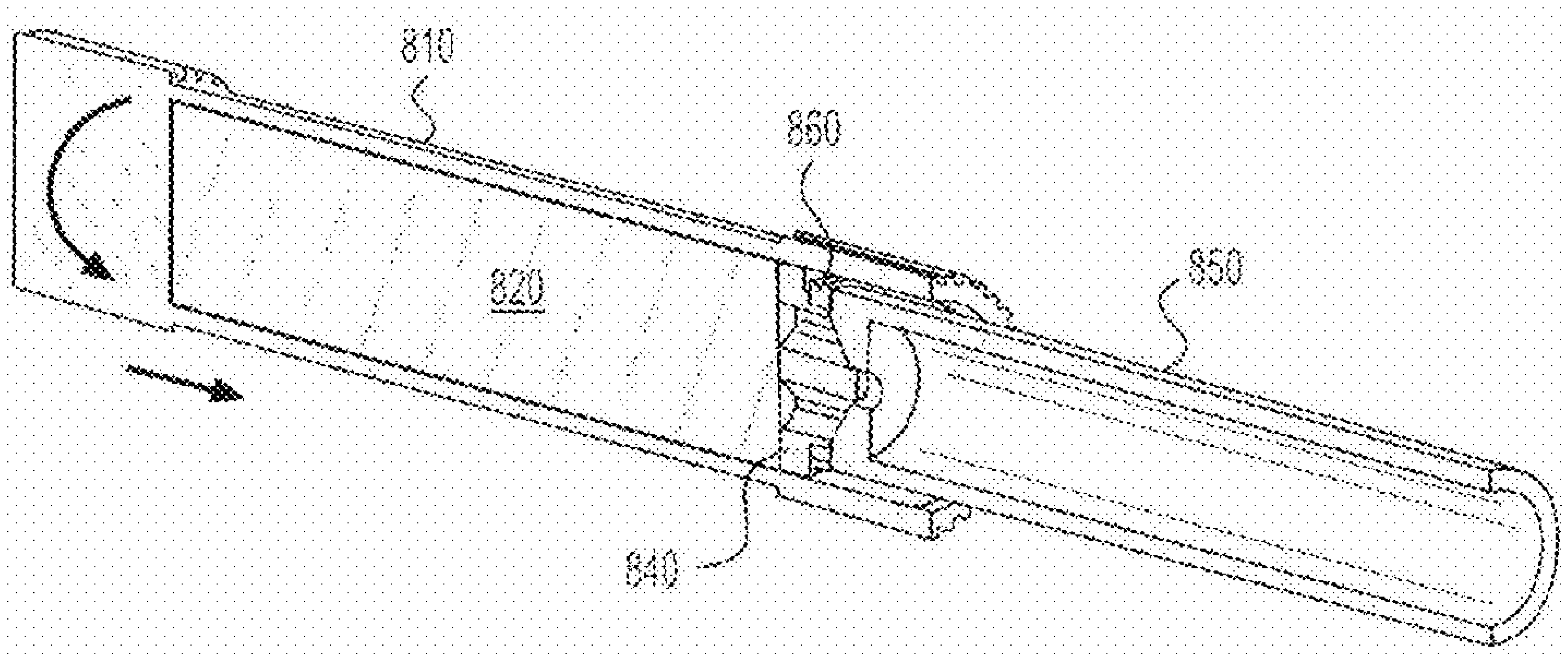

FIG. 8B

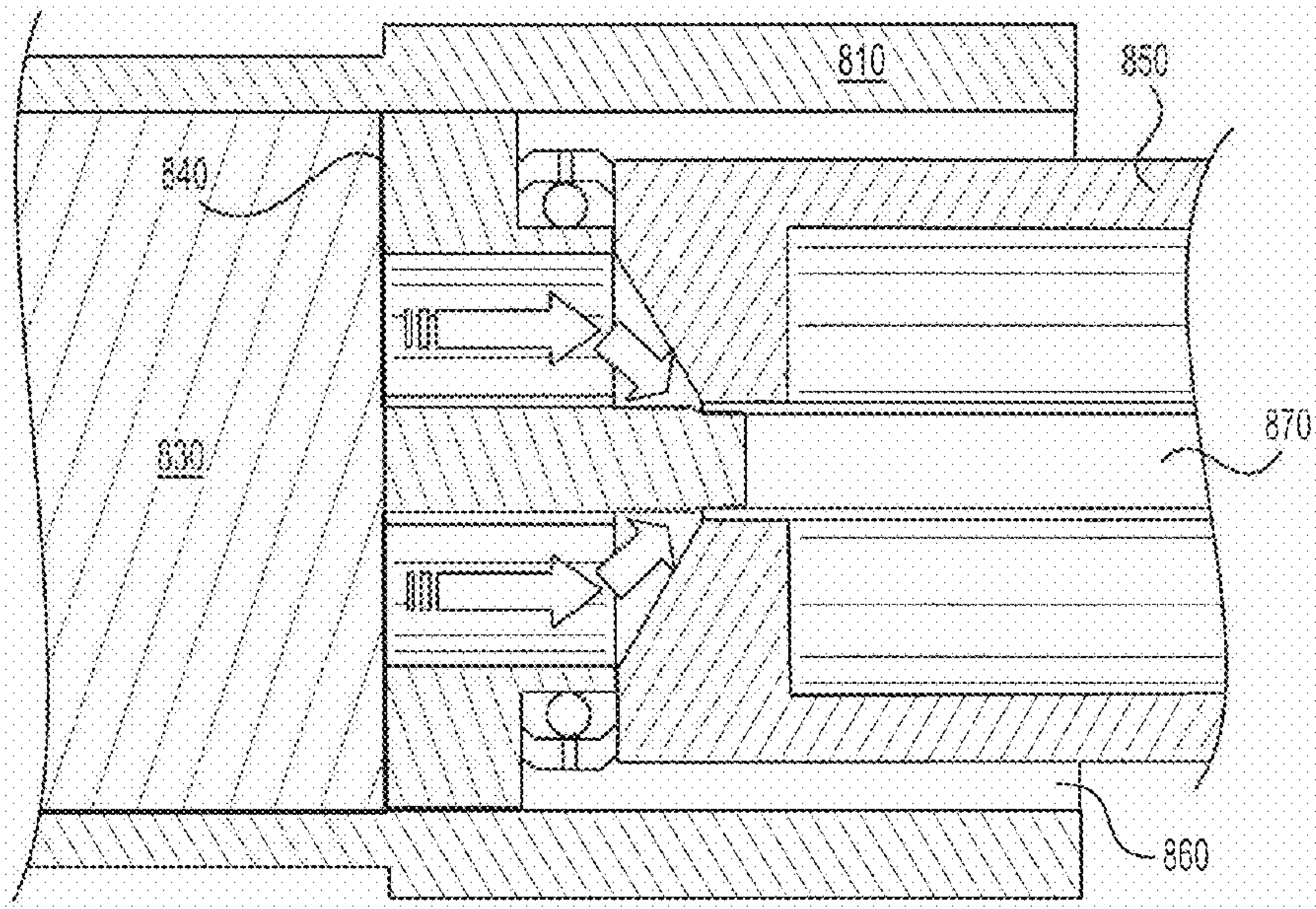

FIG. 8C

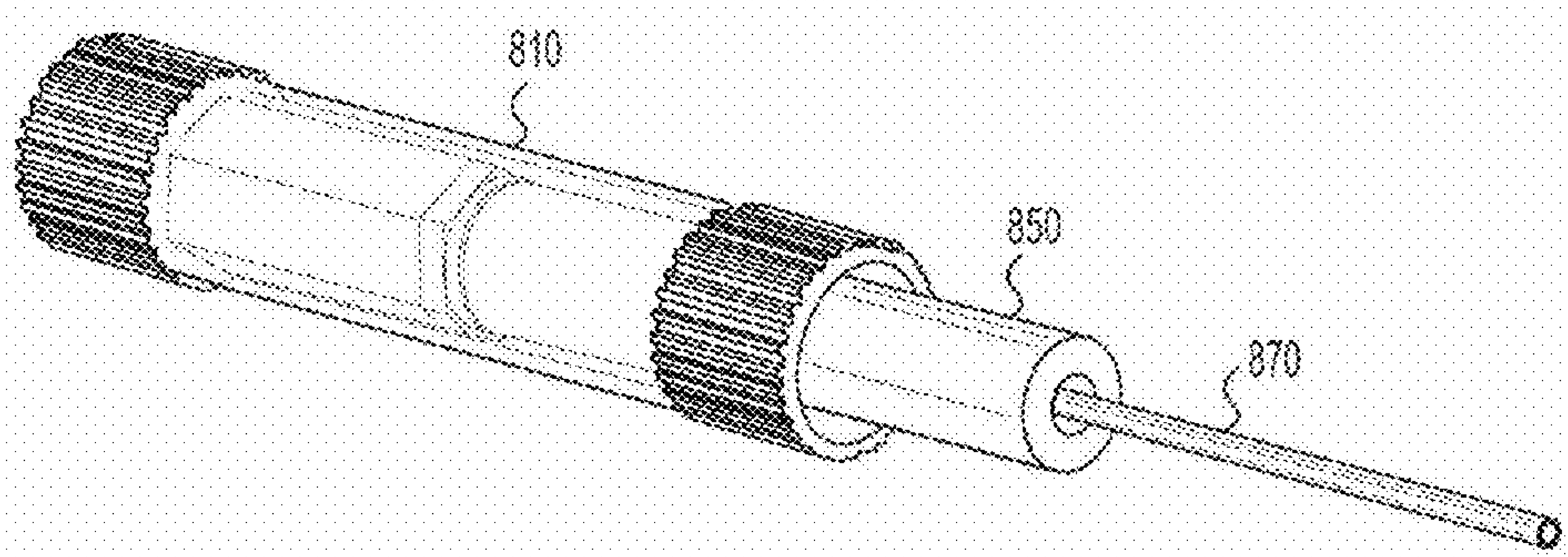

FIG. 8D

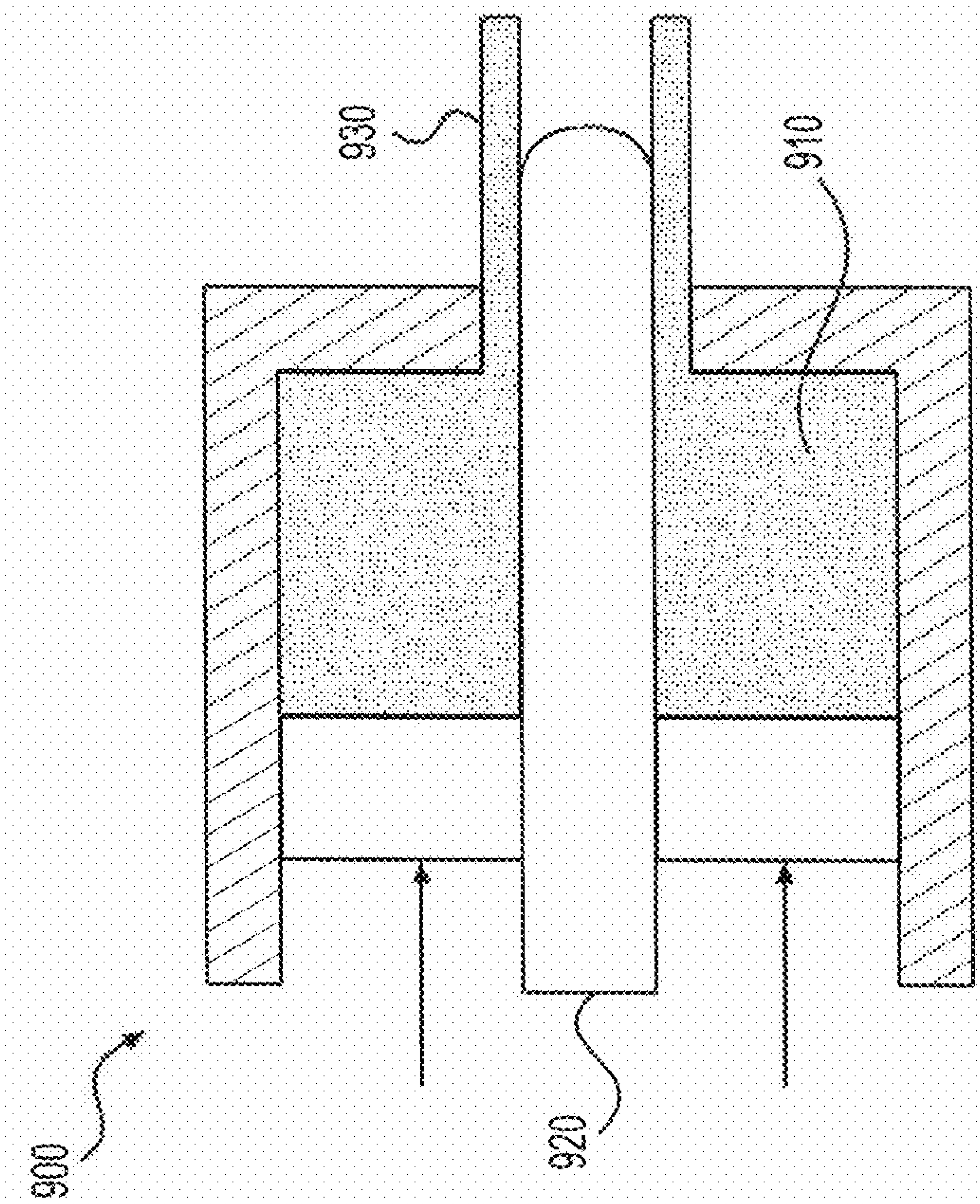

FIG. 9

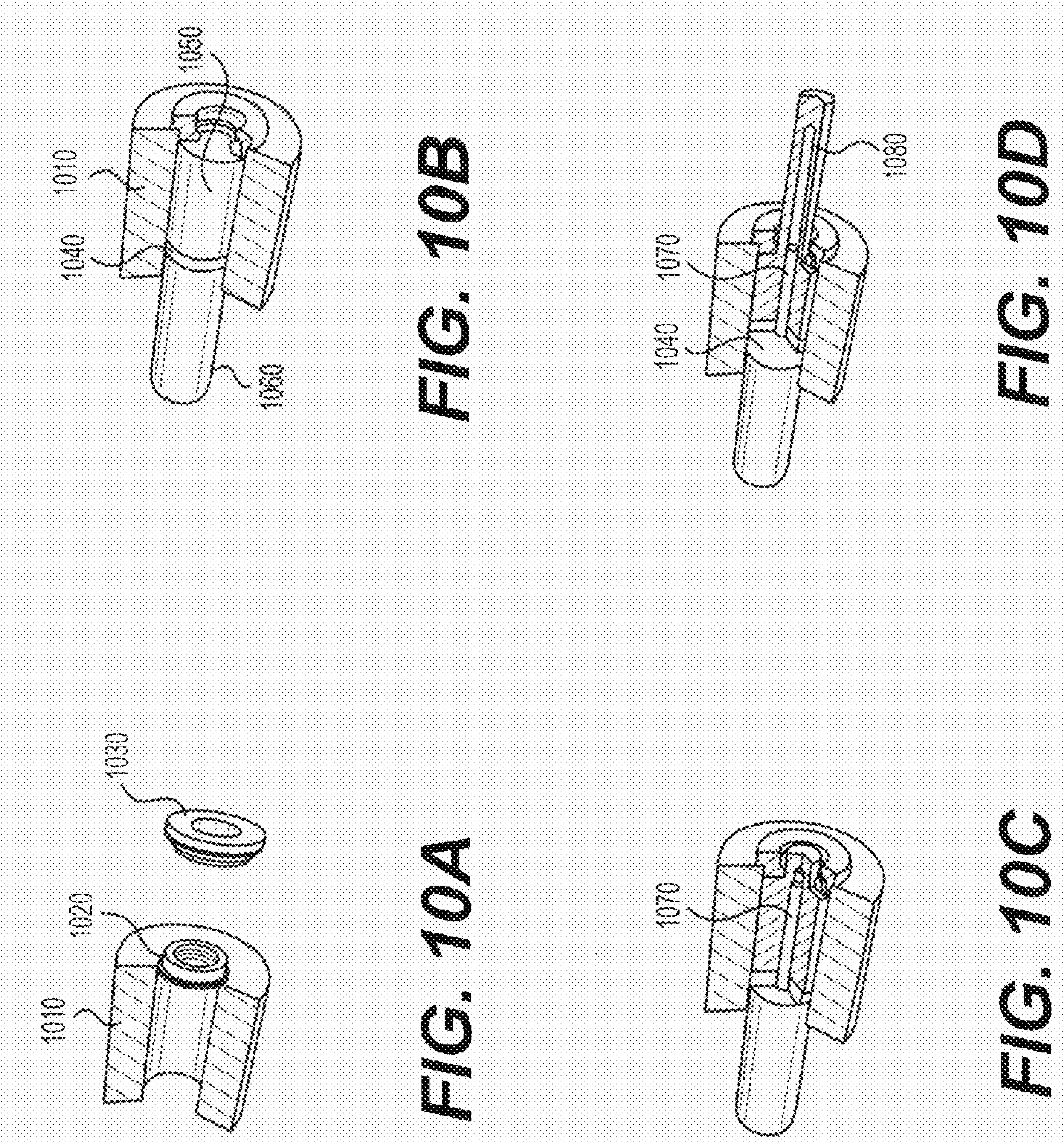

FIG. 10A

FIG. 10B

FIG. 10C

FIG. 10D

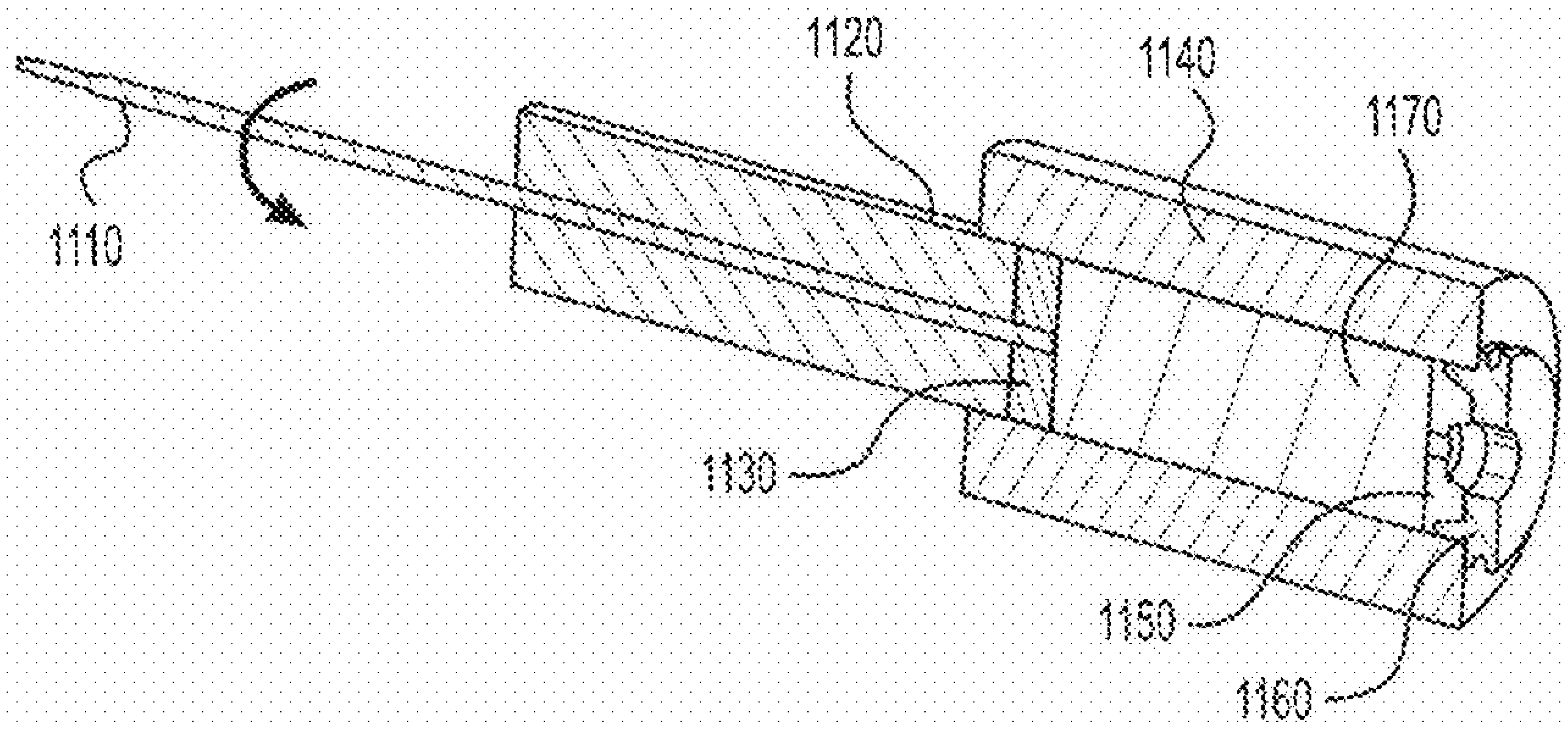

FIG. 11A

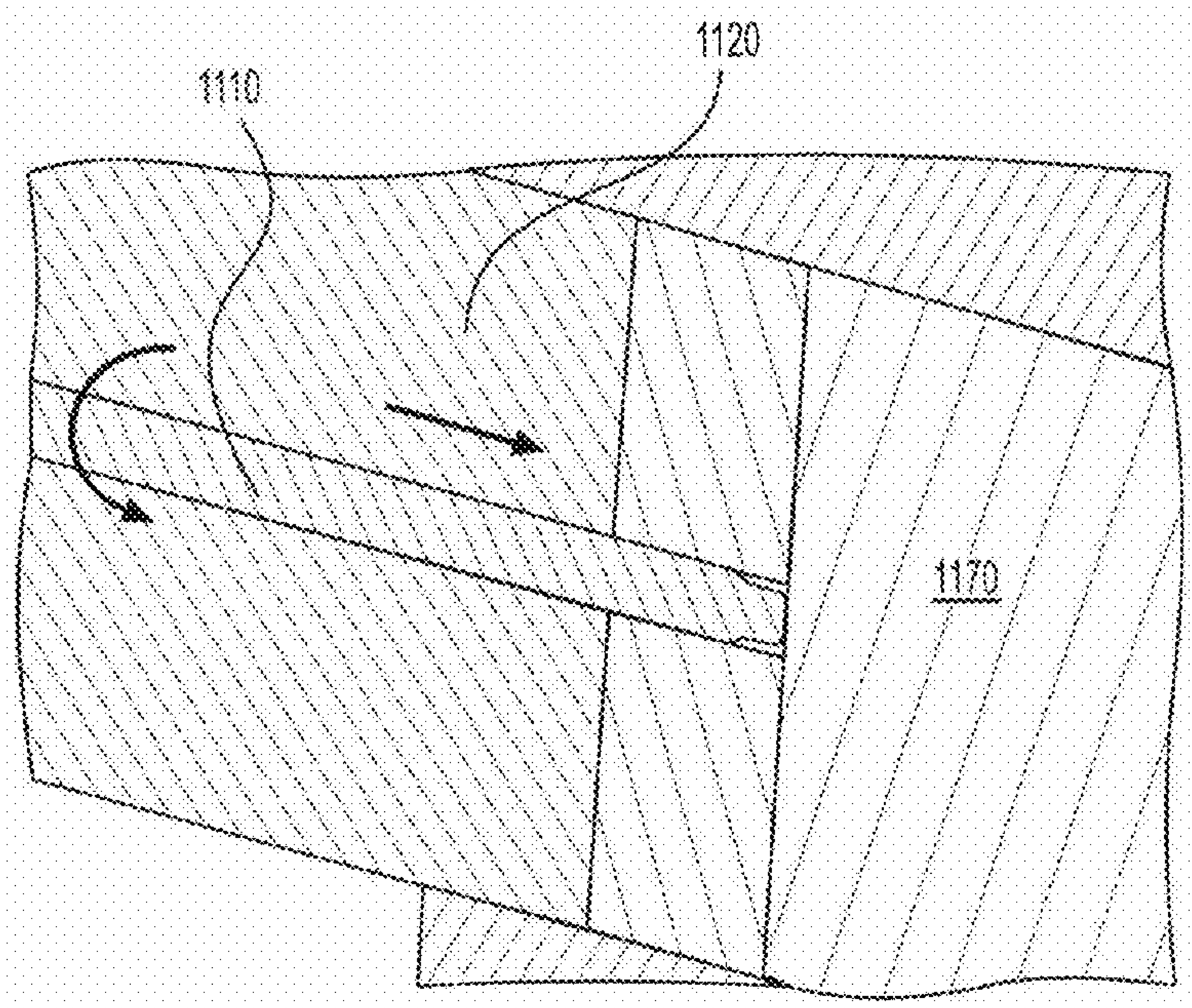

FIG. 11B

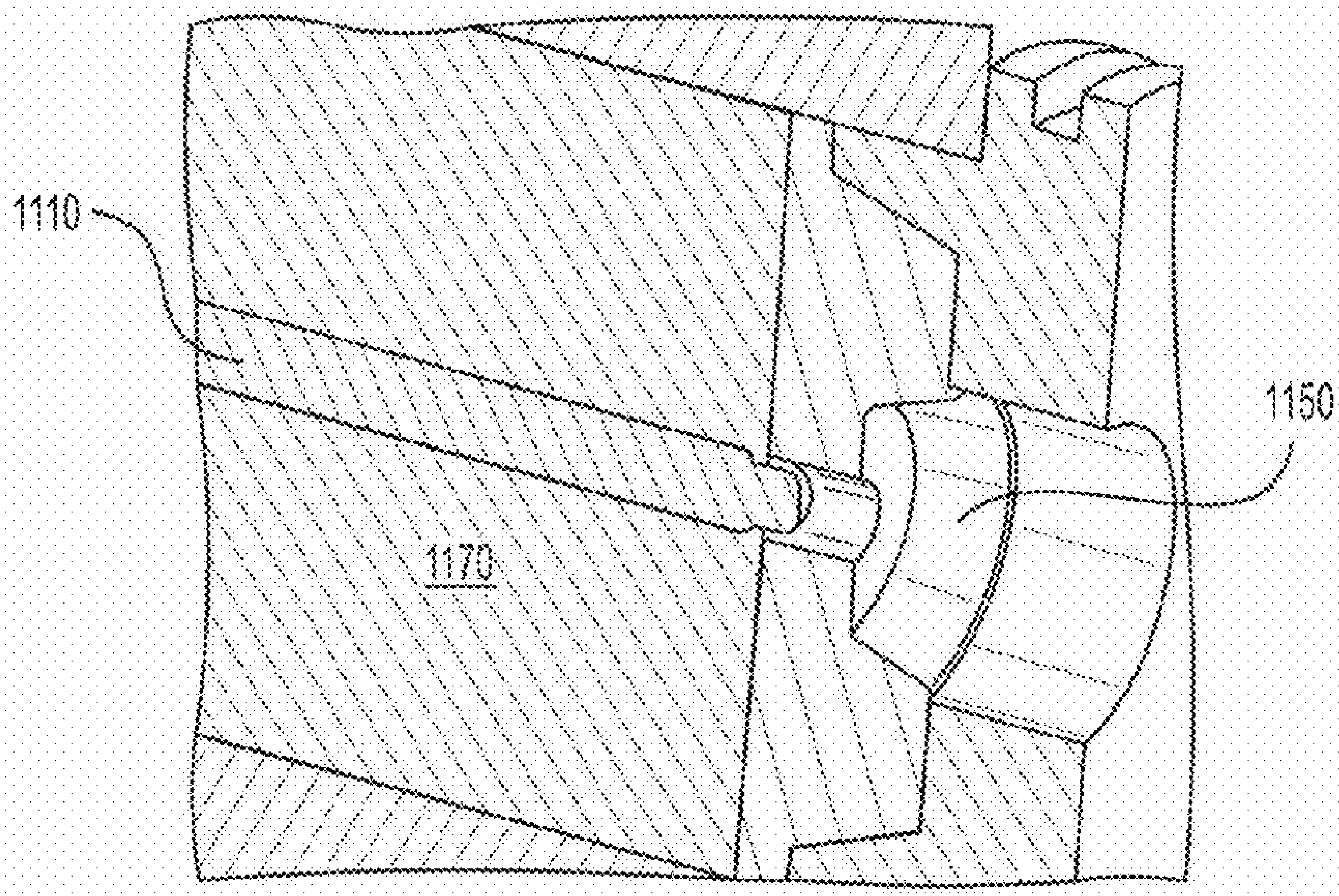

FIG. 11C

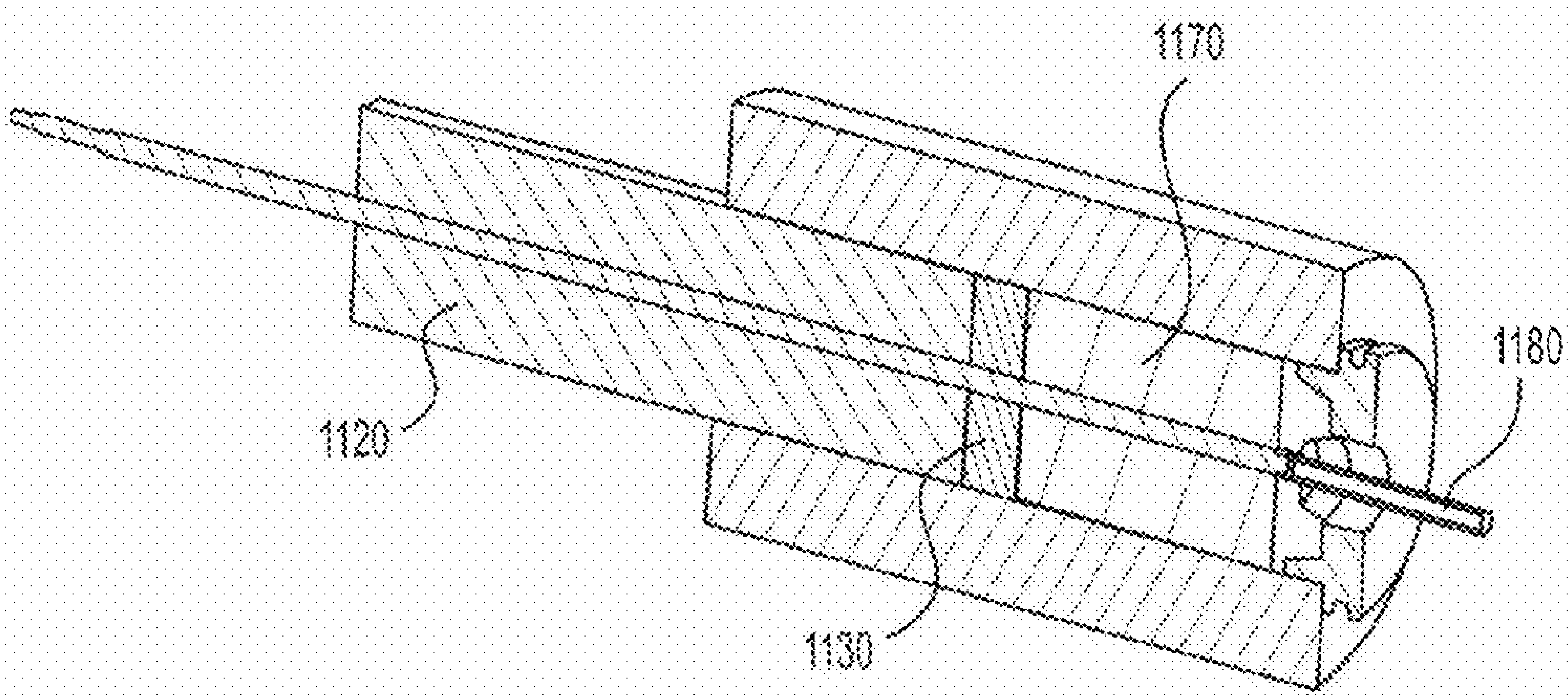

FIG. 11D

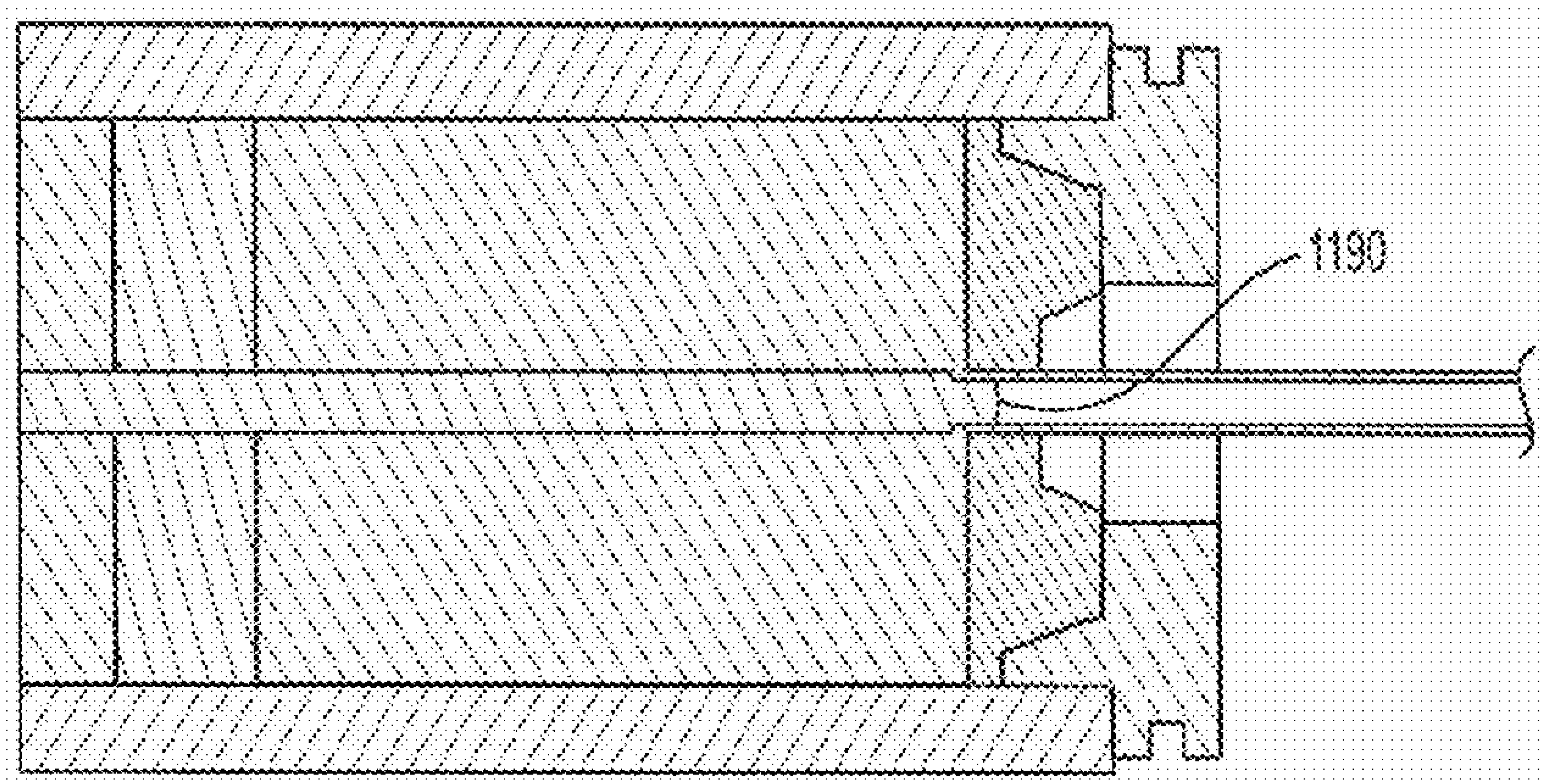

FIG. 11E

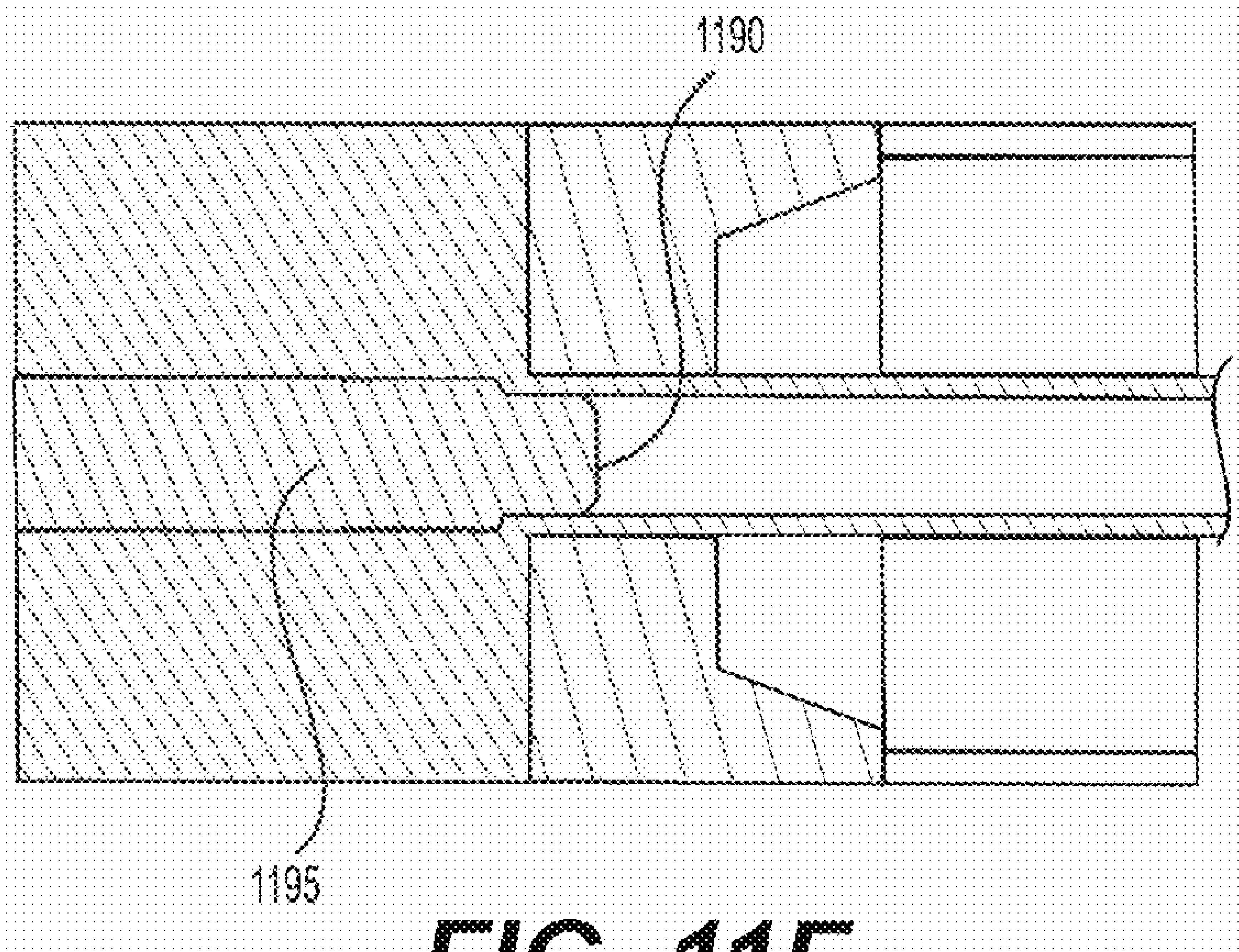

FIG. 11F

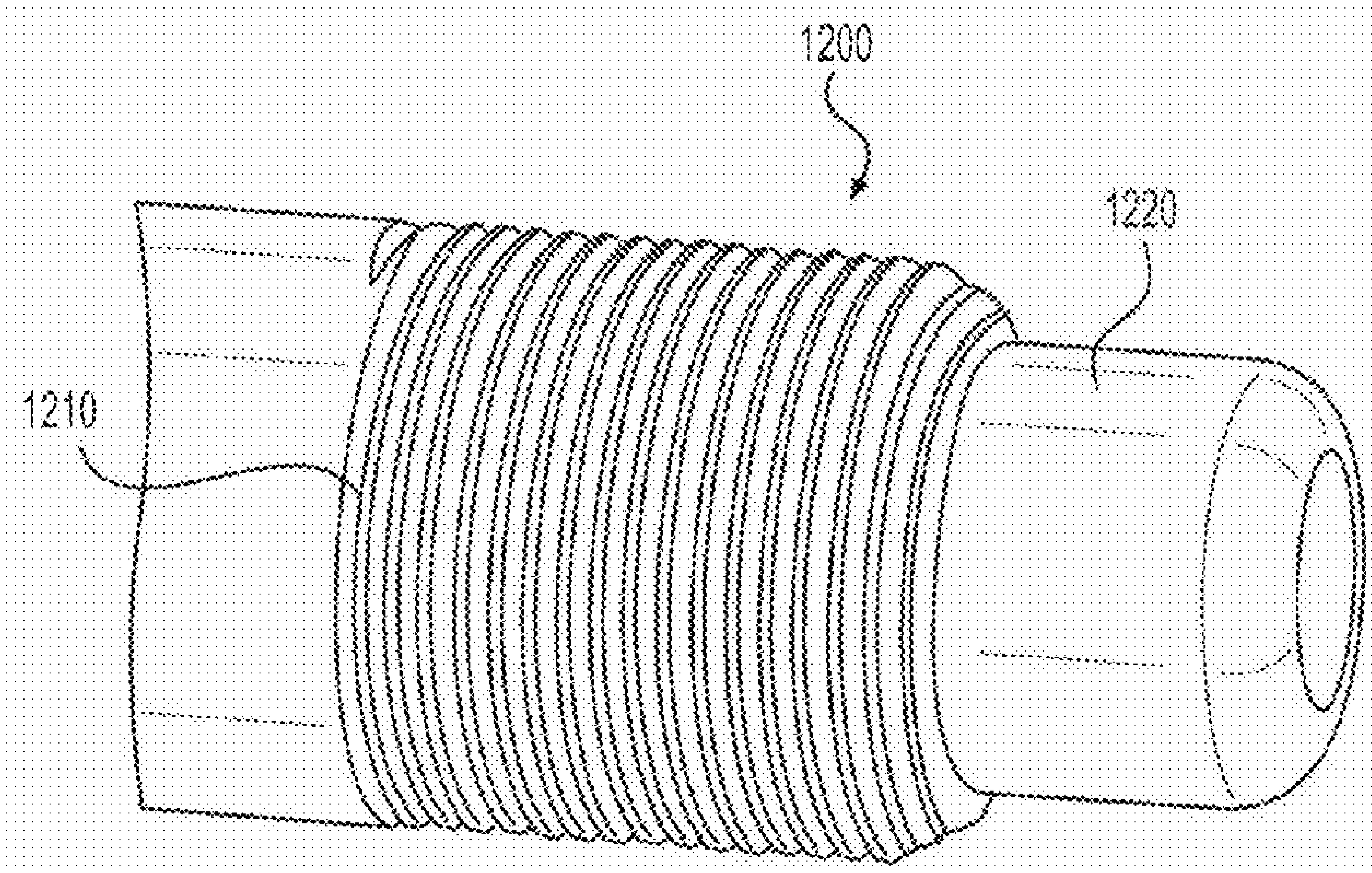

FIG. 12

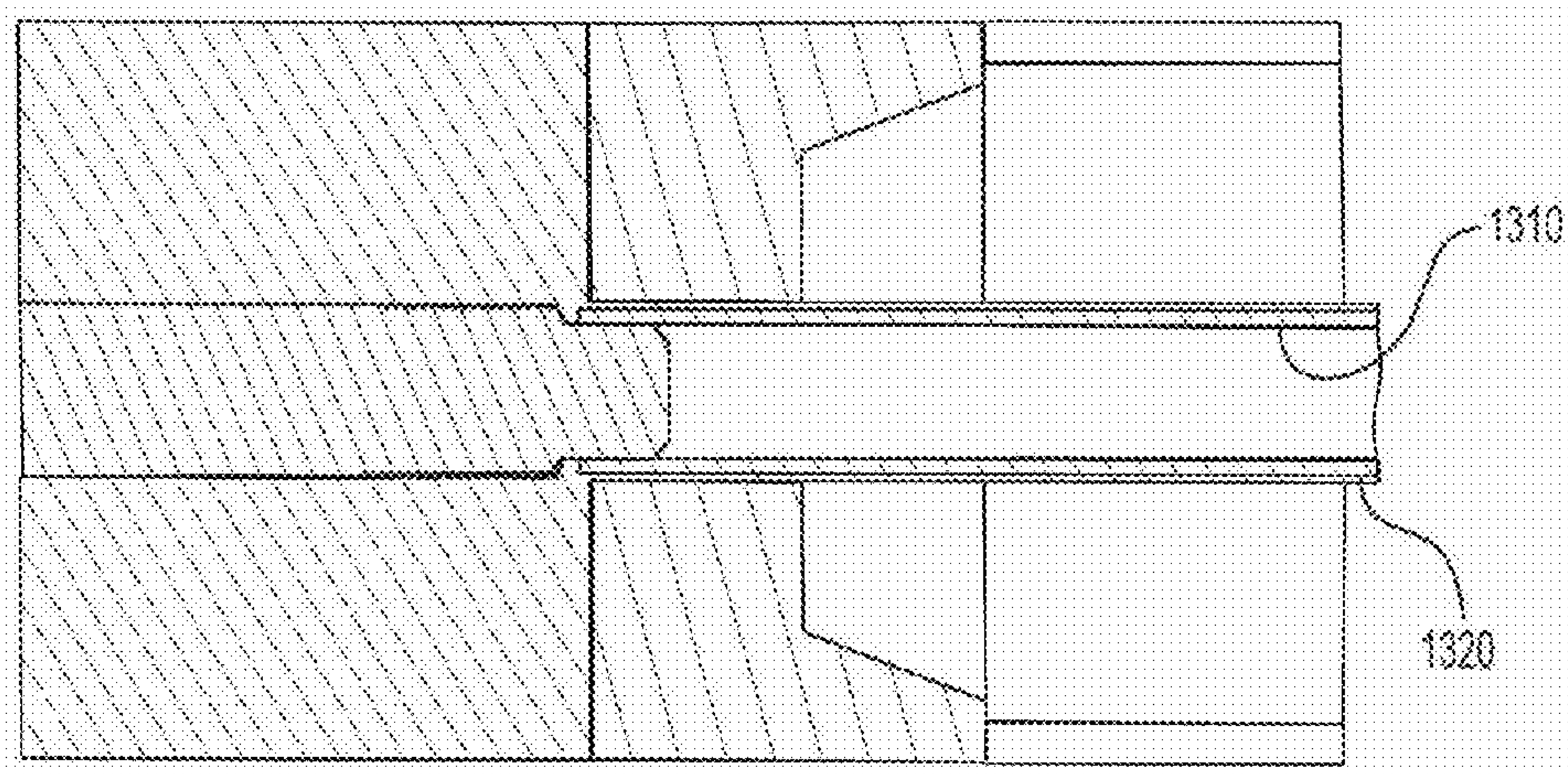

FIG. 13

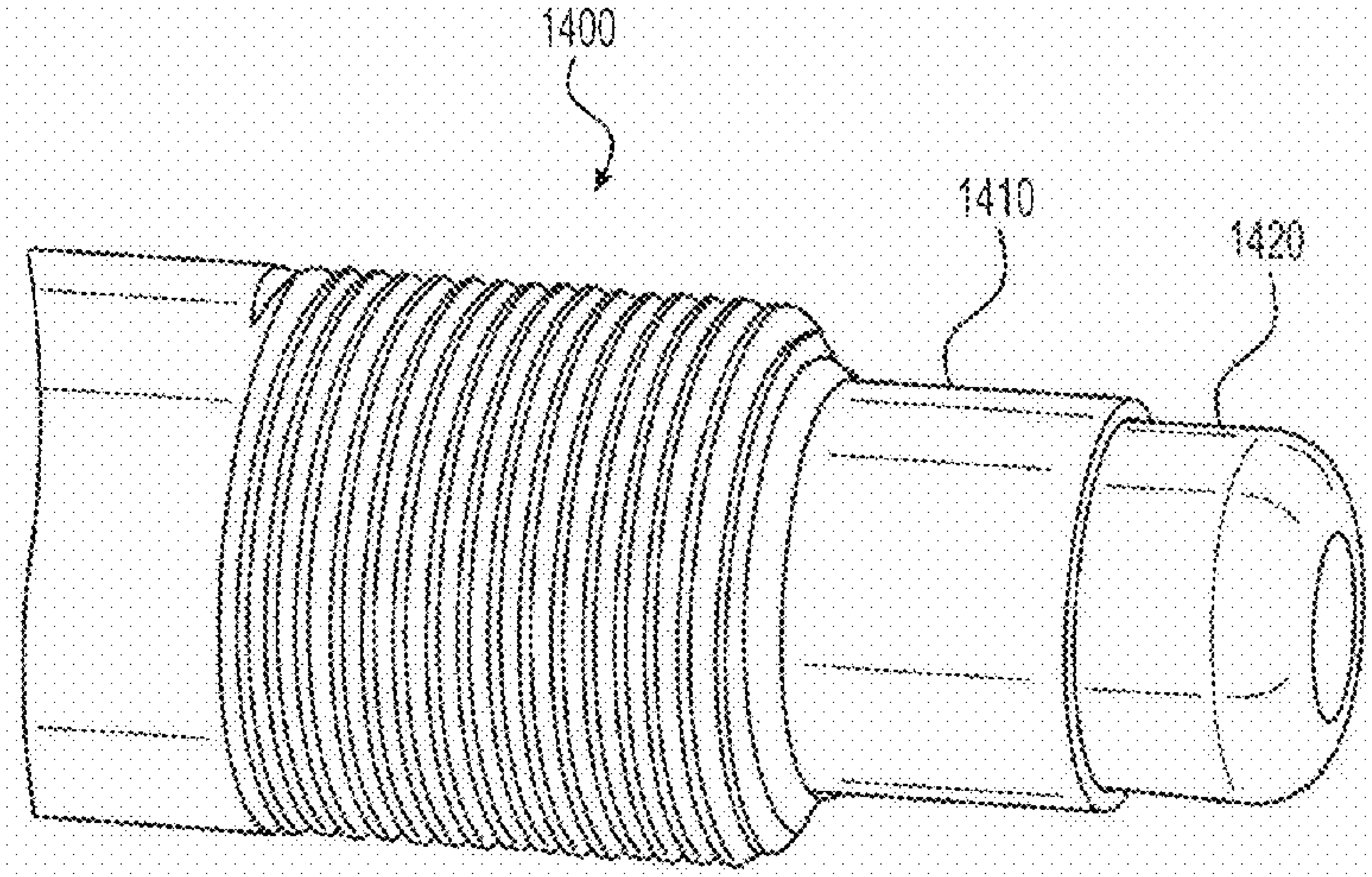

FIG. 14

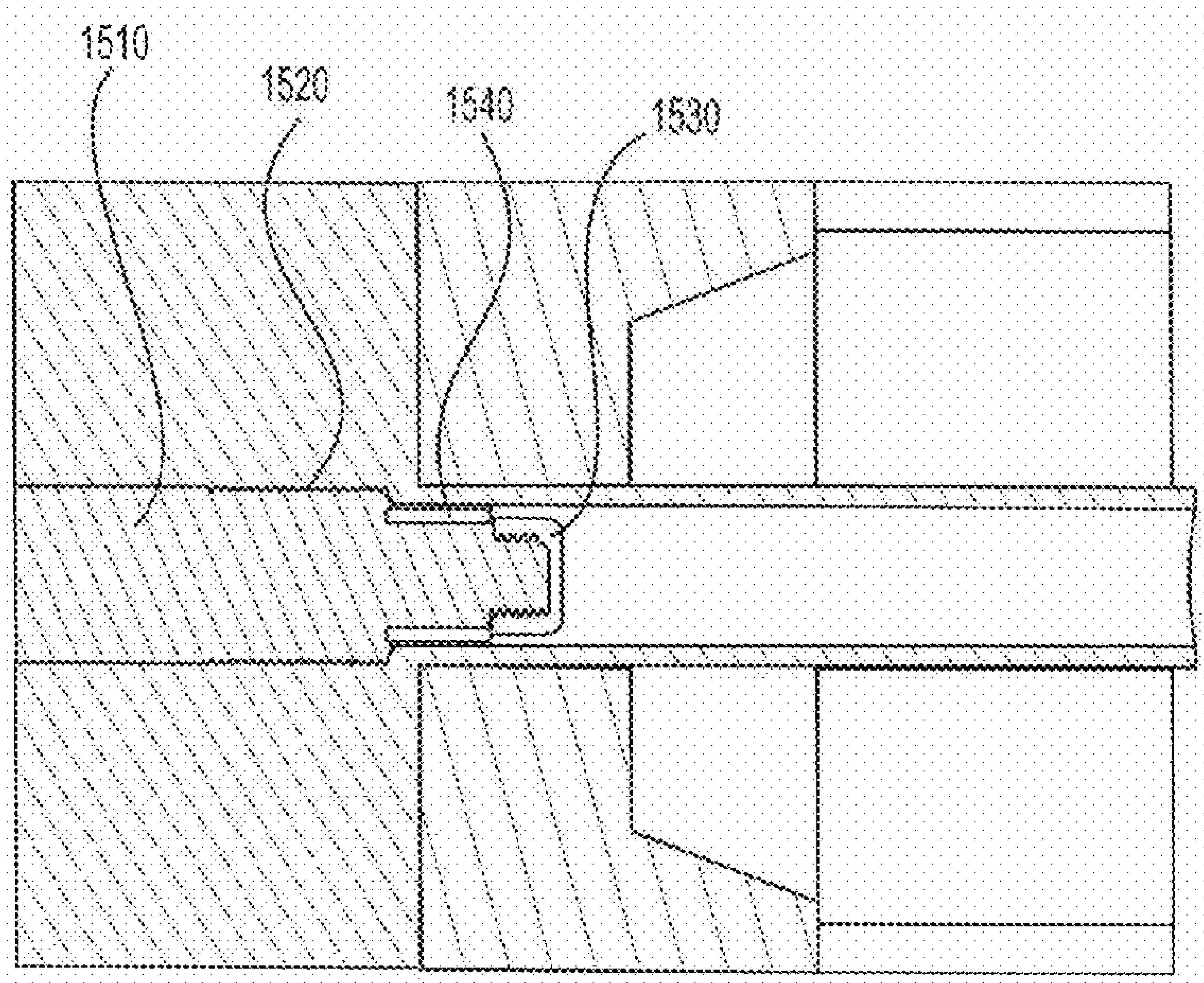

FIG. 15

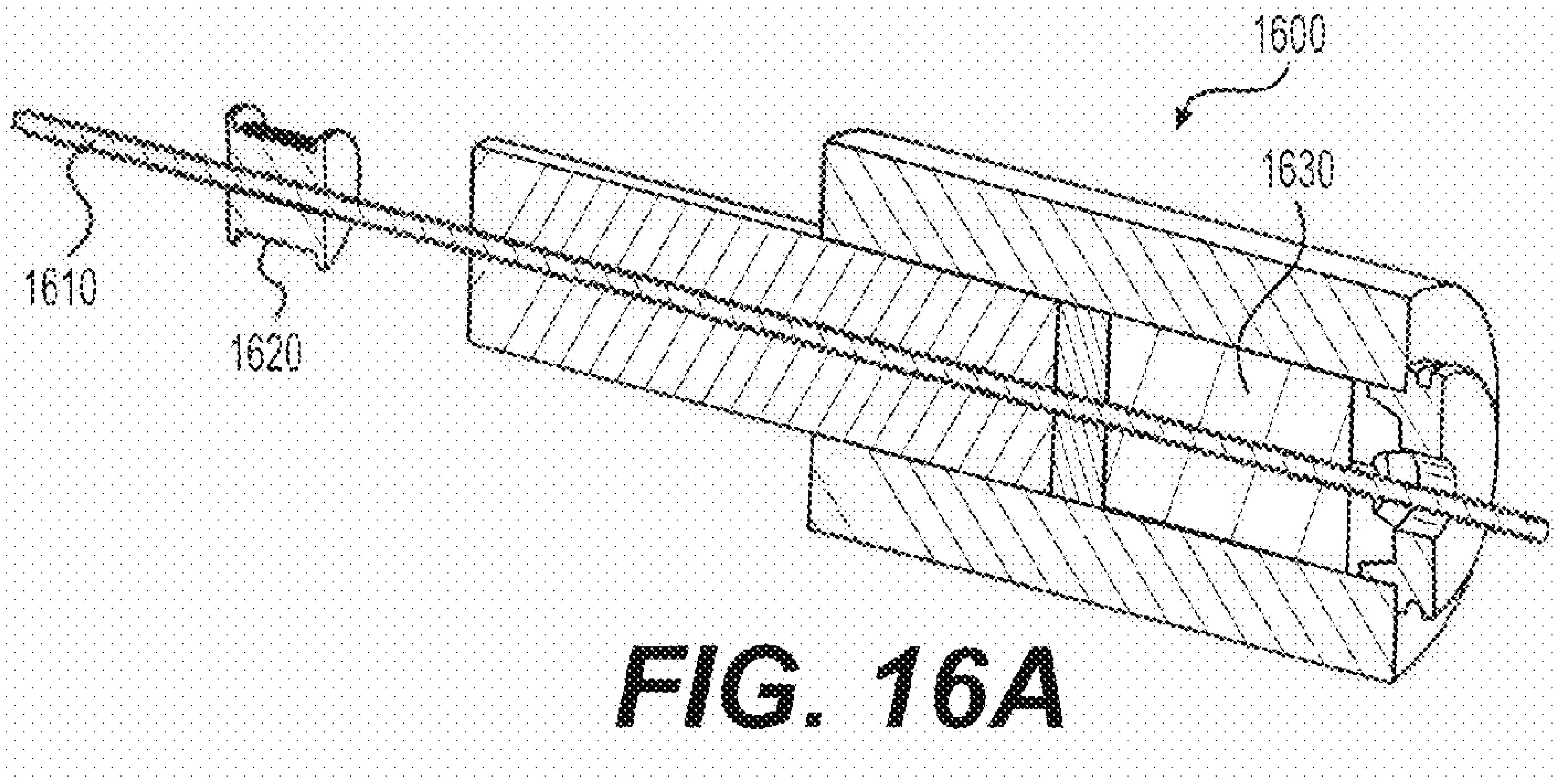

FIG. 16A

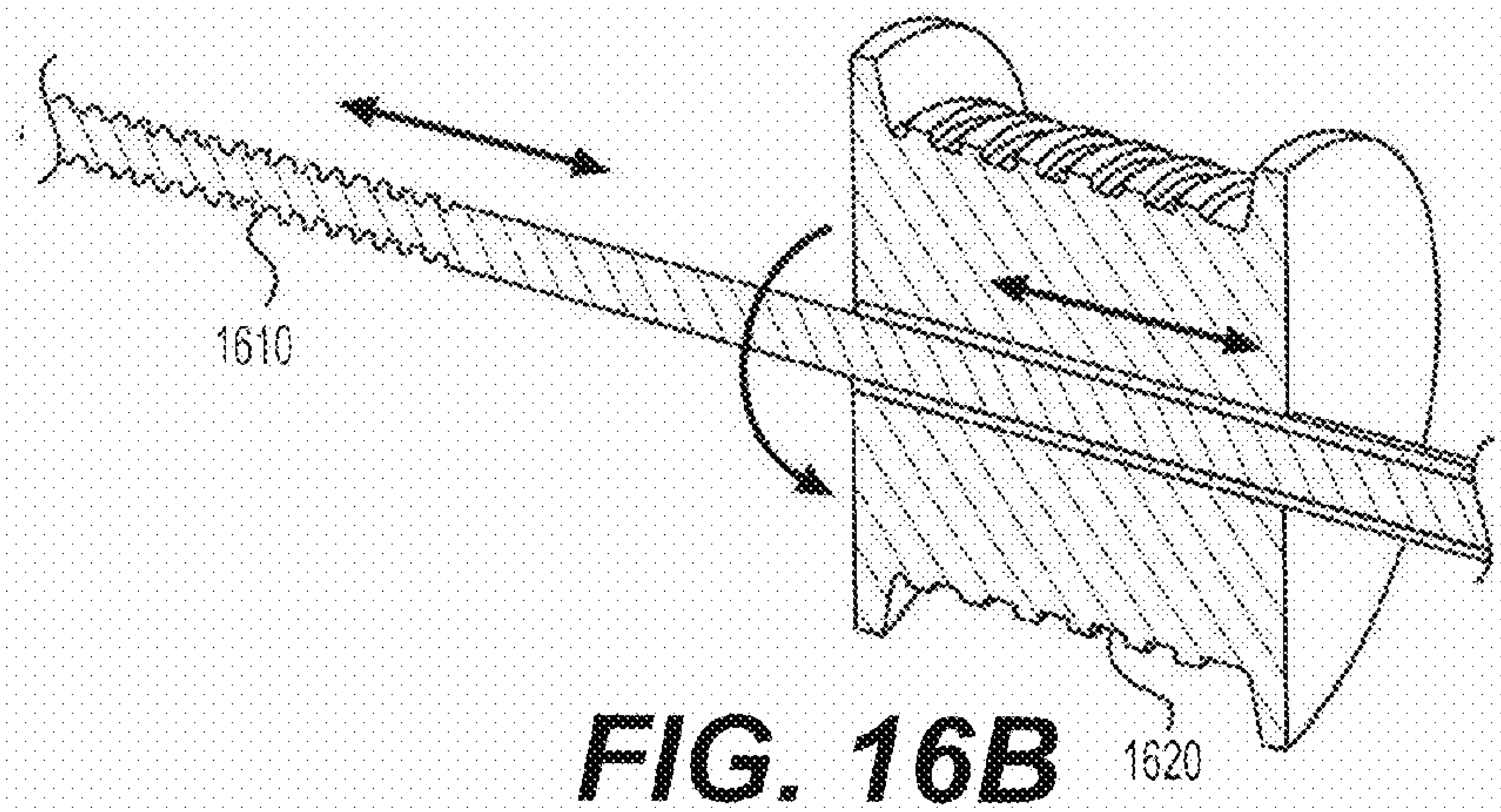

FIG. 16B

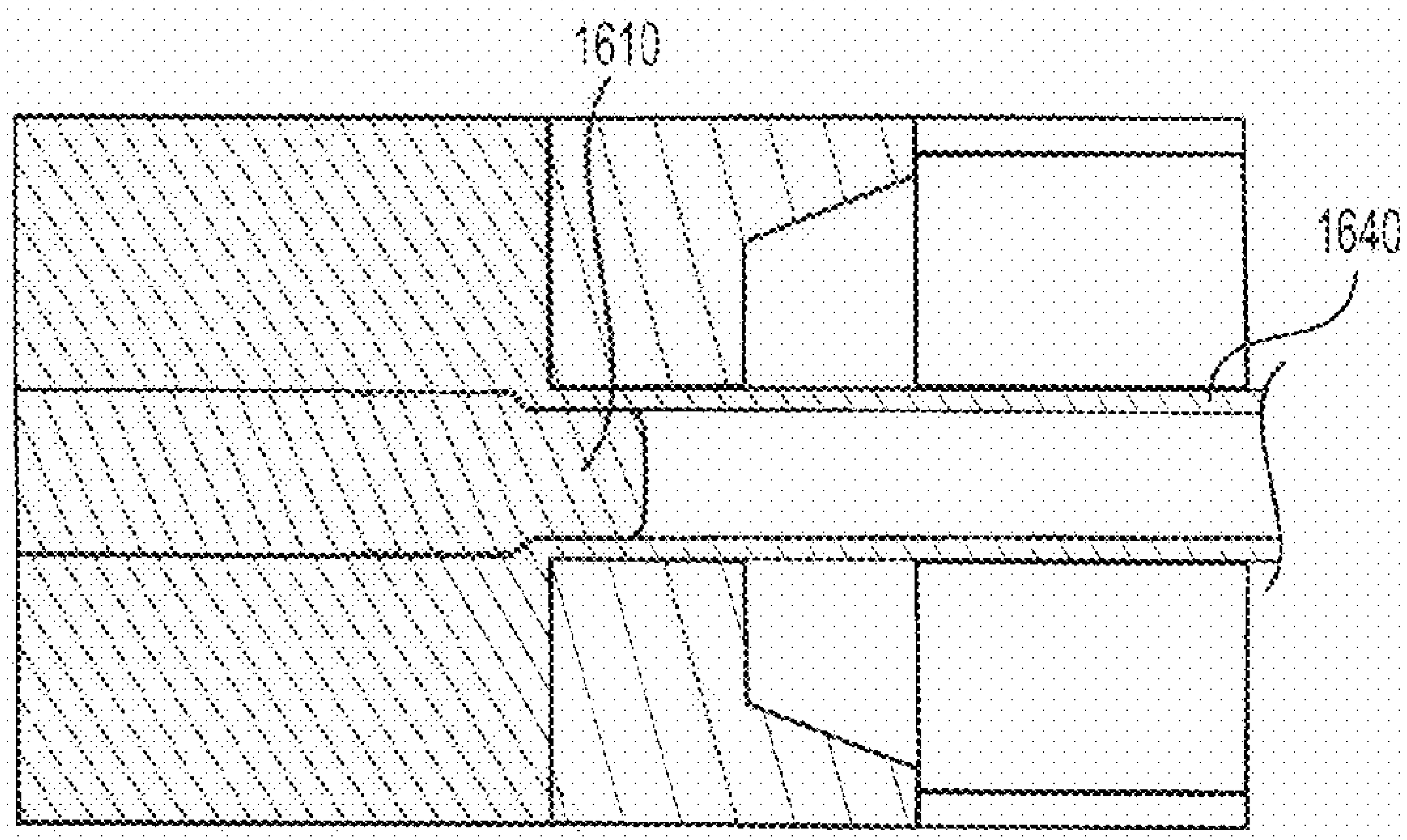

FIG. 16C

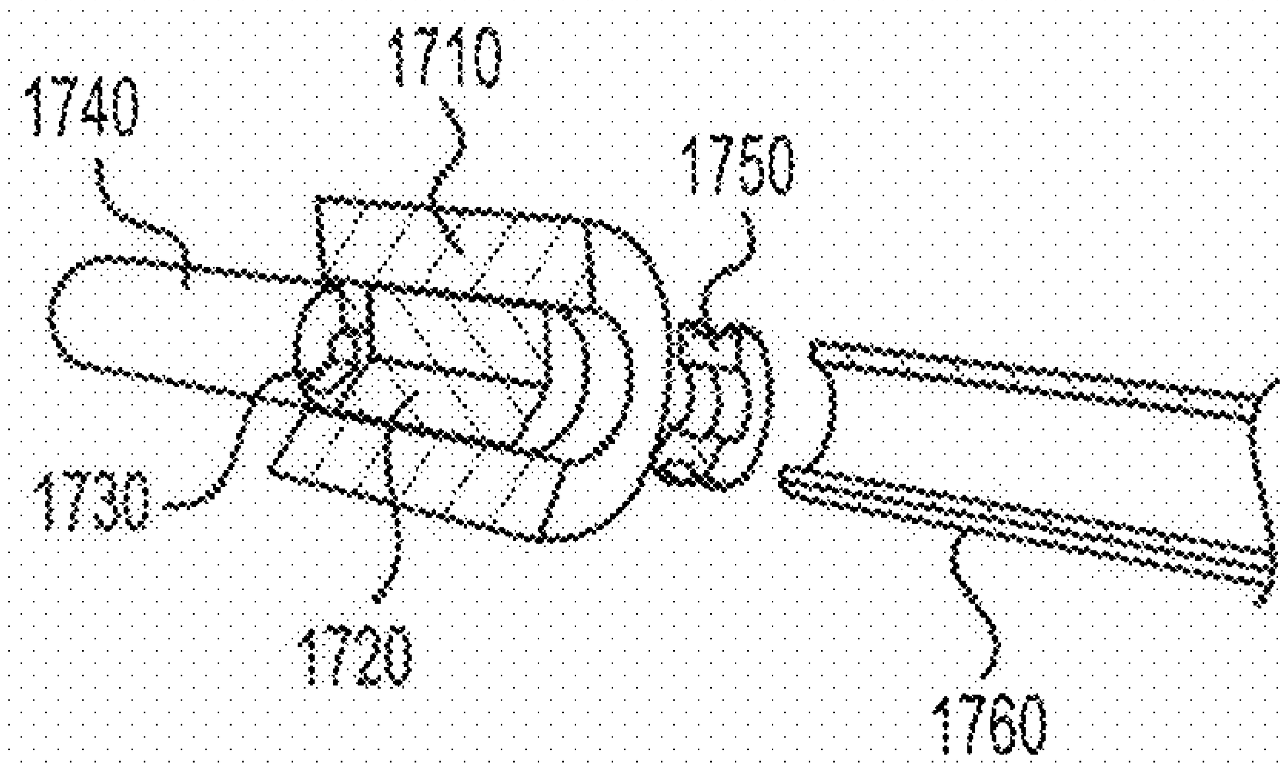

FIG. 17A

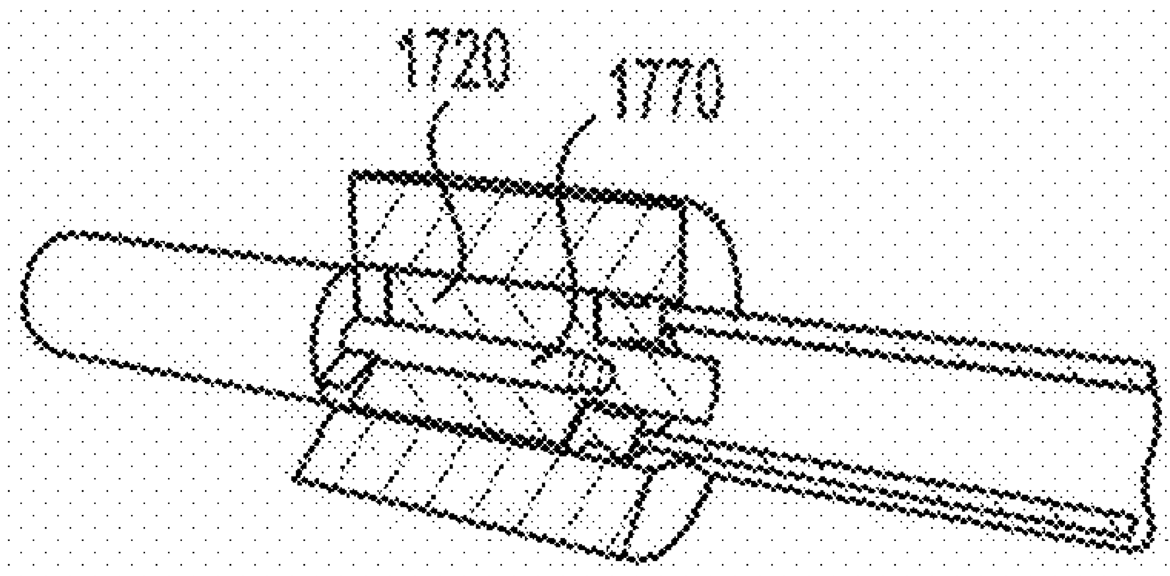

FIG. 17B

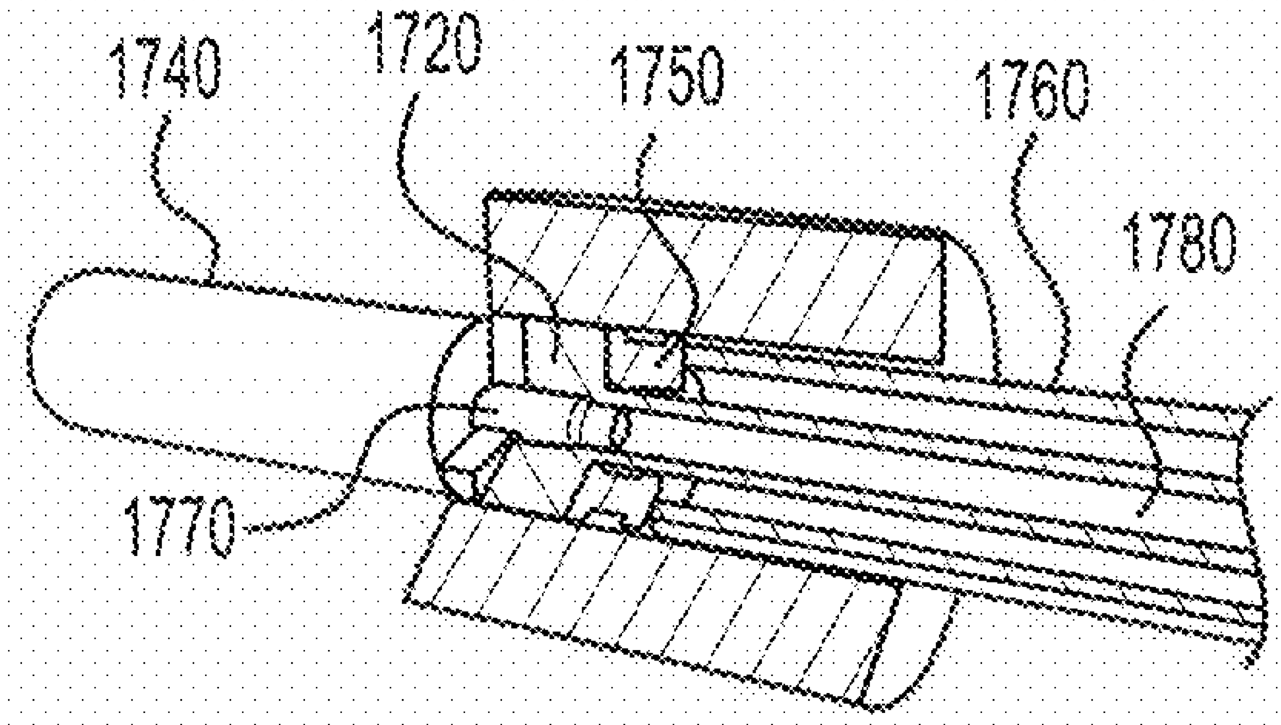

FIG. 17C

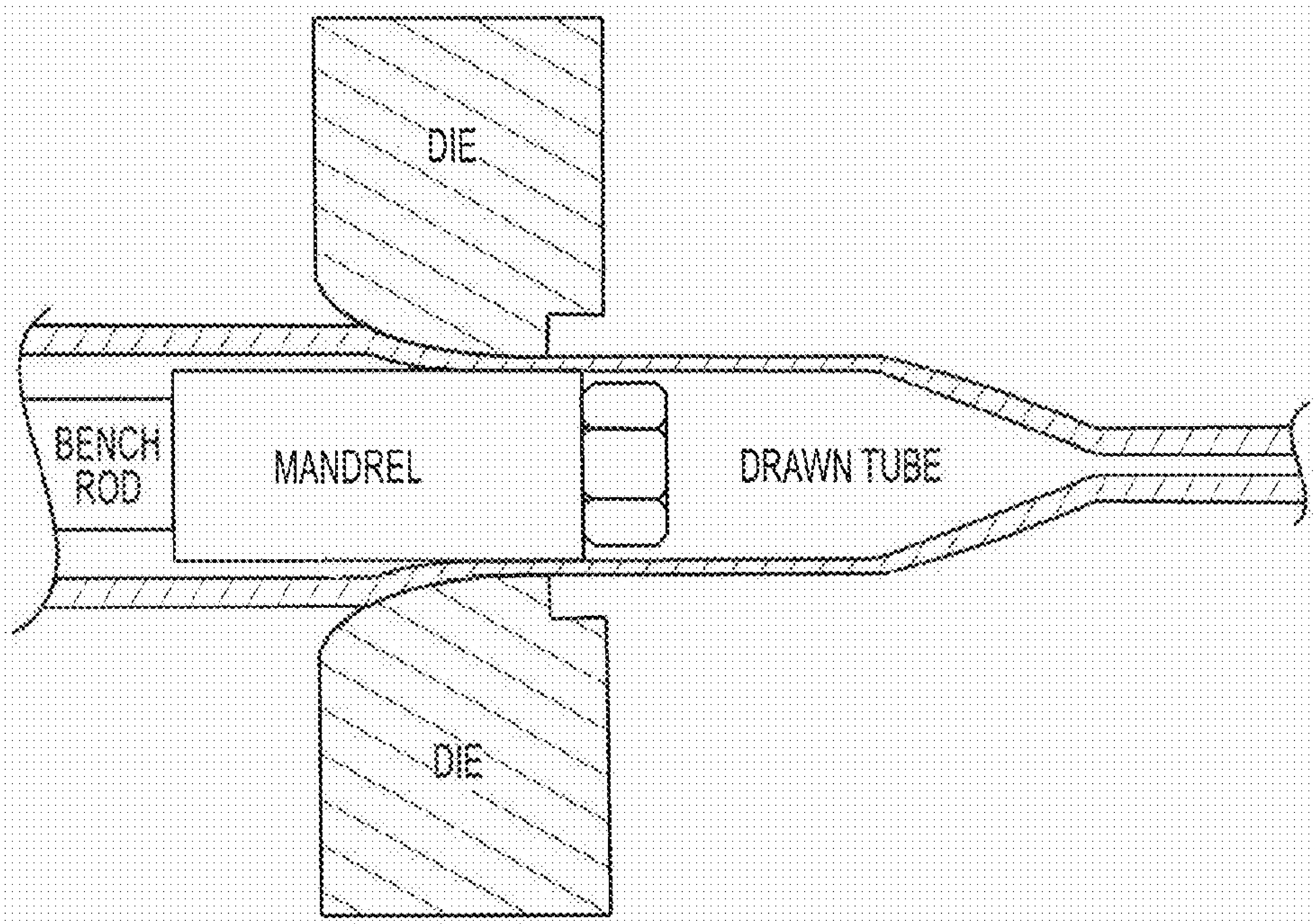

FIG. 18

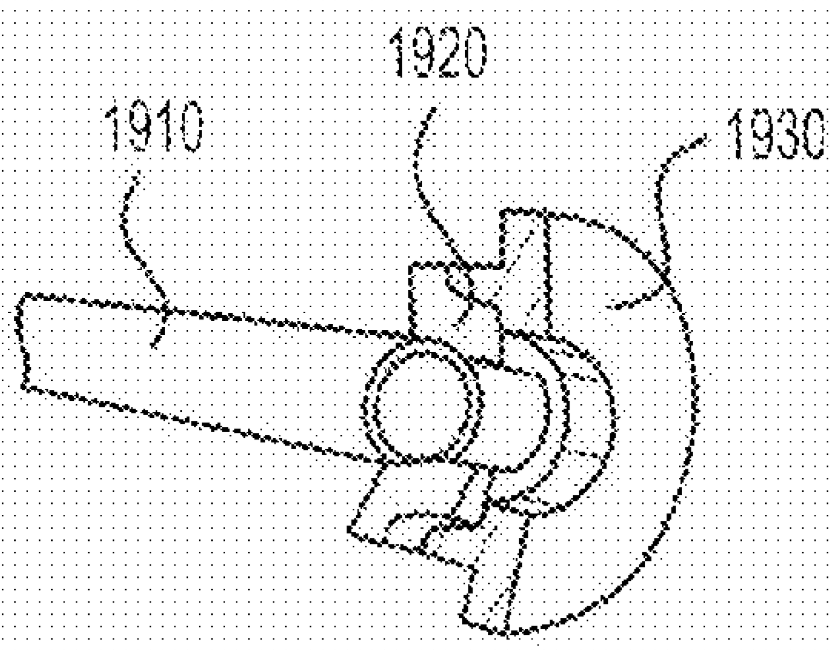

FIG. 19A

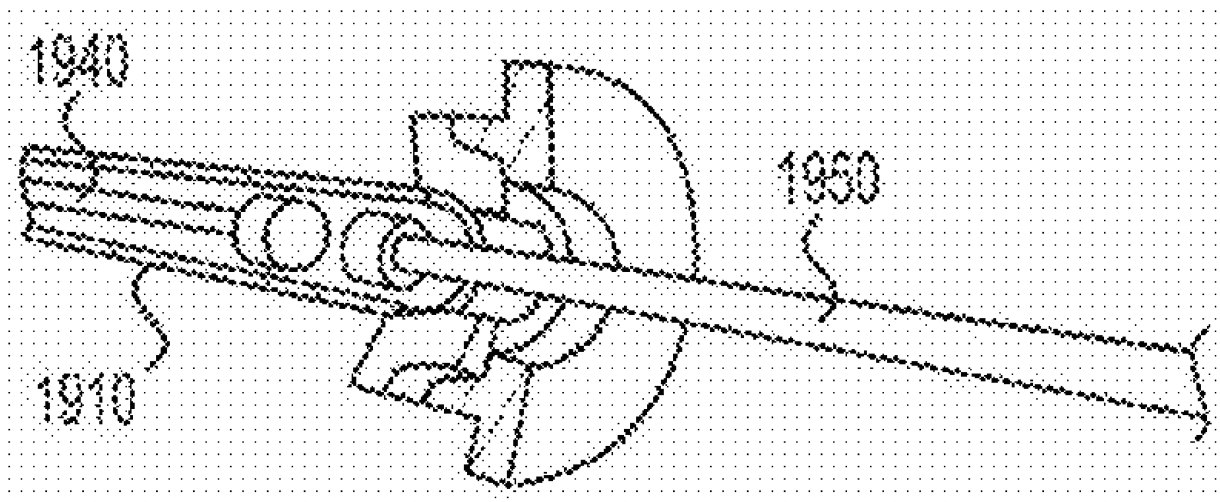

FIG. 19B

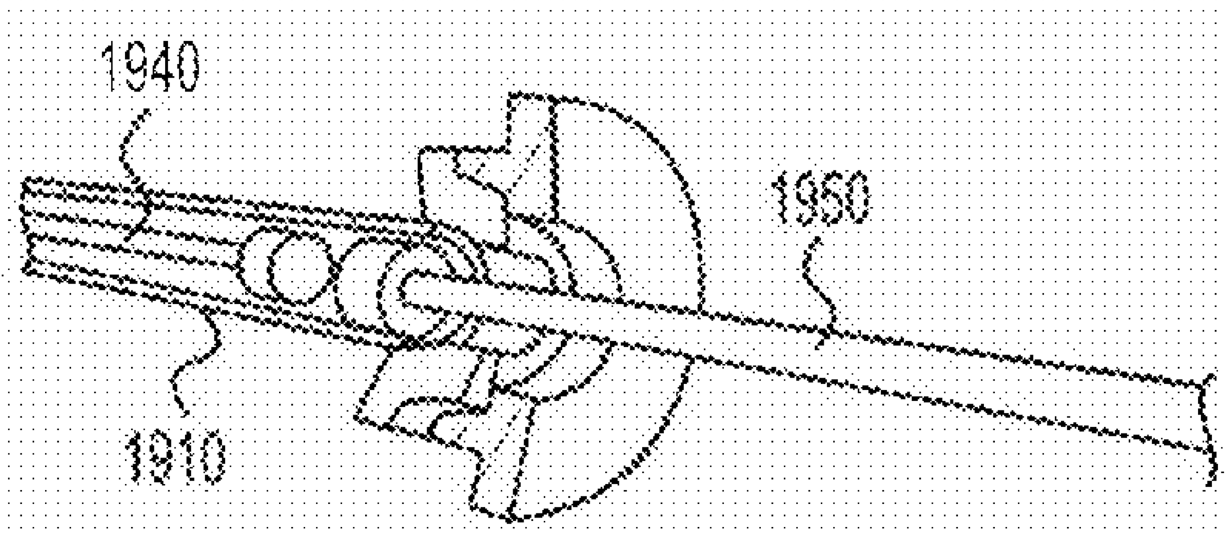

FIG. 19C

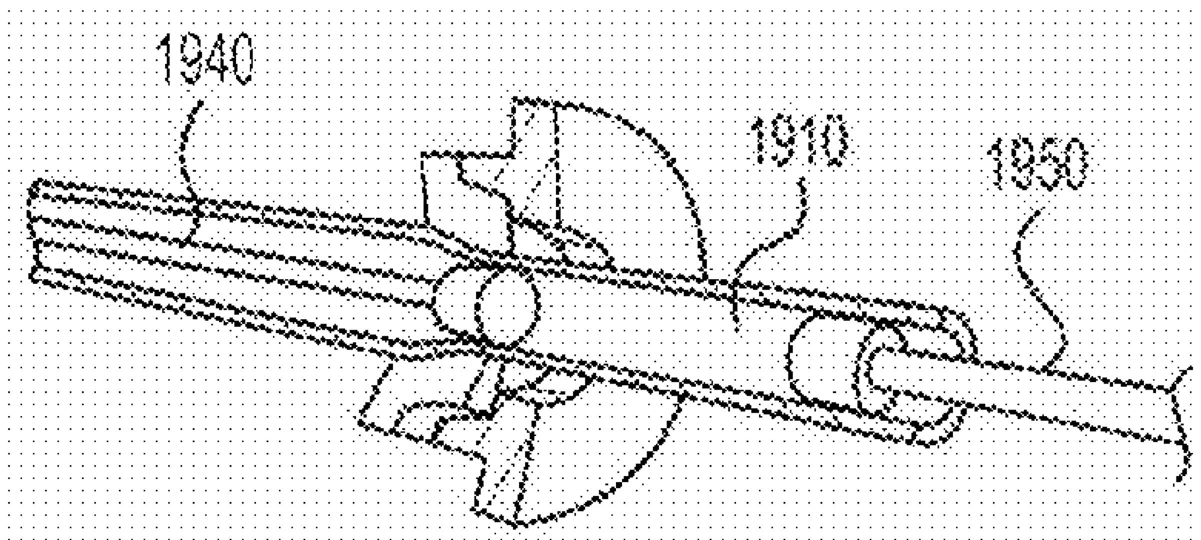

FIG. 19D

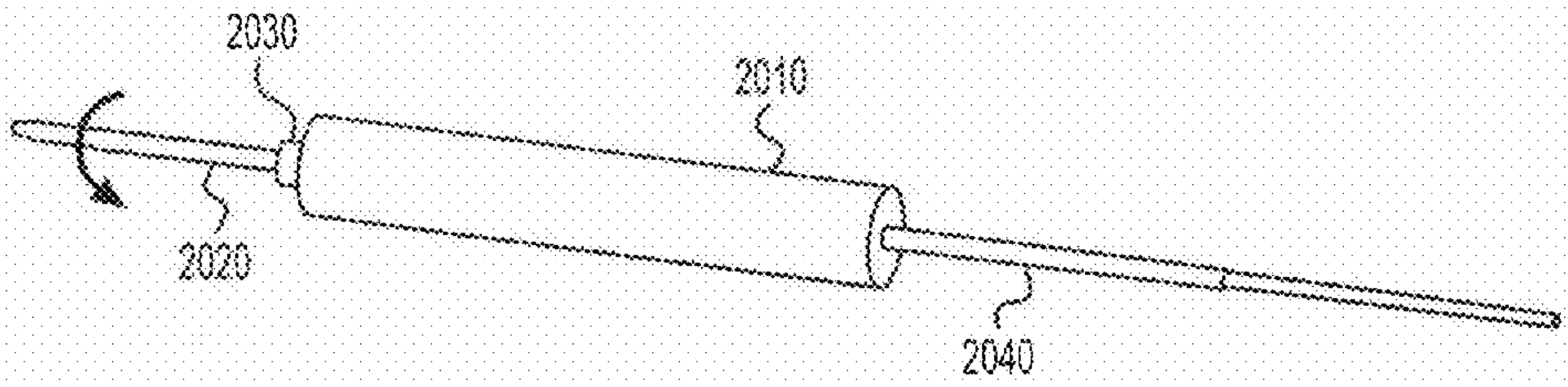

FIG. 20A

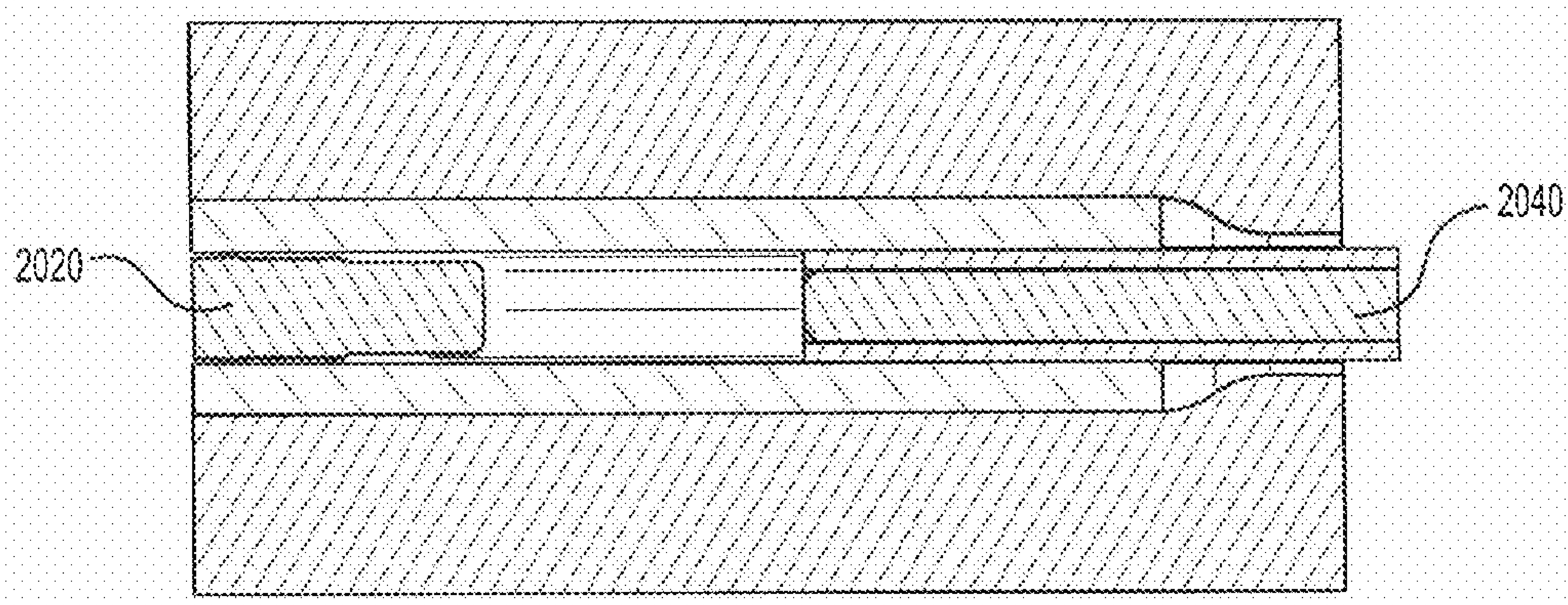

FIG. 20B

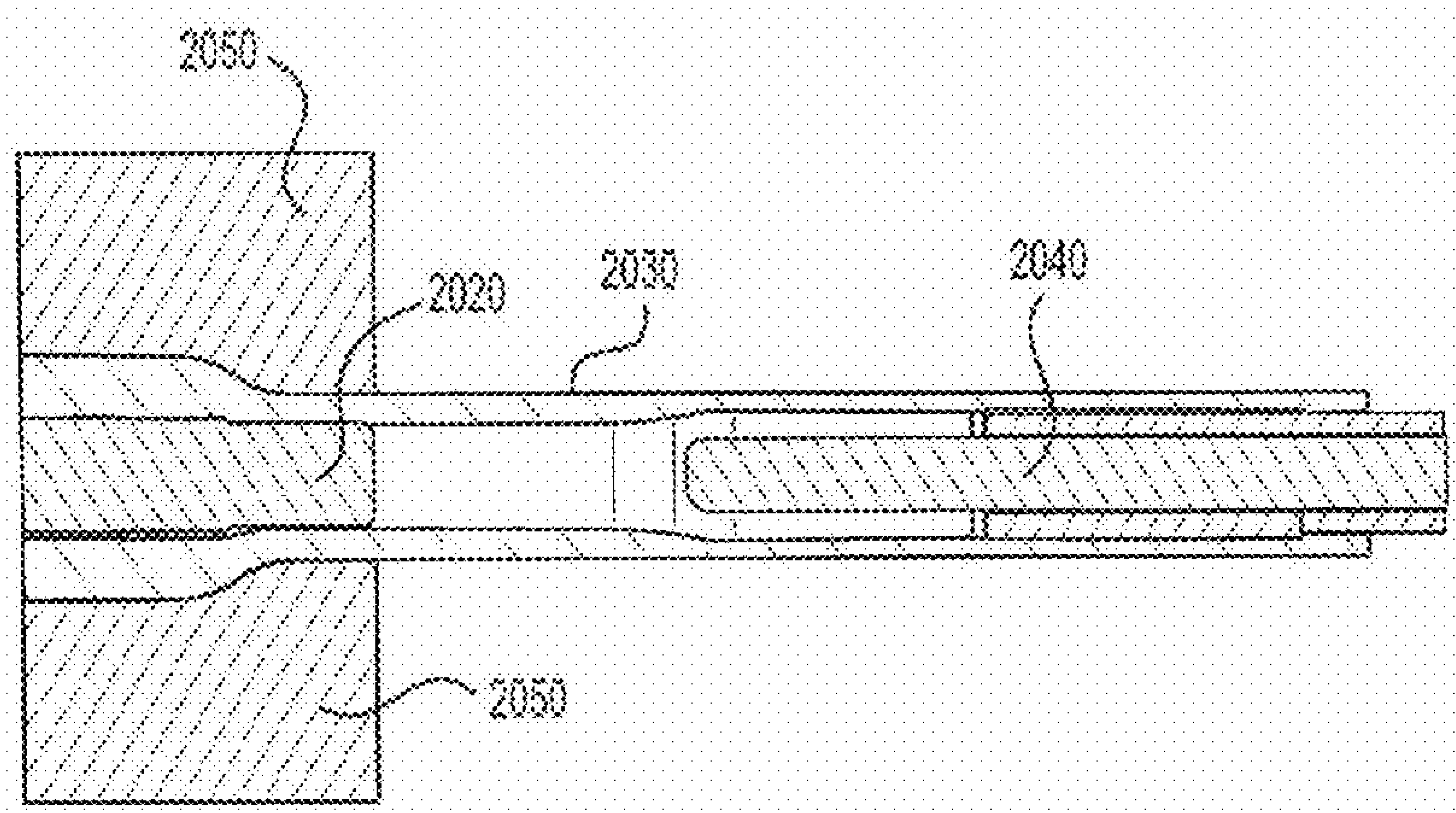

FIG. 20C

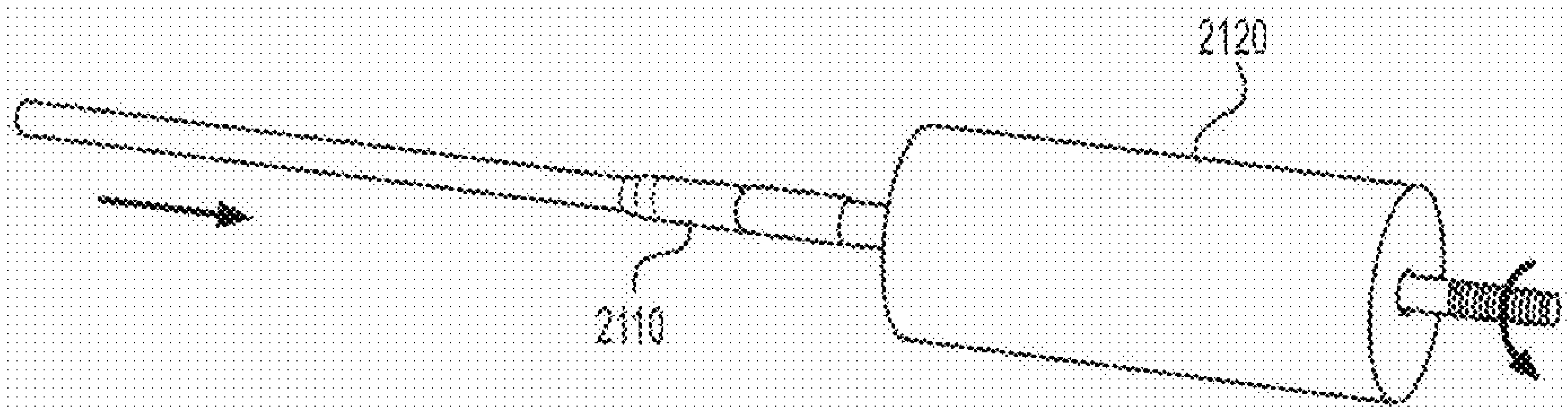

FIG. 21A

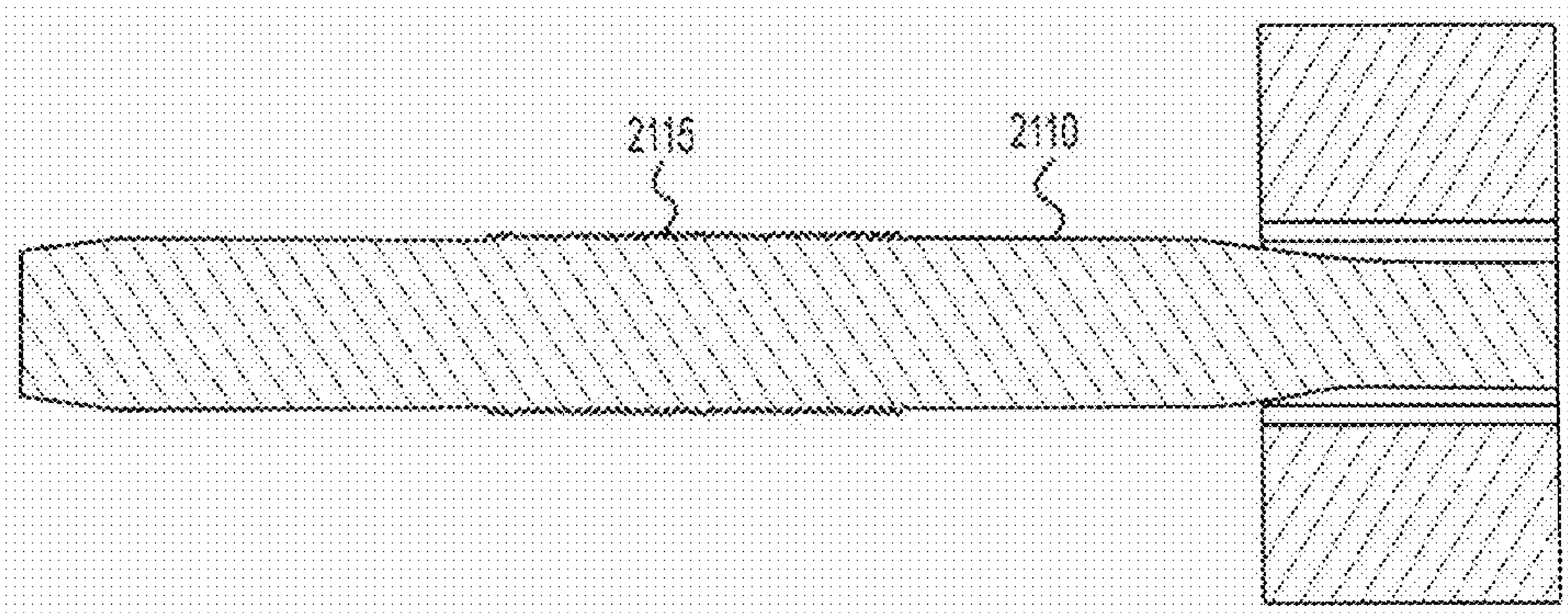

FIG. 21B

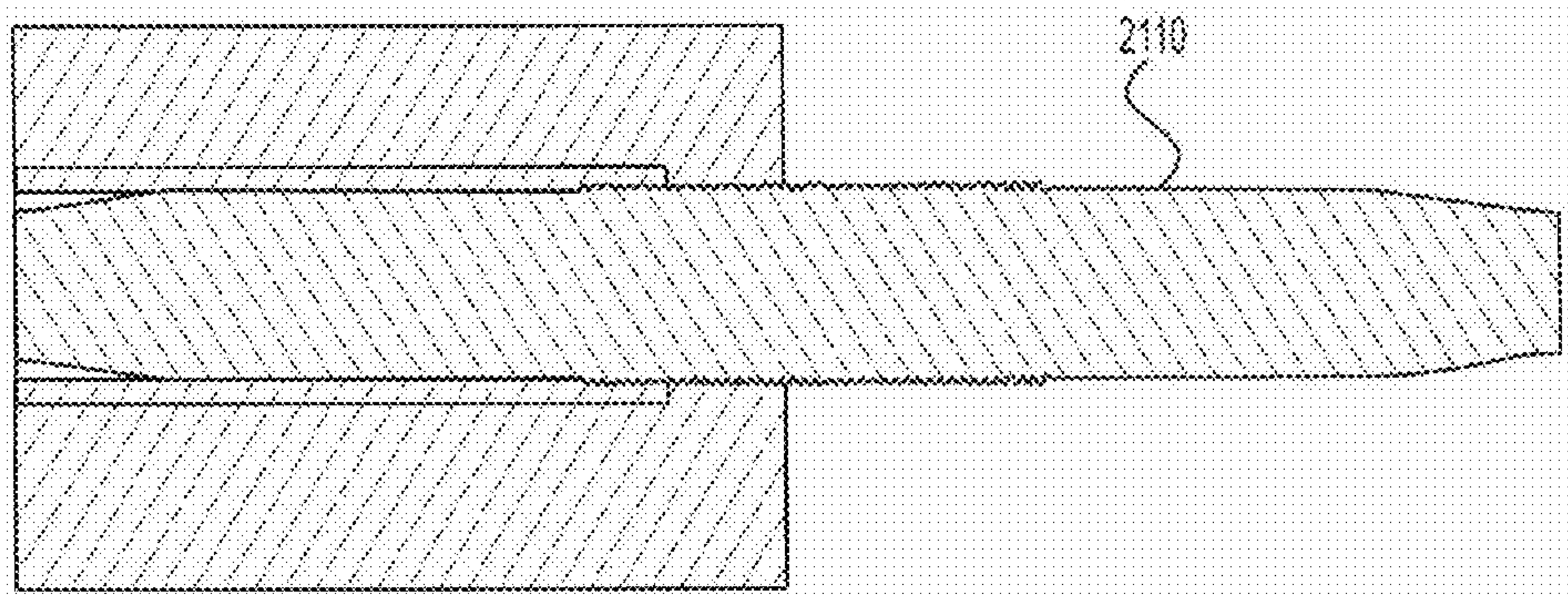

FIG. 21C

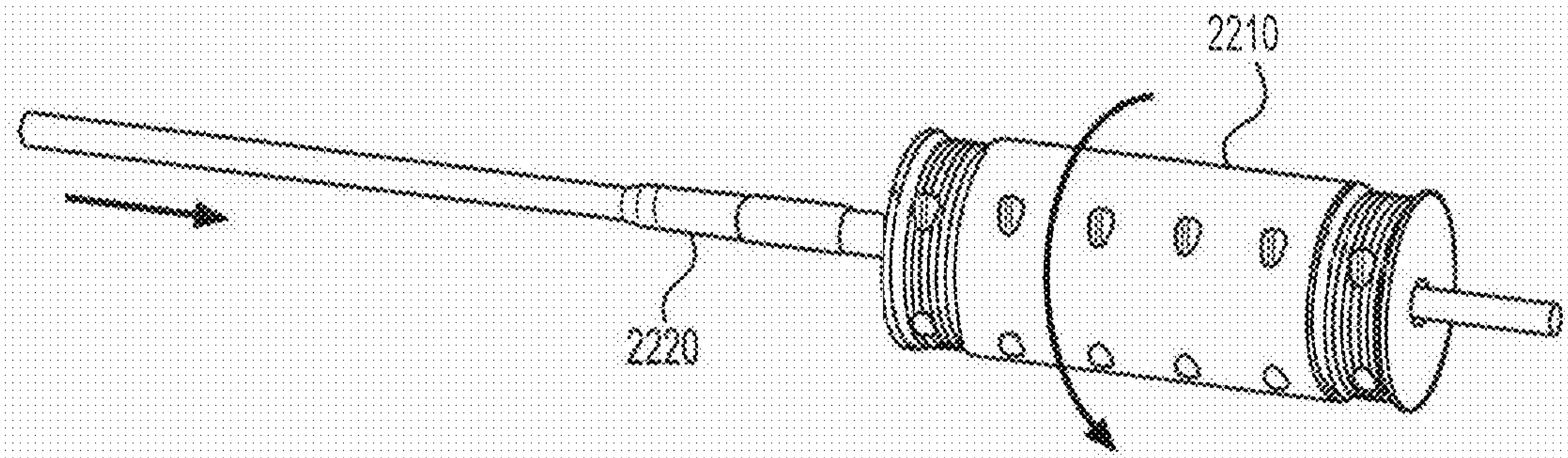

FIG. 22

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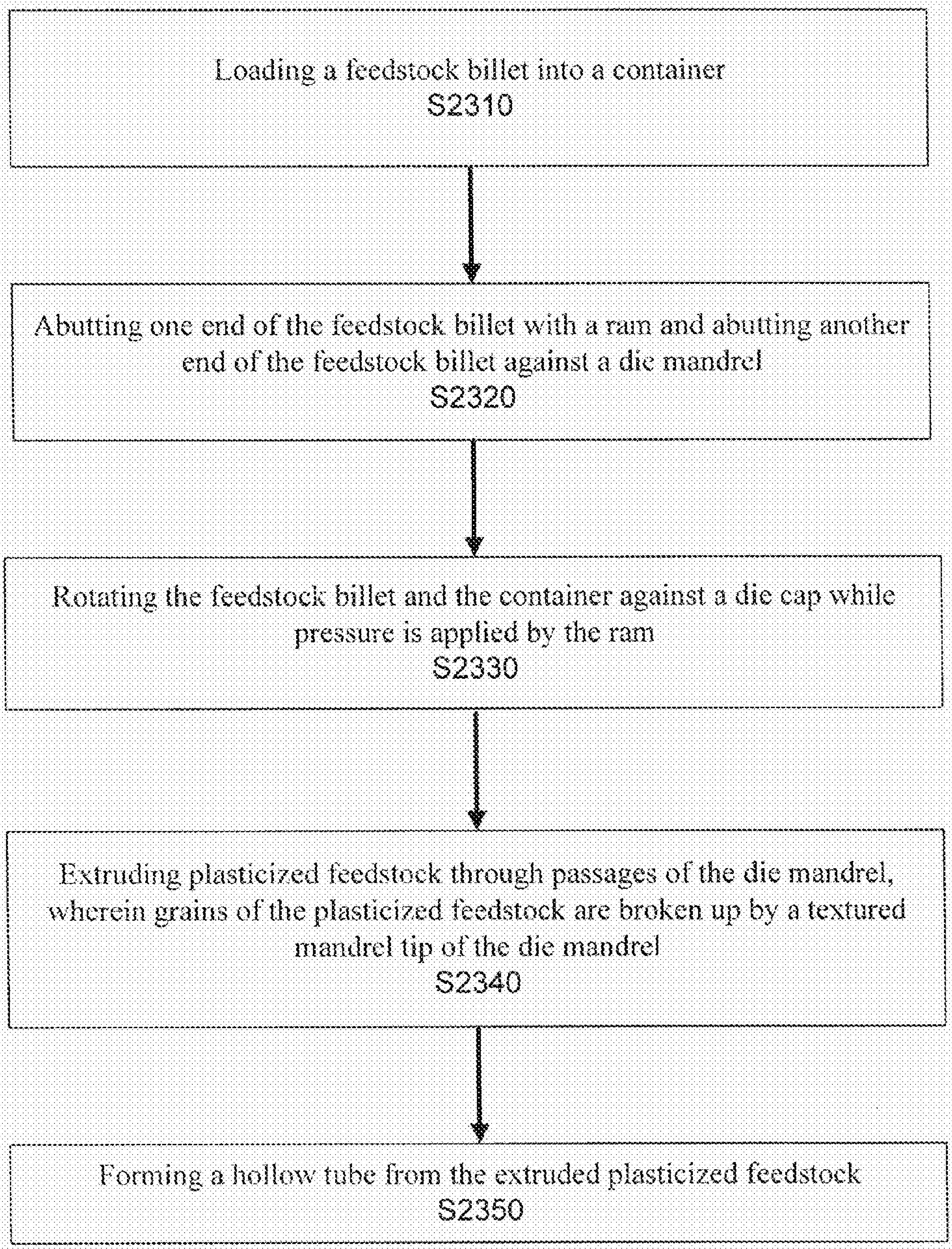
Fig. 23


Loading a feedstock billet into a container
S2310
Abutting one end of the feedstock billet with a ram and abutting another end of the feedstock billet against a die mandrel
S2320
Rotating the feedstock billet and the container against a die cap while pressure is applied by the ram
S2330
Extruding plasticized feedstock through passages of the die mandrel, wherein grains of the plasticized feedstock are broken up by a textured mandrel tip of the die mandrel
S2340
Forming a hollow tube from the extruded plasticized feedstock
S2350

2400

Fig. 24

Loading a feedstock billet into a container
S2410

