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(54) VARIABLE THICKNESS EXTRUSION FOR VARIABLE EXTRUDATE PRODUCT PROPERTIES

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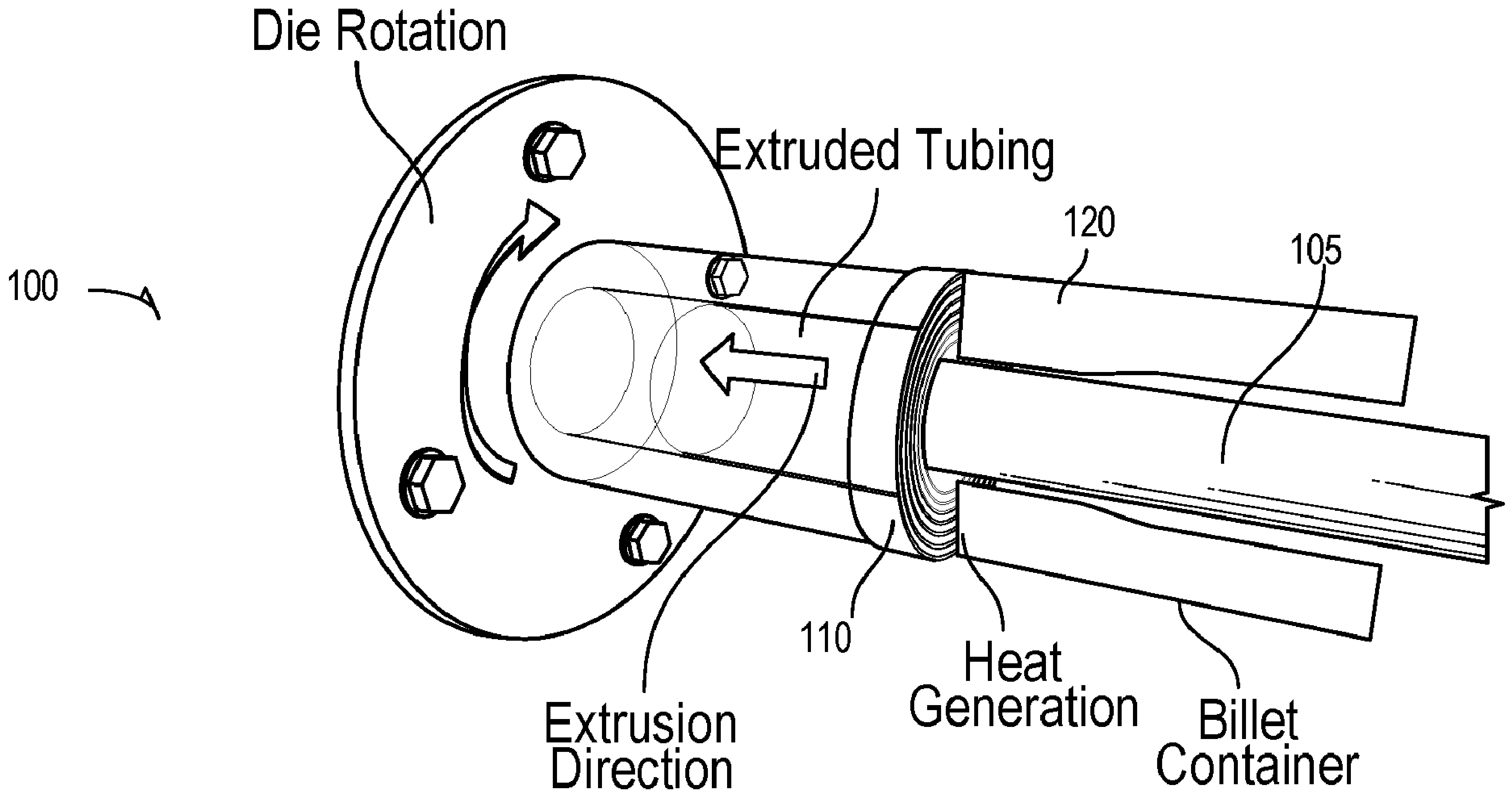
(57) ABSTRACT

A method for solid phase processing (SPP) of a feedstock is provided. The method can include providing relative rotation and translation between an extrusion die and a feedstock, where the die has an extrusion aperture through which a tapered mandrel extends. A first and second extrudate portions can each be generated via the aperture. An axial position of the tapered mandrel can be adjusted relative to the die face during the rotation and translation such that a second extrudate portion is generated having a different inner dimension compared to the first portion, thereby varying a wall thickness between portions.