Abutting one end of the feedstock billet with a ram and a concentrically-located mandrel, and abutting another end of the feedstock billet against a die
S2420

Piercing through the feedstock billet with the concentrically-located mandrel up to the die
S2430

Applying pressure to the feedstock billet by the ram
S2440

Extruding plasticized feedstock through the die and over a textured portion of the concentrically-located mandrel, wherein grains of the plasticized feedstock are broken up by the textured portion of the concentrically-located mandrel
S2450

Forming a seamless tube from the extruded plasticized feedstock
S2460

2500

Fig. 25

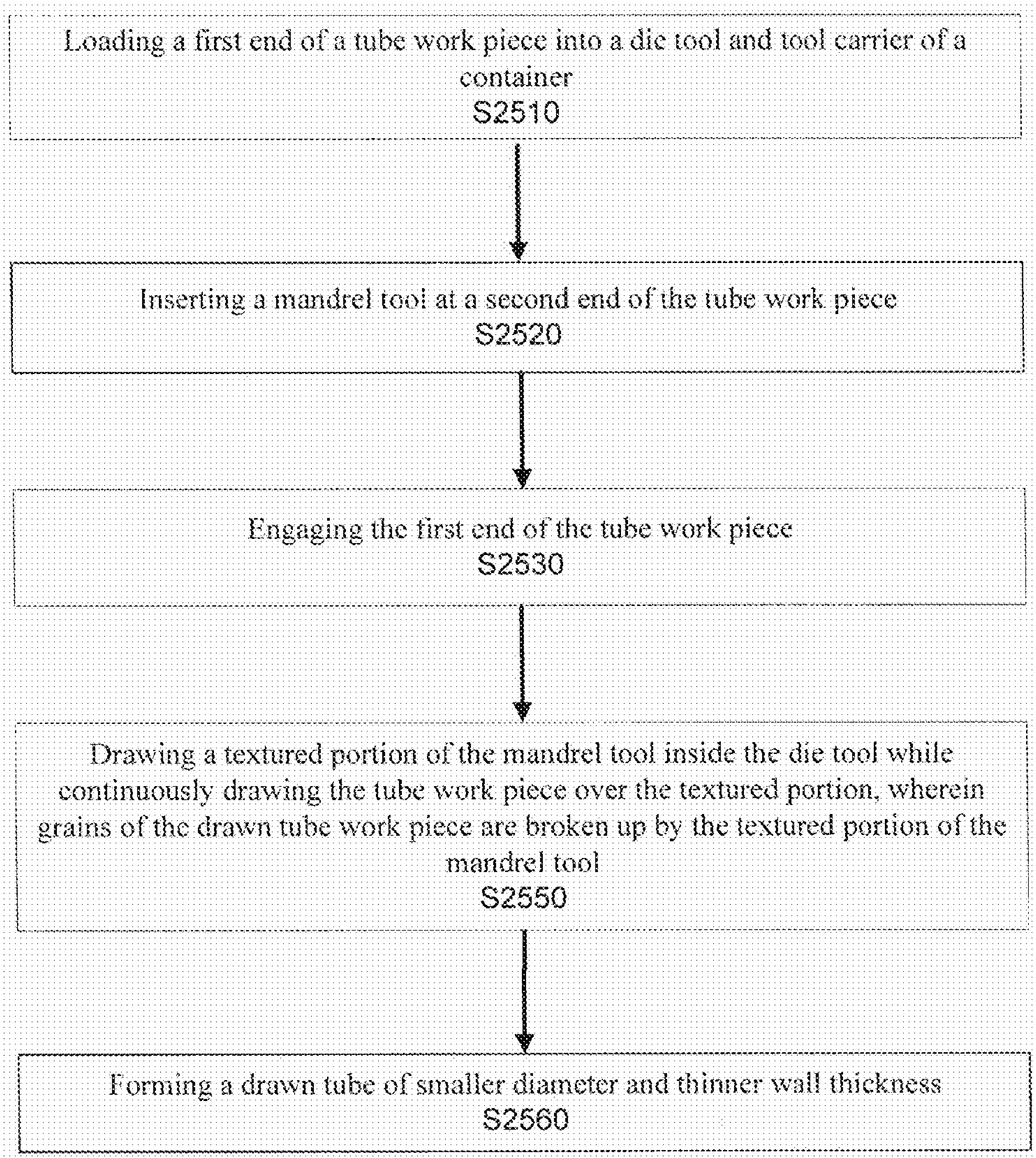

Loading a first end of a tube work piece into a die tool and tool carrier of a container
S2510
Inserting a mandrel tool at a second end of the tube work piece
S2520
Engaging the first end of the tube work piece
S2530
Drawing a textured portion of the mandrel tool inside the die tool while continuously drawing the tube work piece over the textured portion, wherein grains of the drawn tube work piece are broken up by the textured portion of the mandrel tool
S2550
Forming a drawn tube of smaller diameter and thinner wall thickness
S2560

Fig. 26

2600

Forcing a starting material across a textured end of a mandrel and through a die in a plasticized state, so that the textured end of the mandrel breaks up existing grains of the starting material
S2610

↓

Forming the pipe from material forced through the die, wherein the formed pipe has fine equiaxed resultant grains in multiple orientations on an interior surface of the formed pipe than the existing grains of the starting material
S2620

FRICTION-STIR EXTRUDERS AND FRICTION-STIR EXTRUSION PROCESSES

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application No. 61/879,397, filed on Sep. 18, 2013, the disclosure of which is incorporated in its entirety by reference herein.

BACKGROUND

[0002] Metal extruded products such as tubes are widely used for various applications in both structural and pressure flow applications. Aluminum tubes produced by conventional extrusion processes are a popular material for scaffolding, medical devices, structural framing, bicycle frames, and heat exchangers. Drawn aluminum tubes are widely used for various applications in both structural and pressure flow applications. Similarly, seamless extruded tubes are also widely used for various applications in both structural and pressure flow applications.

[0003] The use of aluminum tubes in heat exchangers is typically limited to low temperature and cryogenic applications, such as processing liquid natural gas (LNG). However, aluminum tubes have been used in seawater service applications such as desalination with moderate to good success. In addition, aluminum tubes have been tested for decades as a candidate material for ocean thermal energy conversion (OTEC) heat exchangers. OTEC is a method for generating electricity based on the temperature difference that exists between deep water and shallow water of a large body of water, such as an ocean, sea, gulf, or large deep lake. An OTEC system utilizes a heat engine, i.e., a thermodynamic device or system that generates electricity based on a temperature differential, which is thermally coupled between relatively warmer shallow water and relatively colder deep water.

[0004] Even though aluminum is a good selection from a cost perspective, the poor resistance to corrosive seawater can result in a lower service life than titanium or stainless steel alternatives. However, aluminum tubes produced with conventional extrusion processes have only found limited usages in heat exchanger applications with seawater service. Corrosion testing reveals that conventionally extruded aluminum alloys can exhibit severe pitting corrosion after two to three years of exposure to seawater. The aluminum samples in the surface seawater corrosion tests exhibited much less pitting occurrences with substantially less maximum depth of pits, relative to the aluminum samples in deep seawater. Deep seawater may be pulled from a depth of approximately 1,000 meters and can cause accelerated pitting corrosion in aluminum tubes because the deep seawater has less dissolved oxygen (DO) and a lower pH than surface seawater. The lower values of DO and pH tend to prevent the natural aluminum oxide layer from reforming to stop growth of initiated pits, as well as prevent new pits from forming. Since deep seawater is generally used in the OTEC thermodynamic cycle, this corrosion phenomenon can affect conventionally extruded tubes.

SUMMARY

[0005] Aspects of the disclosure can include a friction-stir mandrel having a textured end portion integral with a body portion. The textured end portion is configured to friction-stir process a starting material that is forced across the textured end portion and through a die in a plasticized state to form a pipe.