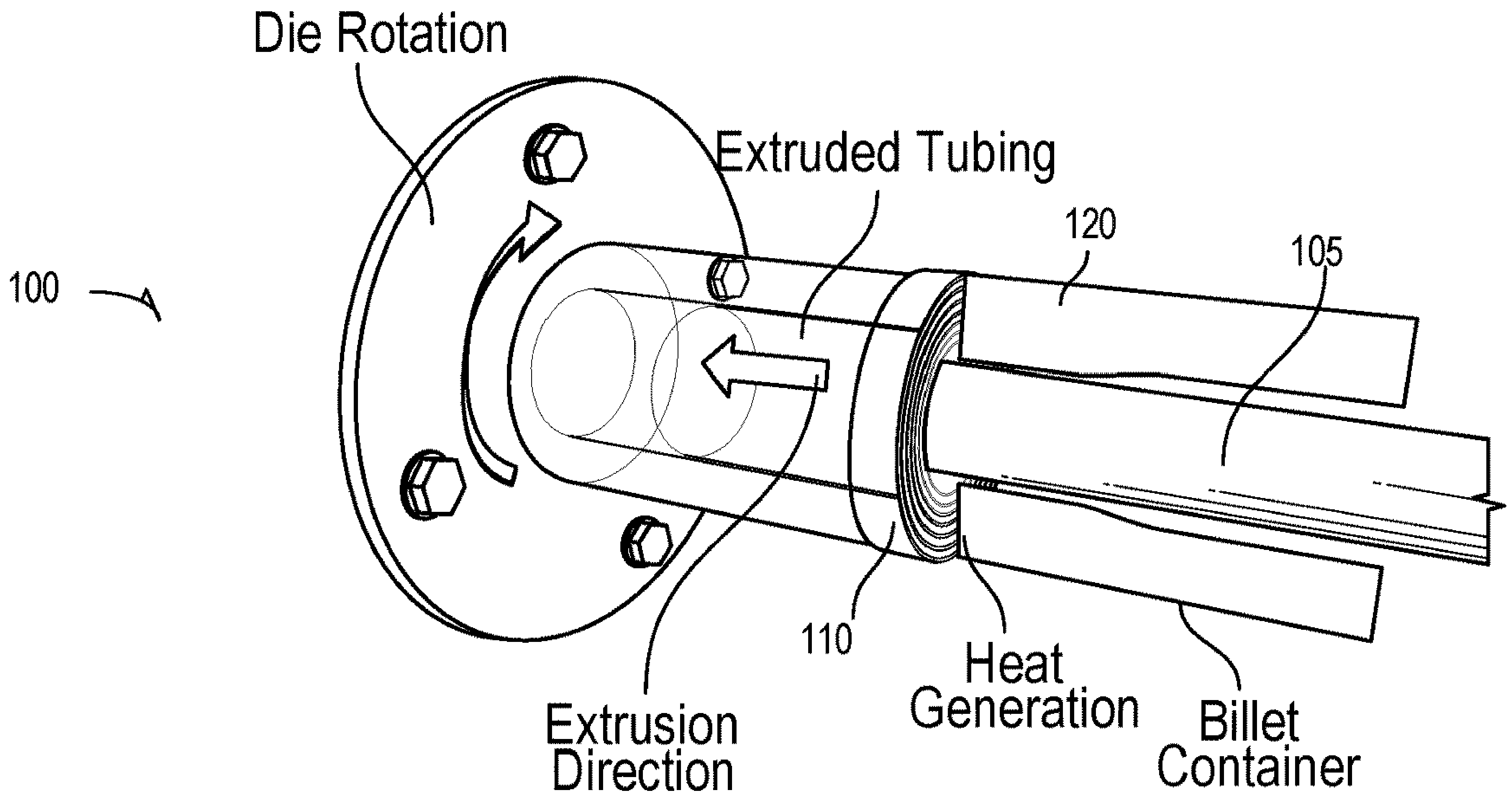

100
Die Rotation
Extruded Tubing
120
105
110
Heat Generation
Billet Container
Extrusion Direction

FIG. 1A

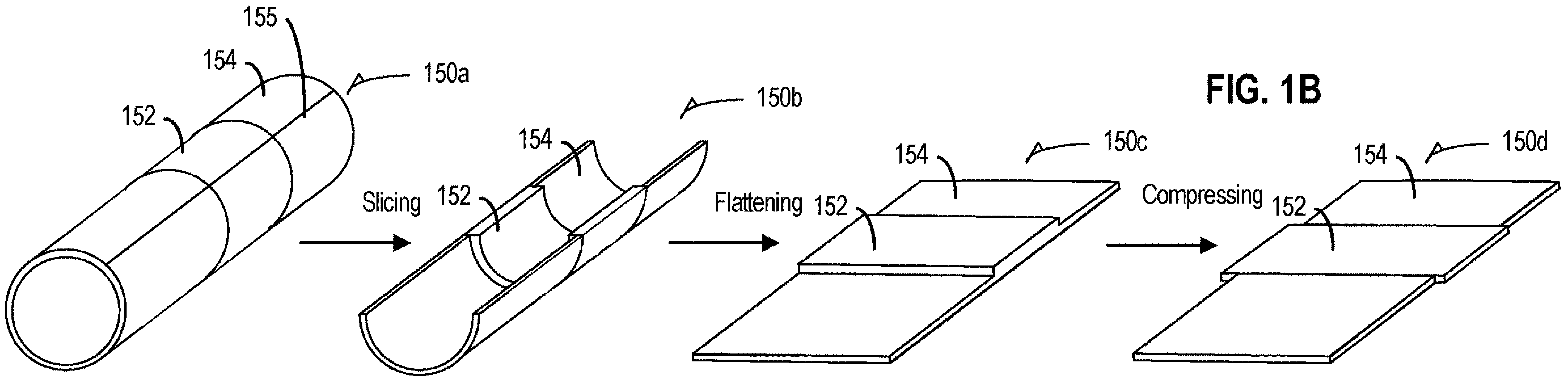

155
154
152
150a
Slicing
154
152
150b
Flattening
152
154
150c
Compressing
152
154
150d