[0006] Embodiments include a method of forming a pipe, having the steps of forcing a starting material across a textured end of a mandrel and through a die in a plasticized state, so that the textured end of the mandrel breaks up existing grains of the starting material. The method also includes the step of forming the pipe from material forced through the die. The formed pipe has smaller resultant grains on an interior surface than the existing grains of the starting material.

[0007] Embodiments include a porthole die friction-stir extrusion method, having the steps of loading a feedstock billet into a container, and abutting one end of the feedstock billet with a ram and abutting another end of the feedstock billet against a die mandrel. The method also includes rotating the feedstock billet and the container against a die cap while pressure is applied by the ram. The method also includes extruding plasticized feedstock through passages of the die mandrel. Grains of the plasticized feedstock are broken up by a textured mandrel tip of the die mandrel. The method also includes forming a hollow tube from the extruded plasticized feedstock.

[0008] Embodiments include a seamless tube friction-stir extrusion method, having the steps of loading a feedstock billet into a container, and abutting one end of the feedstock billet with a ram and a concentrically-located mandrel, and abutting another end of the feedstock billet against a die. The method may also include piercing through the feedstock billet with the concentrically-located mandrel up to the die, and applying pressure to the feedstock billet by the ram. The method also includes extruding plasticized feedstock through the die and over a textured portion of the concentrically-located mandrel. Grains of the plasticized feedstock are broken up by the textured portion of the concentrically-located mandrel. The method also includes forming a seamless tube from the extruded plasticized feedstock.

[0009] Embodiments include a tube friction-stir drawing method, having the steps of loading a first end of a tube work piece into a die tool and tool carrier of a container, and inserting a mandrel tool at a second end of the tube work piece. The method also includes engaging a gripper at the first end of the tube work piece, and drawing a textured portion of the mandrel tool inside the die tool by the gripper while continuously drawing the tube work piece over the textured portion. Grains of the drawn tube work piece are broken up by the textured portion of the mandrel tool. The method also includes forming a drawn tube of smaller diameter and thinner wall thickness.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Various exemplary embodiments will be described in detail with reference to the following figures, wherein:

[0011] FIG. **1** is a schematic diagram of an OTEC power generation system according to one embodiment;

[0012] FIG. **2** is a cross-sectional view of a heat exchanger according to one embodiment;

[0013] FIGS. **3**A-**3**B are illustrations of porthole die extrusion systems according to one embodiment;

[0014] FIGS. **4**A-**4**D are illustrations of a porthole die extrusion process according to one embodiment;

[0015] FIGS. **5**A-**5**C are illustrations of a porthole friction-extrusion system according to one embodiment;

[0016] FIG. **6** is an illustration of an extrusion mandrel and die according to one embodiment;

[0017] FIGS. **7**A-**7**C are illustrations of an indirect friction-extrusion system according to one embodiment;

[0018] FIGS. **8**A-**8**D are illustrations of an integral hollow punch and die cap, and a decoupled die mandrel according to one embodiment;

[0019] FIG. **9** illustrates a seamless tube extruder and extrusion process according to one embodiment;

[0020] FIGS. **10**A-**10**D illustrate a seamless tube extrusion process in detail according to one embodiment;

[0021] FIGS. **11**A-**11**F illustrate a friction-extruded seamless tube process according to one embodiment;

[0022] FIG. **12** illustrates an active end of a mandrel tool according to one embodiment;

[0023] FIG. **13** illustrates a produced tubing according to one embodiment;

[0024] FIG. **14** illustrates a rotating mandrel tool and a non-rotating bearing according to one embodiment;

[0025] FIG. **15** illustrates a mandrel with a threaded extension and cylindrical screw cap according to one embodiment;

[0026] FIGS. **16**A-**16**C illustrate a two-piece mandrel according to one embodiment;

[0027] FIGS. **17**A-**17**C illustrate an indirect friction-extrusion method for seamless tubes according to one embodiment;

[0028] FIG. **18** illustrates a tube-drawing extrusion process according to one embodiment;

[0029] FIGS. **19**A-**19**D illustrate a tube-drawing extrusion process in detail according to one embodiment;

[0030] FIGS. **20**A-**20**C illustrate a friction-extrusion tube drawing process according to one embodiment;

[0031] FIGS. **21**A-**21**C illustrate a rotating mandrel and a non-rotational container according to one embodiment;