FIG. 1B

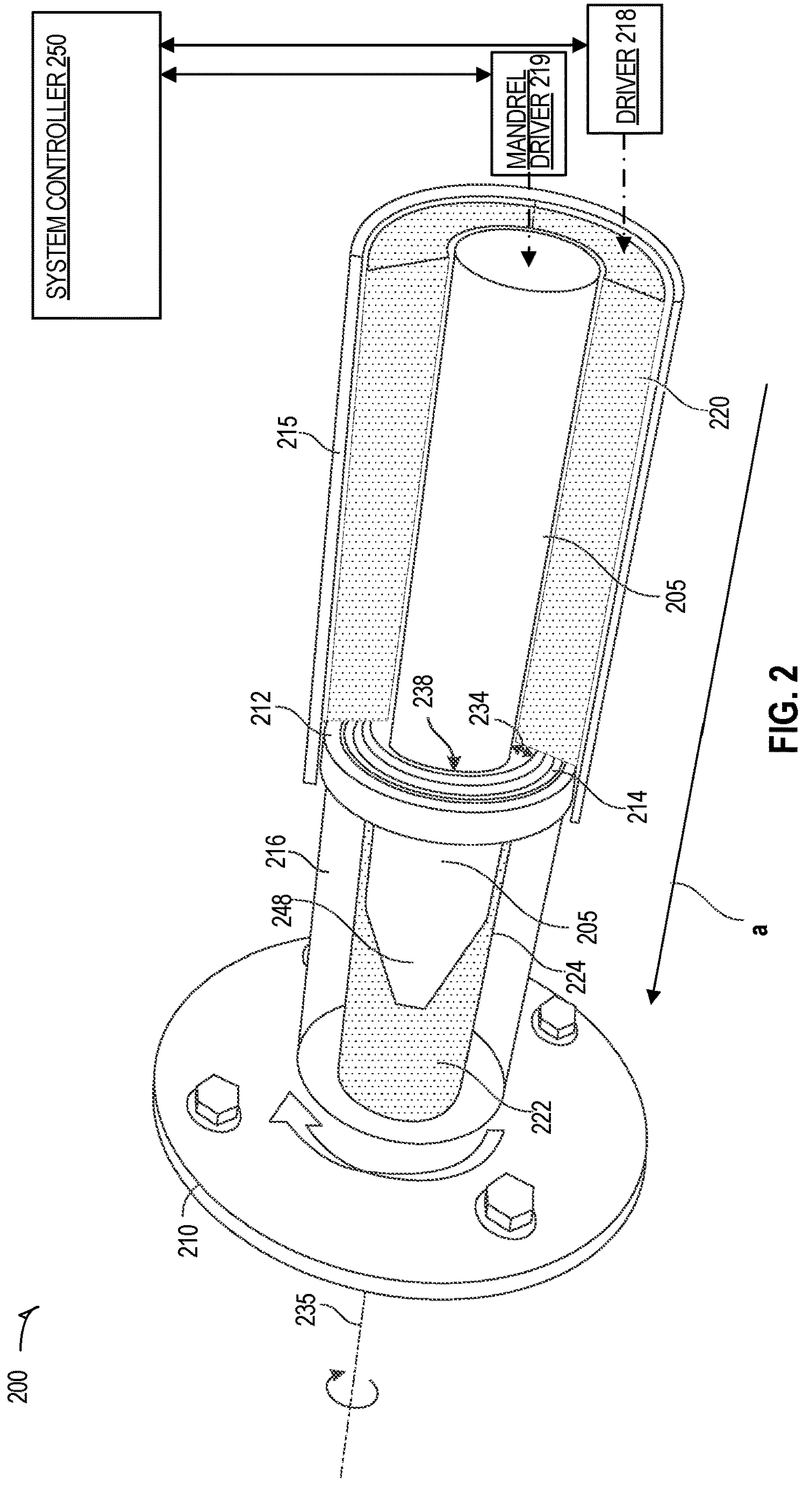

SYSTEM CONTROLLER 250