[0032] FIG. **22** illustrates a rotating container and a non-rotational mandrel according to one embodiment;

[0033] FIG. **23** is a flowchart showing an exemplary porthole die extrusion method according to one embodiment;

[0034] FIG. **24** is a flowchart showing an exemplary seamless tube extrusion method according to one embodiment;

[0035] FIG. **25** is a flowchart showing an exemplary tube drawing method according to one embodiment; and

[0036] FIG. **26** is a flowchart showing an exemplary pipe forming method according to one embodiment.

DETAILED DESCRIPTION

[0037] Aluminum tubes can be used in heat exchangers, such as those used in an ocean thermal energy conversion (OTEC) operation. FIG. **1** is a schematic diagram of an exemplary OTEC power generation system according to one embodiment. However, other OTEC power generation systems can be used with embodiments described herein. As shown, the OTEC system **100** can include an offshore platform **102**, a turbo-generator **104**, a closed-loop conduit **106**, an evaporator **110-1**, a condenser **110-2**, a hull **112**, multiple pumps **114**, **116**, and **124**, and multiple conduits **120**, **122**, **128**, and **130**.

[0038] Offshore platform **102** is a tension leg offshore platform, which has buoyant hull **112**, and also includes a deck, caissons, and pontoons. The hull **112** is supported above seabed **136** by rigid tension legs that are anchored to the seabed **136** at deployment location **134**. For clarity, the deck, caisson, pontoons, and tension legs are not illustrated in FIG. **1**.

[0039] In some embodiments, offshore platform **102** is deployed at a deployment location in a body of water other than an ocean (e.g., a lake, sea, etc.). In some embodiments, offshore platform **102** is an offshore platform other than a tension leg offshore platform, such as a semi-submersible, spar, drill ship, jack-up offshore platform, grazing plant, or the like. Other offshore platform types are contemplated by embodiments described herein.

[0040] Turbo-generator **104** is a turbine-driven generator mounted on hull **112**. Turbo-generator **104** generates electrical energy in response to a flow of fluid and provides the generated electrical energy on output cable **138**. Closed-loop conduit **106** is a conduit for conveying working fluid **108** through evaporator **110-1**, condenser **110-2**, and turbo-generator **104**.

[0041] Evaporator **110-1** is a shell-and-tube heat exchanger that is configured to transfer heat from warm seawater in surface region **118** and working fluid **108**, thereby inducing the working fluid **108** to vaporize. Condenser **110-2** is a shell-and-tube heat exchanger that is configured to transfer heat from vaporized working fluid **108** to cold seawater from deep-water region **126**, thereby inducing condensation of vaporized working fluid **108** back into liquid form. Evaporator **110-1** and condenser **110-2** are mechanically and fluidically coupled with offshore platform **102**.

[0042] Turbo-generator **104**, closed-loop conduit **106**, evaporator **110-1**, and condenser **110-2** collectively form a Rankine-cycle engine that generates electrical energy based on the difference in the temperature of water in surface region **118** and the temperature of water in deep-water region **126**. In operation, pump **114** pumps working fluid **108** in liquid form through closed-loop conduit **106** to evaporator **110-1**. Ammonia is an example of a working fluid **108** that can be used in OTEC systems. However, other fluids that evaporate at the temperature of the water in surface region **118** and condense at the temperature of the water in deep-water region **126** can be used as working fluid **108**, and are contemplated by embodiments described herein.

[0043] Pump **116** draws warm seawater from surface region **118** into evaporator **110-1** via conduit **120**. In some OTEC deployments, the water in surface region **118** is at a substantially constant temperature of approximately 25 degrees centigrade (subject to weather and sunlight conditions). At evaporator **110-1**, heat from the warm water is absorbed by working fluid **108**, which induces the working fluid **108** to vaporize. After passing through evaporator **110-1**, the now slightly cooler water is ejected back into ocean **140** via conduit **122**. The output of conduit **122** is usually located deeper in ocean **140** than surface region **118** to avoid decreasing the average water temperature in the surface region **118**.

[0044] The expanded working fluid **108** vapor is forced through turbo-generator **104**, thereby driving the turbo-generator **104** to generate electrical energy. The generated electrical energy is provided on output cable **138**. After passing through turbo-generator **104**, the vaporized working fluid **108** enters condenser **110-2**.

[0045] Pump **124** draws cold seawater from deep-water region **126** into condenser **110-2** via conduit **128**. Deep-water region **126** can be approximately 1000 meters below the surface of the body of water, at which depth water is at a substantially constant temperature of a few degrees centigrade. The cold water travels through condenser **110-2**, where it absorbs heat from the vaporized working fluid **108**. As a result, working fluid **108** condenses back into liquid form.

After passing through condenser **110-2**, the now slightly warmer water is ejected into ocean **140** via conduit **130**. The output of conduit **130** is usually located at a shallower depth in ocean **140** than that of deep-water region **126** to avoid increasing the average water temperature in the deep-water region **126**. Pump **114** pumps the condensed working fluid **108** back into evaporator **110-1** where it is vaporized again, thereby continuing the Rankine cycle that drives turbo-generator **104**.

[0046] FIG. **2** is a cross-sectional view of a shell-and-tube heat exchanger according to an embodiment described herein. An exemplary heat exchanger includes a shell **202**, a primary fluid inlet **204**, an input manifold **206**, an output manifold **208**, a primary fluid outlet **210**, a secondary fluid inlet **212**, a secondary fluid outlet **214**, and multiple tubes **216**, tube plates **220**, and baffles **224**. Heat exchanger **110** enables efficient heat transfer between a primary fluid that flows through tubes **216** and a secondary fluid that flows through shell **202**, such that the secondary fluid flows across the outer surface of each of the tubes **216**. With reference to FIG. **1**, the primary fluid is working fluid **108** and the secondary fluid is seawater. Shell **202** is a housing that includes a material suitable for long-term exposure to seawater. Shell **202** and tube plates **220** collectively define a flow vessel for conveying seawater from secondary fluid inlet **212** to secondary fluid outlet **214**.

[0047] Working fluid **108** is conveyed to each of tubes **216** by primary fluid inlet **204** and input manifold **206**. In similar fashion, working fluid **108** is collected from each of tubes **216** at output manifold **208** and provided to primary fluid outlet **210**. Primary fluid inlet **204** and primary fluid outlet **210** are fluidically coupled with closed-circuit conduit **106**, such that heat exchanger **110** forms part of the closed-circuit conduit.

[0048] Seawater is provided to shell **202** at secondary fluid inlet **212**. In evaporator **110-1**, secondary fluid inlet **212** is fluidically coupled with conduit **120**. In condenser **110-2**, secondary fluid inlet **212** is fluidically coupled with conduit **128**. Seawater exits shell **202** through secondary fluid outlet **214**. In evaporator **110-1**, secondary fluid outlet **214** is fluidically coupled with conduit **122**. In condenser **110-2**, secondary fluid inlet **214** is fluidically coupled with conduit **130**. FIGS. **1** and **2** depict secondary fluid inlet **212** and secondary fluid outlet **214** on the same side of the heat exchanger. However, secondary fluid inlet **212** and secondary fluid outlet **214** can be located on opposite sides of the heat exchanger to facilitate efficient heat transfer between the primary and secondary fluids.

[0049] In one embodiment, each of the tubes **216** is a conduit of aluminum alloy having length, inner diameter, and tube wall thickness that are selected for efficient thermal coupling between seawater and working fluid **108**. A shell-and-tube heat exchanger suitable for a modern OTEC system can include five to six thousand tubes having a length of up to thirty feet. Each of the tube plates **220** is a mechanically rigid circular plate of aluminum alloy having a plurality of holes **218**. Each end of the tubes **216** is joined to a different one of the tube plates **220** at holes **218** to collectively define a tubesheet **222**.

[0050] Baffles **224** can be transverse baffles that induce a transverse component to the flow of seawater through the heat exchanger. In some embodiments, baffles **224** also provide support for the tubes **216** in the region between the tube plates **220**. Baffles **224** include a plurality of through-holes for the tubes **216**. The number and placement of baffles **224** is a matter of heat exchanger design, and one skilled in the art would recognize that any practical number of baffles **224** can be included in the heat exchanger. Tube plates **220** and baffles **224** hold the tubes in an arrangement that facilitates heat transfer between seawater flowing along the outer surfaces of the tubes **216** and working fluid **108** that flows through the tubes **216**.

[0051] One method of forming metal tubes, including aluminum tubes is a porthole die extrusion process. FIG. **3**A is an illustration of a direct porthole die extrusion system in which a die mandrel **310** is coupled with a die cap **320**, and feedstock material **330** such as aluminum material is forced through the die mandrel **310** and through the die cap **320** to form a tubular finished product **340**. The top drawing of FIG. **3**B illustrates a direct extrusion process in which a ram **350** pushes against a billet **360** to force the billet material through a stationary die **370** to form an extruded hollow tube **380**. The bottom drawing of FIG. **3**B illustrates an indirect extrusion process in which a hollow punch **390** with an integral die **395** presses against the billet inside a container. The extruded billet material **380** is forced through the orifice within the hollow punch **390**.

[0052] FIGS. **4**A-**4**D illustrate a porthole die extrusion process in more detail. A container **410** provides structural support for the dynamic process. A die mandrel **420** and a coupled die cap **430** are inserted into the container **410**. A die carrier **440** and an aluminum billet **450** are inserted into the die carrier **440** in FIG. **413**. A press disc **460** is butted against the back side of the aluminum billet **450**. In FIG. **4**C, a ram **470** is butted against the press disc **460**. FIG. **4**D illustrates the tube extrusion **480** as the ram **470** forces the aluminum billet material **450** through the die cap **430** and die mandrel **420** to form a hollow tube. During the extrusion process, the die mandrel **420** and die cap **430** remain stationary while the feedstock material is forced through the die mandrel bridge and separated into four distinct material flow paths. The plasticized material re-welds in the die cap **430** and forms a tubular shape over the die mandrel **420**.

[0053] One short-coming of the porthole die extrusion process described with reference to FIGS. **3**A-**4**D is the finished product has poor resistance to pitting corrosion in a saltwater environment, such as that of an OTEC system. A major cause for the poor corrosion resistance is the presence of a large grain surface. In addition, the products of this extrusion process have low mechanical properties, such as bending, fatigue, and fracture toughness.

[0054] Incorporating friction extrusion tools and processes break down the original grains of feedstock metal into fine grains. Most or all of the precipitates are dissolved back into the base metal, resulting in extruded products having very fine equiaxed grains and much cleaner grain boundaries with fewer and smaller precipitates on the tube inside surface of the extrusions. The grains are also equiaxed in the direction of extrusion, whereby any cross-section of a friction-extruded tube will show a homogenous grain size. Friction-extruded tubes can still be heat treated after extruding, such as aging to improve mechanical properties like tensile strength, as well as improve corrosion resistance. Friction-extruded products also exhibit better mechanical properties, and therefore have a much longer service life, as compared to conventionally extruded products.

[0055] FIG. **5**A illustrates an exterior view of a direct friction-extrusion system **500**. A container **510** holds the die mandrel and die cap in place during the extrusion. A motor

520 and a pulley and drive belt system **530** power the extrusion process, which exerts a force against the feedstock metal via a ram **540**. A metal tube will be extruded to the right side of the figure.

[0056] FIG. **5**B is a cross-sectional view of the friction-extrusion system **500** during the extrusion process. In embodiments described herein, the die mandrel **550** is decoupled from the die cap **560**. The die mandrel **550** and cylinder **570** containing the feedstock **580** (illustrated by the right-pointed arrow) spin together at a high rotational speed, while the die cap **560** remains non-rotational. Frictional heating and considerable force from the ram **540** results in severe plastic deformation of the feedstock **580**.

[0057] As the plasticized feedstock **580** enters the stationary die cap **560**, the material flowing through the die mandrel **550** is frictionally-processed in the weld chamber **590** when the material comes in contact with the features of the stationary die cap **560**, as illustrated in FIG. **5**C. As a result, the frictionally processed material flows over the male piece of the die mandrel **550** to form an extruded tube **595** with very fine grains. FIG. **5**C illustrates the extruded tube **595**, produced by a rotating container **570** and feedstock **580**, as well as a rotating die mandrel **550**. However, the die cap **560** is fixed, i.e., not rotating. The decoupled die mandrel **550** and die cap **560** provide a fine-grained surface on the inner surface of the extruded tube **595**.

[0058] In some embodiments illustrated in FIG. **6**, the die cap has a conical feature **610** to allow for less pressure and enhanced material flow characteristics in the weld zone. In other embodiments, the die mandrel tip has a textured surface **620** to assist with shearing through material grains and to refine the microstructure for round shape extrusions. The textured surface **620** includes, but is not limited to surfaces containing features, such as threads, ridges, studs, and protrusions. The tip of the mandrel can have a plain cylindrical feature for forming a smooth diameter tube. In still other embodiments, a mandrel bearing **630** can promote a smooth interior finish on the resultant extruded tube. The bearing is held in place with a bearing nut **640** that is attached to the die mandrel, and does not affect the forming of the tube. During operation, the textured die mandrel **620** and feedstock **650** rotate, but the mandrel bearing **630** does not rotate because it has a rotational degree of freedom from the die mandrel and is held stationary by the extrusion forces applied to the bearing exterior.

[0059] FIGS. **7**A-**7**C illustrate an indirect friction-extrusion system, according to embodiments described herein. FIG. **7**A is a cross-sectional view of a setup assembly of an indirect friction-extrusion system in which a container **710** and billet **720** rotate, while die mandrel **730** and die cap **740** remain non-rotational. FIG. **7**B is a close-up view showing material flowing through the die mandrel **730** to form a tube **750**. The hollow punch **740** is integral with the die cap and is coupled with the die mandrel **730** using threaded fasteners **760**. FIG. **7**C is an isometric view showing a container **710** moving towards a stationary hollow punch **740** to produce a length of tubing **750**.

[0060] Two different embodiments are described for an indirect friction-extrusion system. In the first embodiment, the die cap and integral hollow punch rotate, while the container remains non-rotational. The hollow punch pushes the die mandrel and die cap into the billet towards the stationary container. In the second embodiment, the rotating container and billet push the billet against a stationary die mandrel, die cap, and hollow punch. As the container is pushed with ram force, the plasticized aluminum billet is forced through the die mandrel and out the die cap, through the hollow punch aperture as a finished tube. The second embodiment is illustrated in FIGS. **7**A-**7**C. FIGS. **7**A-**7**C also illustrate a hollow punch that is integral with the die cap and is coupled with the die mandrel as a single integral assembly.

[0061] Another embodiment includes a hollow punch that is integral with the die cap, but is decoupled with the die mandrel and is separated by a thrust bearing, with reference to FIGS. **8**A-**8**D. FIG. **8**A illustrates a container **810** with a hex boss **820**, which is configured to receive a hex-shaped billet **830**. Any other polygonal-shaped boss and billet combination is contemplated by embodiments described herein. FIG. **8**B illustrates that the container **810** and enclosed billet **830**, as well as the die mandrel **840** are rotating, while the die cap and integral hollow punch **850** are stationary. The integrated hollow punch and die cap **850** are coupled with the die mandrel **840** using threaded fasteners, wherein the thrust bearing **860** rotates with the container **810** and billet **830**. FIG. **8**C illustrates the plasticized billet material is forced through openings in the die cap **850**. The roughened surface of the rotating die mandrel **840** breaks up large grains of billet material **830**. As a result, the extruded tube **870** contains fine-grain material on the interior surface of the tube. FIG. **8**D illustrates the length of tubing **870** produced as the container and billet material move towards the stationary hollow punch.

[0062] Some embodiments include removing the male mandrel portion and using a die cap designed with a non-circular geometric shape, such as a square, hexagon, or other polygonal shape. Some embodiments include non-circular geometric shapes that also have a non-circular hollow. The initial circular hollow can be formed into a non-circular shape, such as a square, hexagon, or other polygonal shape through the use of a secondary die.

[0063] FIGS. **3**A-**8**D illustrate embodiments for porthole die extruders and porthole die extrusion processes. Embodiments for seamless extruders and seamless extrusion processes are described herein under.

[0064] FIG. **9** illustrates a seamless tube extruder **900** and extrusion process. A billet **910** is pierced with a mandrel **920**, while pressure is applied to the billet material. The extruded material forms a hollow seamless tube **930** over the mandrel **920**. All of the components illustrated in FIG. **9** are stationary or only allowed to move in one axis, i.e. towards the die and away from the die. Seamless extruded tubes can be produced in this manner by either a direct process (a moving ram forced against the billet material) or an indirect process (a die is forced against a stationary billet).

[0065] FIGS. **10**A-**10**D illustrate the seamless tube extrusion process in detail. A container **1010** receives a die tool **1020** and tool holder **1030** in FIG. **10**A. A press disc **1040** is pressed against a back end of a billet **1050**, and a ram **1060** is positioned against the press disc **1040**. The press disc **1040**, billet **1050**, and ram **1060** are positioned inside the carrier **1010**, as illustrated in FIG. **10**B. A mandrel **1070** pierces the billet **1050**, as illustrated in FIG. **10**C. The ram **1060** continues to press against the billet **1050** to force billet material through the die **1020** and over the surface of the mandrel **1070**, as illustrated in FIG. **10**D. The ram **1060** continues to press against the billet **1050** until the billet material **1050** has been extruded, to form a resultant hollow tube **1080**. The press disc **1040**, scrap billet, and tube **1080** are removed from the container **1010** at the conclusion of the processing.

[0066] One short-coming of the seamless tube extrusion process described with reference to FIGS. **10A-10D** is the resultant tubes, particularly aluminum tubes have poor resistance to pitting corrosion, especially in a saltwater environment such as OTEC heat exchangers. Incorporating frictional heating and extensive plastic deformation into a seamless tube extrusion process improves the strength and corrosion resistance of seamless tubing. During friction extrusion, the original grains of the feedstock metal are broken down into fine grains. In addition, most or all of the precipitates are dissolved back into the base metal. The resultant extruded products have very fine grains and much cleaner grain boundaries, as well as fewer and smaller precipitates inside of the tubing. This resultant microstructure exhibits better mechanical properties and much better resistance to corrosive environments, such as seawater. As a result, the service life of the tubing is greatly extended.

[0067] FIGS. **11A-11F** illustrate how friction processing is incorporated into the seamless extrusion process described above. FIG. **11A** illustrates that a rotating mandrel **1110** is used against a non-rotating ram **1120**, press disc **1130**, container **1140**, die **1150**, and die carrier **1160**. A lateral force presses the ram **1120** against the billet **1170** as the mandrel **1110** rotates into the billet **1170**, as illustrated in FIG. **11B**. The rotation of the mandrel **1110** stirs the billet **1170** near the die **1150** opening, as illustrated in FIG. **11C**. This refines the grains of the feedstock material before it is formed into a tube. The mandrel **1110** spins at a high rotational speed while all other components remain in a non-rotational state. Frictional heating, as well as a high force from the ram results in severe plastic deformation of the feedstock. As the plasticized feedstock is pressed against the back face of the die **1150**, the material grain structure is broken up as a result of shearing forces from the mandrel **1110**. The ram **1120** continues to press against the press disc **1130** and billet **1170** to extrude a resultant seamless tube **1180**, as illustrated in FIG. **11D**.

[0068] The frictionally processed material flows through a mandrel tip **1190** to form an extruded tube with a smooth interior finish and very fine grains, as illustrated in FIG. **11E**. In addition, the mandrel can have textured features **1195**, including but not limited to threads, ridges, studs, and protrusions that assist with breaking up grains and causing the material to flow towards the die opening, as illustrated in FIG. **11F**.

[0069] FIG. **12** illustrates an exemplary active end of a mandrel **1200**. A textured or featured surface **1210** assists with breaking up the large grains in the billet material. Any textured or featured surface that breaks down the grains of the material can be used, including but not limited to a threaded surface, a ridged surface, a studded surface, or other protrusions on an end portion of the mandrel **1200**. The smooth tip **1220** provides a smooth finish on the interior surface of the tubing. The smooth tip also minimizes the amount of excess billet material extruded at end of the resultant tubing. This prevents the excess extruded billet material from forming along the interior walls of the resultant tubing. In addition, the smooth tip **1220** can prevent or reduce a shearing zone on the interior surface near the end of the resultant tubing, caused by the rotating threaded region **1210** of the mandrel **1200**. The mandrel **1200** described herein and illustrated in FIG. **12** produces continuously extruded tubing, such as twenty to fifty foot length tubing with a fine grain structure. The threaded features **1210** of the mandrel **1200** effectively break up the grain structure in the tube wall and reconsolidate the material to produce a refined grain structure. The seamless friction extrusion process continuously pushes the billet out of the die, as illustrated in FIG. **13** to produce a fine grained interior surface **1310** along the entire length of the tubing **1320**.

[0070] In some embodiments as illustrated in FIG. **14**, the rotating mandrel **1400** is designed with a bearing **1410** on the tip, such that the bearing remains non-rotating as the feedstock flows over the bearing. The inside diameter profile of the tubing is last formed by the mandrel tip **1420**.

[0071] There may be instances in which an extrusion force is very large, which will lower or completely prevent the bearing from rotating. This can cause an overly preferential interior finish. In order to account for this or counter this effect, the mandrel **1510** has a textured extension **1520** to allow a cylindrical screw cap **1530** to tighten against the bearing **1540** to keep it in place, as illustrated in FIG. **15**. The bearing **1540** and cylindrical screw cap **1530** are designed with a high strength material to allow piercing of the billet.

[0072] In some embodiments, the mandrel is a two-piece assembly with one piece rotating and the other piece non-rotating, as illustrated in FIGS. **16A-16C**. The two-piece mandrel **1600** works similar to a retractable pin tool. A pin portion **1610** of the mandrel forms the inside diameter of a tube, while a pin tool shoulder portion **1620** of the mandrel stirs the billet **1630**, as illustrated in FIG. **16A**. The mandrel shoulder portion **1620** can be coupled with a gear or pulley to rotate independent of the mandrel pin portion **1610**. The mandrel pin portion **1610** is kept stationary so that it does not rotate with the mandrel shoulder portion **1620**, as illustrated in FIG. **16B**. This allows the extruded material to form over a stationary mandrel to produce a better surface finish. FIG. **16C** illustrates the billet extruding over the mandrel pin portion **1610** to form an extruded tube **1640**.