MANDREL DRIVER 219
DRIVER 218
215
220
205
238
234
212
214
216
248
205
224
222
210
235
200
a

FIG. 2

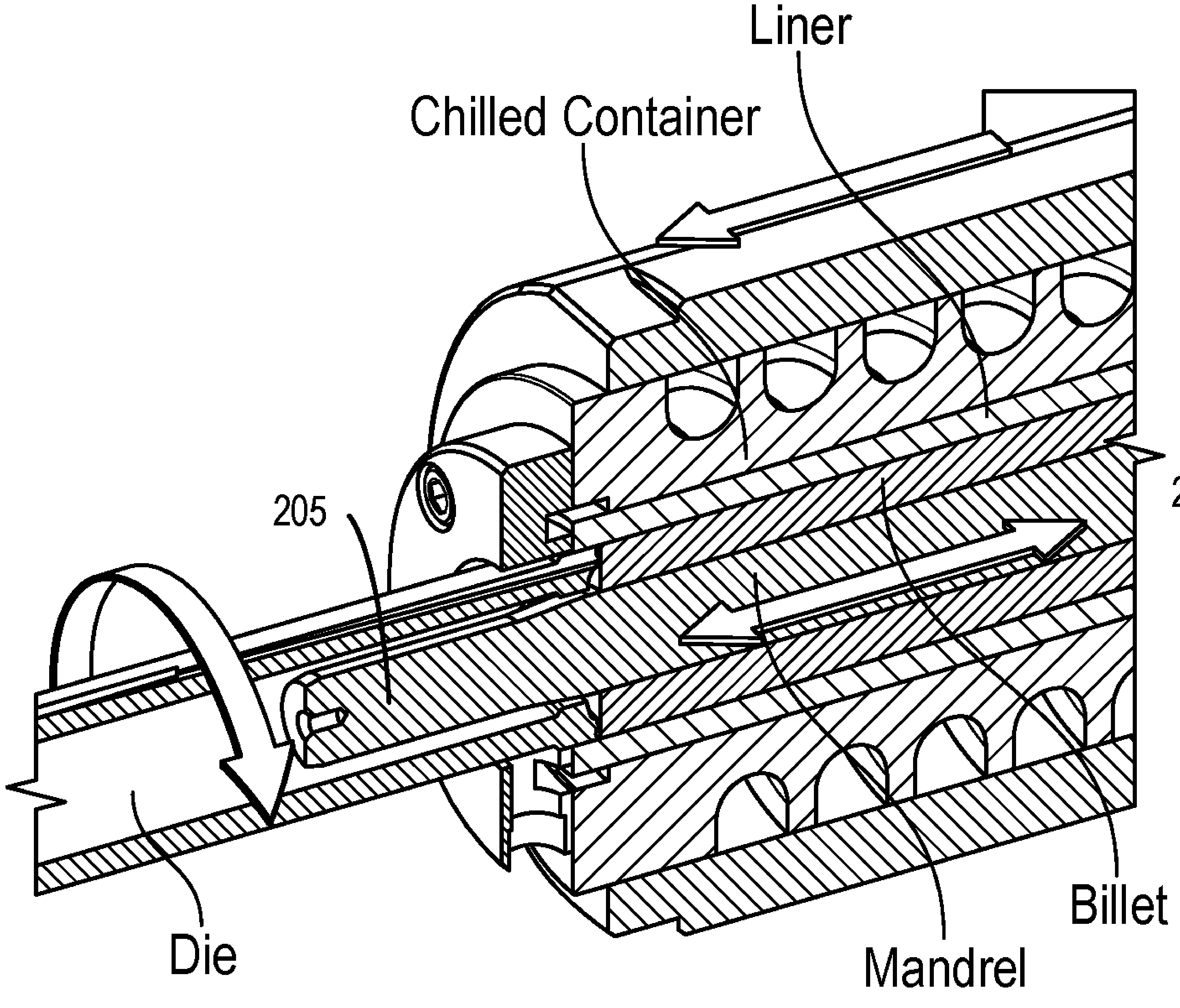


FIG. 3A

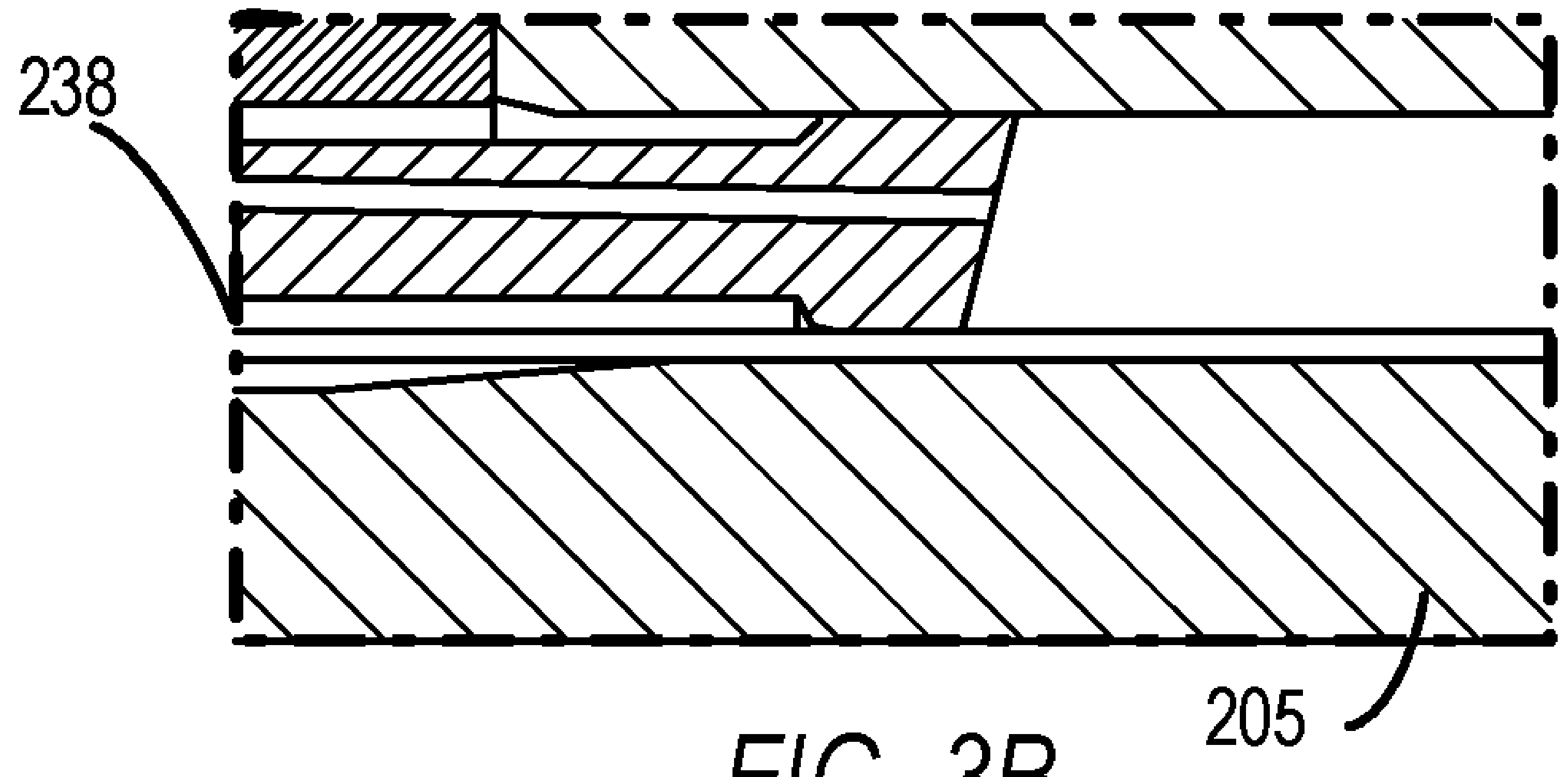