[0073] An indirect extrusion method can also be used to produce seamless friction extruded tubes with reference to FIGS. **17A-17C**. FIG. **17A** is a cross-sectional view illustrating a container **1710** holding a billet **1720**. A press disc **1730** and a ram **1740** with a mandrel are butted against one end of the billet **1720**, and a die **1750** and hollow punch **1760** are coupled with the billet **1720** at the other end. FIG. **17B** illustrates a mandrel **1770** piercing the billet **1720**. In FIG. **17C**, the hollow punch **1760** presses against the billet **1720** to form a continuous extruded tube **1780**. As illustrated in FIGS. **17A-17C**, the hollow punch **1760** pushes against the die **1750** and billet **1720** while the ram **1740** remains stationary in an indirect extrusion method. In addition, the mandrel **1770** retracts as the container punch presses forward to maintain the positioning near the die **1750** in an indirect extrusion process. As the hollow punch **1760** applies force against the die **1750** and billet **1720**, the tube **1780** is extruded over the mandrel **1770** and out through the hollow punch **1760**.

[0074] In some embodiments of the indirect extrusion method, the die and feedstock billet are heated before the extrusion process begins. In other embodiments, the die and feedstock billet require minimal heating or no heating prior to the extrusion process because frictional heat is generated in the weld chamber. Temperatures of approximately 700-800 degrees F. are needed for aluminum or an aluminum alloy metal to reach a moldable viscosity.

[0075] Both the direct and the indirect seamless extrusion processes can be implemented with the mandrel tool described above to produce seamless friction-extruded tubing. For example, the mandrel illustrated in FIGS. **17B-17C**

can be rotating while the hollow punch presses against the billet, which would break up the large grains normally present in a seamless extruded tube. In addition, the tip of the mandrel can be threaded to further break up the large grains and produce a fine grained interior finish on the tubing.

[0076] In some embodiments, the feedstock material can be a billet containing recycled metal, such as machining chips, powder, or scrap. The feedstock is capped with a solid metal cylinder with a hole through the center, which matches the outer diameter of the mandrel tool. Since the ram action pushes the semi-loose metal chips, scrap, and/or powder through the die mandrel without sufficient heating, the metal washers are set on the top and bottom of the feedstock billet to allow sufficient heating of the feedstock before the plasticized material is allowed to enter the weld chamber. The washer on the top of the billet presses against the ram and prevents metal from extruding past the ram in the opposite direction of the die.

[0077] Another process related to extrusion of tubing is tube drawing. A tube drawing process is usually performed as a secondary operation after a tube has been seamless extruded, porthole die extruded, or electric resistance welded (ERW). The starting work piece can be oversized and drawn down to a smaller diameter and a smaller wall thickness, as illustrated generally in FIG. **18**.

[0078] The tube-drawing process is illustrated in detail in FIGS. **19**A-**19**D. A work piece **1910** is installed against a die **1920** and tool carrier **1930**, as illustrated in FIG. **19**A. A mandrel **1940** is inserted into the back end of the work piece **1910**, as illustrated in FIG. **19**B. The mandrel **1940** is pushed forward until it is located concentrically within the opening of the die **1920**. A gripper **1950** is inserted into the tube from the front end until it is positioned behind the die **1920** and tool carrier **1930**, also illustrated in FIG. **19**B. The gripper **1950** has an expanding mandrel on the end of its rod that will tighten onto the inside of the tube wall, illustrated in FIG. **19**C. The gripper **1950** grips with enough force to pull the tube through the die **1920** and out of the tool carrier **1930**. The gripper **1950** continues to pull the work piece **1910** through the die **1920** and over the mandrel **1940** to reform the tube diameter and wall thickness to its final dimensions, illustrated in FIG. **19**D. All of the components are either stationary or are allowed to move in just one axis, i.e. towards or away from the die **1920**. A tube drawing process can use either a direct process or an indirect process.

[0079] A modification of the above-described drawing process incorporates friction extrusion into the tube work piece during the drawing process to produce a fine grain interior surface of the drawn tubes. FIG. **20**A illustrates an exterior view of the container **2010** with a mandrel **2020** inserted into the left-side view of the work piece **2030** and a gripper **2040** inserted into the right-side of the work piece **2030**. FIG. **20**A illustrates the mandrel **2020** is rotating, while the container **2010** remains stationary.

[0080] FIG. **20**B is an interior view of the mandrel **2020** end section in near vicinity to the gripper **2040** end section within the work piece tubing. The mandrel **2020** end has a tapered cap design, with a threaded configuration adjacent to the tapered cap. As the mandrel **2020** is rotated, the threads break up the large grains of the interior surface of the work piece. As a result, small fine grains are formed on the interior surface of the reworked work piece.

[0081] FIG. **20**C illustrates the gripper **2040** pulling on the work piece **2030**. The mandrel **2020** is lodged between the upper and lower sections of the die **2050**, which forces the work piece **2030** to be thinned at the exit point of the tool carrier. As a result, the tube is extended in length and the tube thickness is reduced. In an example, a ten-foot length original work piece can be used to form a thirty-foot length finished tube. The tapered cap of the mandrel tool produces a smooth interior finish.

[0082] In other embodiments, a textured mandrel **2110** is rotated while pulled from one end of a tube work piece located inside of a stationary container **2120** completely out through the opposite end of the tube work piece, as illustrated in FIG. **21**A. The mandrel **2110** is rotated while it is pulled through the tube work piece. FIG. **21**B illustrates a textured region **2115** of the mandrel **2110**, which breaks up large grains of the original tube work piece as it is pulled from one end of the work piece to the other end. Fine grains result on the interior surface of the drawn tubing. The mandrel **2110** has a smaller textured portion on one end that is used to rotate the mandrel **2110** and pull the mandrel **2110** through the tube work piece. The non-textured portion of the mandrel **2110** will be the same or almost the same dimension as the inside diameter of the tube. The textured portion of the mandrel **2110** has features, such as threads, ridges, studs, or protrusions that are slightly larger in diameter than the non-textured portion, such that the threads, ridges, studs, or protrusions engage and stir the tube wall without penetrating through the tube wall into the container, as illustrated in FIG. **21**C.

[0083] The container can be split into two halves and bolted or clamped together, such that the resultant drawn friction-extruded tube can be easily removed. In addition, the smaller diameter sections of the mandrel shaft can be supported with bearings and/or linear bearings that stabilize the mandrel along the length that extends beyond the container. The bearings help control run-out of the mandrel at significant distances away from the rotary motion source, such as a motor or spindle.

[0084] FIG. **22** illustrates an alternative embodiment in which the container **2210** rotates, while the mandrel **2220** remains non-rotational. The container can have integral features, such as pulley drives that allow a belt drive to rotate the container. The drive mechanism includes, but is not limited to a geared motor or a hydraulic motor. Since the tube needs to rotate with the container, the tube ends are expanded into each end of the container using a mechanical or hydraulic expander tool. Alternatively, the tube work piece can be held in place by a gripper mechanism on each end of the tube, or the tube work piece can be gripped or secured in such a way that the container is no longer required. The tube can be easily removed from the container after it has been expanded and friction-drawn within the container, since the two halves are bolted together.

[0085] For a substantially long mandrel tool, the shaft can have a hex feature or other torque-driving feature that allows the use of shaft guides along the tube length to assist with transmitting torque, which is applied to the mandrel tool from the spinning container and the tube. The shaft guides can be fixed to a grounded structure and have a matched hex or other torque-driving feature that allows the shaft to move in only one linear direction.

[0086] The end of the mandrel tool has a textured end and a smooth end cap, as previously described. Therefore, the textured surface of the mandrel tool breaks up the large grains on the interior surface of the original tube work piece. The textured surface of the mandrel includes, but is not limited to features, such as a threaded surface or a surface containing ridges, studs, or other protrusions. The interior of the resultant drawn tube has small grains and a smooth surface.

[0087] Conventionally-drawn tubing has nominal grain sizes similar to rolled plates and frequently has very large grains on the interior surface. As a result, the tubing has a low resistance to corrosive environments, especially on a large grain surface. The tubing also has low mechanical properties, pertaining to bendability, fatigue, and fracture toughness.

[0088] By implementing friction extruding and stir welding processes described herein, the inside surface of the tube is treated to produce a fine grain microstructure, which has significant corrosion advantages over conventionally-drawn tubing. It has a high resistance to corrosive environments on the ends and the interior surface. Mechanical properties, such as bendability, fatigue resistance, and fracture toughness are increased when embodiments described herein are practiced.

[0089] Feedstock material includes, but is not limited to aluminum and aluminum alloys, titanium and titanium alloys, steels and steel alloys including stainless steels, copper and copper alloys, and super alloys containing nickel, molybdenum, chromium, and cobalt. Some embodiments include heating the dies and feedstock billet before the extrusion process begins. However, other embodiments require minimal or no heating prior to the extrusion process because adequate frictional heat is generated within the weld chamber. Still other embodiments include using a billet of recycled metal scrap, machining chips, or powder.

[0090] One embodiment includes using titanium feedstock chips or powder to form tubing according to embodiments previously described herein. Conventional titanium processing and stainless steel processing are quite costly. However, titanium and stainless steels formed from a billet of scrap metal or powder metal according to the porthole die friction-extruded tube and the seamless friction-extruded tube methods described herein can provide a much more economical mode of tube manufacturing for titanium and stainless steel tubing.

[0091] Some embodiments include incorporating metal matrix composite particles, such as aluminum oxides, silicon carbides, and boron carbides, as well as carbon nano-particles into a composite billet in conjunction with embodiments described herein for porthole die friction-extruded tubes, seamless friction-extruded tubes, and drawn friction-extruded tubes. The carbon nano-particles can be mixed with a metal feedstock, such as aluminum to form a matrix nanocomposite billet. The friction-extrusion mandrels and processes described herein provide smaller finer grains on the interior surface of the tubing. The nano-particles improve the mechanical and metallurgical properties of the tubing for a higher strength-to-weight ratio and high temperature resistance to allow for higher operating temperatures. As a result, the carbon nano-particle matrix friction-extrusion tubing can be extended to conditions comparable to titanium tubing, but at a cost of that for aluminum tubing. In addition, friction extruding enables mass production of the nanocomposite tubing.

[0092] Embodiments described herein provide corrosion-resistant tubing that can be used in a saltwater environment, such as in OTEC heat exchangers. Another embodiment includes a thermal desalination system and method in which seawater is flash evaporated off the exterior of the heat exchanger tubes. Fresh water is condensed on the inside of the tubes.

[0093] Embodiments described herein for porthole die friction-stir extruded tubes, seamless friction-stir extruded tubes, and friction-stir drawn tubes provide advantages of a very fine grain size on the interior surfaces of the tubes, high resistance to corrosive environments, both on the surface and the interior of the tubes, and high mechanical properties such as bending, fatigue, and fracture toughness. These advantages are realized by a friction-stir mandrel tool, which includes a textured end portion that is integral with a body portion. The textured end portion is configured to friction-stir process a starting material forced across the textured end portion and through a die in a plasticized state to form a pipe. The textured end portion includes, but is not limited to features, such as threads, ridges, studs, or protrusions. The starting material can include a metal, such as aluminum or an aluminum alloy.

[0094] The friction-stir mandrel tool can be configured to rotate while the starting material remains rotationally stationary. Likewise, the mandrel tool can be configured to remain rotationally stationary while the starting material rotates. The mandrel tool can also have a smooth cap formed over an end of the textured end portion, wherein the smooth cap is configured to provide a final smooth interior surface on the formed pipe. A diameter of the textured end portion is slightly larger than an inside diameter of the formed pipe, and smaller than an outside diameter of the formed pipe. In some embodiments, the mandrel tool is integral with the die. In other embodiments, the mandrel tool is configured to pierce through the starting material. In a tube-drawn process, the mandrel tool is configured to be drawn into the die in conjunction with drawing the starting material over the mandrel tool.

[0095] FIG. **23** is a flowchart showing an exemplary porthole die friction-stir extrusion method **2300**. A feedstock billet is loaded into a container in step S**2310**. One end of the feedstock billet is abutted with a ram, and another end of the feedstock billet is abutted against a die mandrel in step S**2320**. The feedstock billet and the container are rotated against a die cap while pressure is applied by the ram in step S**2330**. Plasticized feedstock is extruded through passages of the die mandrel in step S**2340**. Grains of the plasticized feedstock are broken up by a textured mandrel tip of the die mandrel. A hollow tube is formed from the extruded plasticized feedstock in step S**2350**. In some embodiments, the die mandrel rotates while the feedstock billet and the container rotate. In other embodiments, an interior surface of the extruded hollow tube is smoothed by a mandrel bearing attached to an end of the textured mandrel tip. In still other embodiments, the plasticized feedstock is extruded through a hollow punch aperture integrally formed with the die mandrel. The plasticized feedstock can be extruded through a rotating hollow punch aperture.

[0096] FIG. **24** is a flowchart showing an exemplary seamless tube friction-stir extrusion method **2400**. A feedstock billet is loaded into a container in step S**2410**. One end of the feedstock billet is abutted with a ram and a concentrically-located mandrel. Another end of the feedstock billet is abutted against a die in step S**2420**. The feedstock billet is pierced with the concentrically-located mandrel up to the die in step S**2430**. Pressure is applied to the feedstock billet by the ram in step **2440**. Plasticized feedstock is extruded through the die and over a textured portion of the concentrically-located mandrel in step S**2450**. Grains of the plasticized feedstock are broken up by the textured portion of the concentrically-located mandrel. A seamless tube is formed from the extruded plasticized feedstock in step S2460. In some embodiments, the concentrically-located mandrel is rotated during the extruding. In other embodiments, a recrystallized microstructure is formed in an interior wall of the seamless tube.

[0097] FIG. **25** is a flowchart showing an exemplary tube friction-stir drawing method **2500**. A first end of a tube work piece is loaded into a die tool and tool carrier of a container in step S**2510**. A mandrel tool is inserted at a second end of the tube work piece in step S**2520**. The first end of the tube work piece is engaged in step S**2530**. A textured portion of the mandrel tool is drawn inside the die tool while the tube work piece is continuously drawn over the textured portion in step S**2550**. Grains of the drawn tube work piece are broken up by the textured portion of the mandrel tool. A drawn tube of smaller diameter and thinner wall thickness is formed in step S**2560**. In some embodiments, the mandrel tool is rotated during the drawing. In other embodiments, the container and the tube work piece are rotated during the drawing.

[0098] FIG. **26** is a flowchart showing an exemplary pipe forming method **2600**. A starting material is forced across a textured end of a mandrel and through a die in a plasticized state in step S**2610**. The textured end of the mandrel breaks up existing grains of the starting material. The pipe is formed from material forced through the die in step S**2620**. The formed pipe has smaller resultant grains on an interior surface than the existing grains of the starting material. The textured end includes, but is not limited to features, such as threads, ridges, studs, or protrusions.

[0099] In addition to a saltwater environment, embodiments described herein can be implemented in several other corrosion-inducing environments, including but not limited to aircraft hydraulic tubing, liquid natural gas cryogenic heat exchangers, and heat exchangers used in an acidic environment. The pharmaceutical and food processing industries require a high degree of cleanliness. Some instances of pharmaceutical and food processing use marine-grade aluminum, such as 50/52 or 58, titanium, or a high nickel-content stainless steel because of the extremely corrosive environment. Embodiments described herein provide an efficient and economical alternative for these environments.

[0100] While the invention has been described in conjunction with the specific exemplary embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, exemplary embodiments as set forth herein are intended to be illustrative, not limiting. There are changes that can be made without departing from the spirit and scope of the invention.

1. A friction-stir mandrel, comprising:

a textured end portion integral with a body portion, the textured end portion configured to friction-stir process a starting material forced across the textured end portion and through a die in a plasticized state to form a pipe.

2. The friction-stir mandrel of claim **1**, wherein the friction-stir mandrel is configured to rotate while the starting material remains rotationally stationary.

3. The friction-stir mandrel of claim **1**, wherein the friction-stir mandrel is configured to remain rotationally stationary while the starting material rotates.

4. The friction-stir mandrel of claim **1**, further comprising a smooth cap formed over an end of the textured end portion, the smooth cap configured to provide a final smooth interior surface on the formed pipe.

5. The friction-stir mandrel of claim **1**, wherein a diameter of the textured end portion is slightly larger than an inside diameter of the formed pipe and smaller than an outside diameter of the formed pipe.

6. The friction-stir mandrel of claim **1**, wherein the friction-stir mandrel is integral with the die.

7. The friction-stir mandrel of claim **1**, wherein the friction-stir mandrel is configured to pierce through the starting material.

8. The friction-stir mandrel of claim **1**, wherein the friction-stir mandrel is configured to be drawn into the die in conjunction with drawing the starting material over the friction-stir mandrel by a tube gripper.

9. The friction-stir mandrel of claim **1**, wherein the starting material comprises a metal.

10. The friction-stir mandrel of claim **9**, wherein the metal comprises aluminum or an aluminum alloy.

11. The friction-stir mandrel of claim **1**, wherein the textured end portion comprises one of threads, ridges, studs, or protrusions.

12. A method of forming a pipe, comprising:

forcing a starting material across a textured end of a mandrel and through a die in a plasticized state, so that the textured end of the mandrel breaks up existing grains of the starting material; and

forming the pipe from material forced through the die, wherein the formed pipe has fine equiaxed resultant grains in multiple orientations on an interior surface of the formed pipe than the existing grains of the starting material.

13. The method of claim **12**, further comprising:

rotating the mandrel while the starting material remains rotationally stationary.

14. The method of claim **12**, further comprising:

rotating the starting material while the mandrel remains rotationally stationary.

15. The method of claim **12**, further comprising:

forming a smooth interior surface on the formed pipe via a smooth cap formed over an end of the textured end.

16. The method of claim **12**, wherein the starting material comprises a metal.

17. The method of claim **16**, wherein the metal comprises aluminum or an aluminum alloy.

18. The method of claim **12**, wherein the textured end comprises one of threads, ridges, studs, or protrusions.

19. The method of claim **12**, wherein the pipe comprises a seamless tube pipe.

20. A porthole die friction-stir extrusion method, comprising:

loading a feedstock billet into a container;

abutting one end of the feedstock billet with a ram and abutting another end of the feedstock billet against a die mandrel;

rotating the feedstock billet and the container against a die cap while pressure is applied by the ram;

extruding plasticized feedstock through passages of the die mandrel, wherein grains of the plasticized feedstock are broken up by a textured mandrel tip of the die mandrel; and

forming a hollow tube from the extruded plasticized feedstock.

21. The porthole die friction-stir extrusion method of claim **20**, further comprising:

rotating the die mandrel while rotating the feedstock billet and the container.

22. The porthole die friction-stir extrusion method of claim **20**, further comprising:

smoothing an interior surface of the extruded hollow tube via a mandrel bearing attached to an end of the textured mandrel tip.

23. The porthole die friction-stir extrusion method of claim **20**, further comprising:

extruding the plasticized feedstock through a hollow punch aperture integrally formed with the die mandrel.

24. The porthole die friction-stir extrusion method of claim **20**, further comprising:

extruding the plasticized feedstock through a rotating hollow punch aperture.

25. The porthole die friction-stir extrusion method of claim **20**, wherein the textured mandrel tip comprises one of threads, ridges, studs, or protrusions.

26. A seamless tube friction-stir extrusion method, comprising:

loading a feedstock billet into a container;

abutting one end of the feedstock billet with a ram and a concentrically-located mandrel, and abutting another end of the feedstock billet against a die;

piercing through the feedstock billet with the concentrically-located mandrel up to the die;

applying pressure to the feedstock billet by the ram;

extruding plasticized feedstock through the die and over a textured portion of the concentrically-located mandrel, wherein grains of the plasticized feedstock are broken up by the textured portion of the concentrically-located mandrel; and

forming a seamless tube from the extruded plasticized feedstock.

27. The seamless tube friction-stir extrusion method of claim **26**, further comprising:

rotating the concentrically-located mandrel during the extruding.

28. The seamless tube friction-stir extrusion method of claim **26**, further comprising:

forming a recrystallized microstructure in an interior wall of the seamless tube.

29. The seamless tube friction-stir extrusion method of claim **26**, wherein the textured portion comprises one of threads, ridges, studs, or protrusions.

30. A tube friction-stir drawing method, comprising:

loading a first end of a tube work piece into a die tool and tool carrier of a container;

inserting a mandrel tool at a second end of the tube work piece;

engaging the first end of the tube work piece;

drawing a textured portion of the mandrel tool inside the die tool while continuously drawing the tube work piece over the textured portion, wherein grains of the drawn tube work piece are broken up by the textured portion of the mandrel tool; and

forming a drawn tube of smaller diameter and thinner wall thickness.

31. The tube friction-stir drawing method of claim **30**, further comprising:

rotating the mandrel tool during the drawing.

32. The tube friction-stir drawing method of claim **30**, further comprising:

rotating the container and the tube work piece during the drawing.

33. The tube friction-stir drawing method of claim **30**, wherein the textured portion comprises one of threads, ridges, studs, or protrusions.

34. The tube friction-stir drawing method of claim **30**, wherein the engaging the first end of the tube work piece includes using a gripper at the first end.

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