FIG. 3B

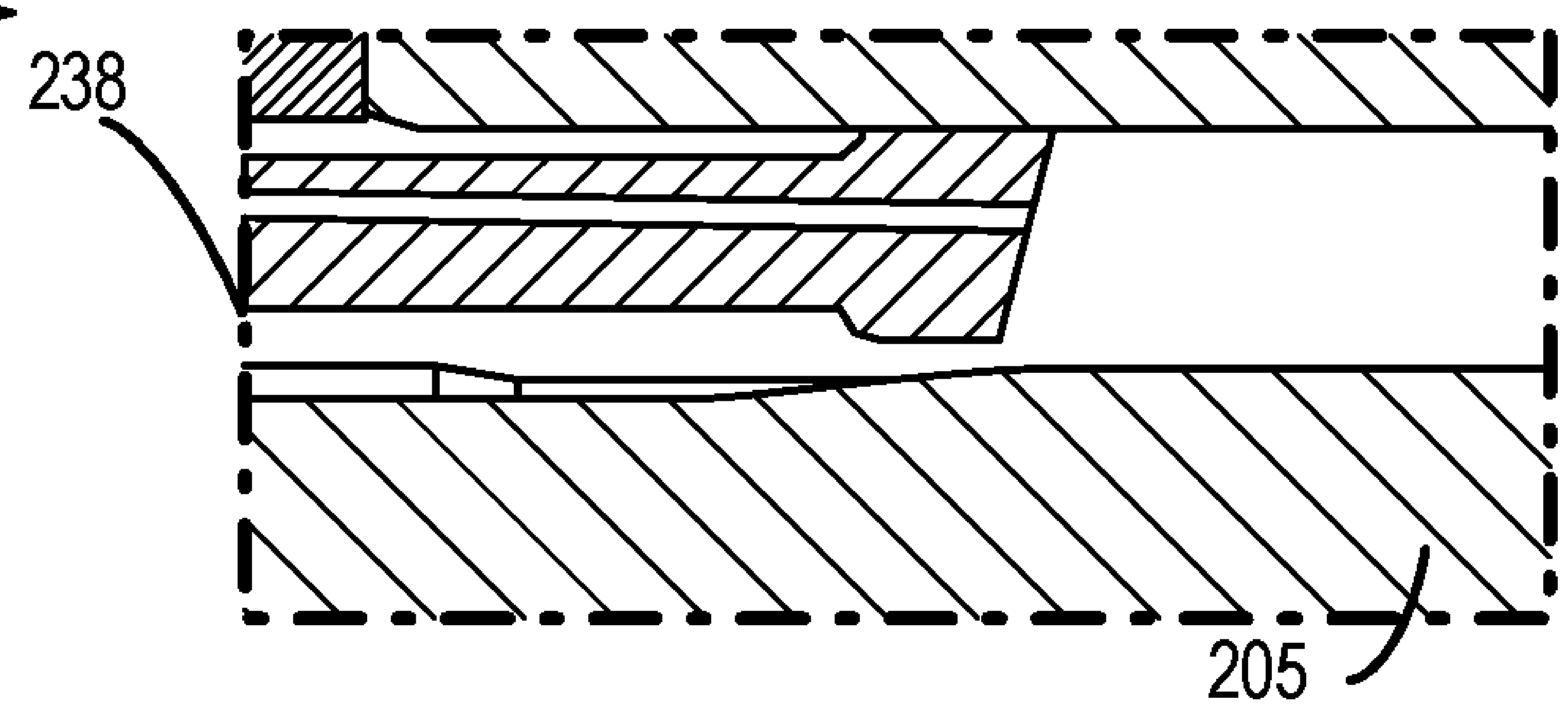


FIG. 3C

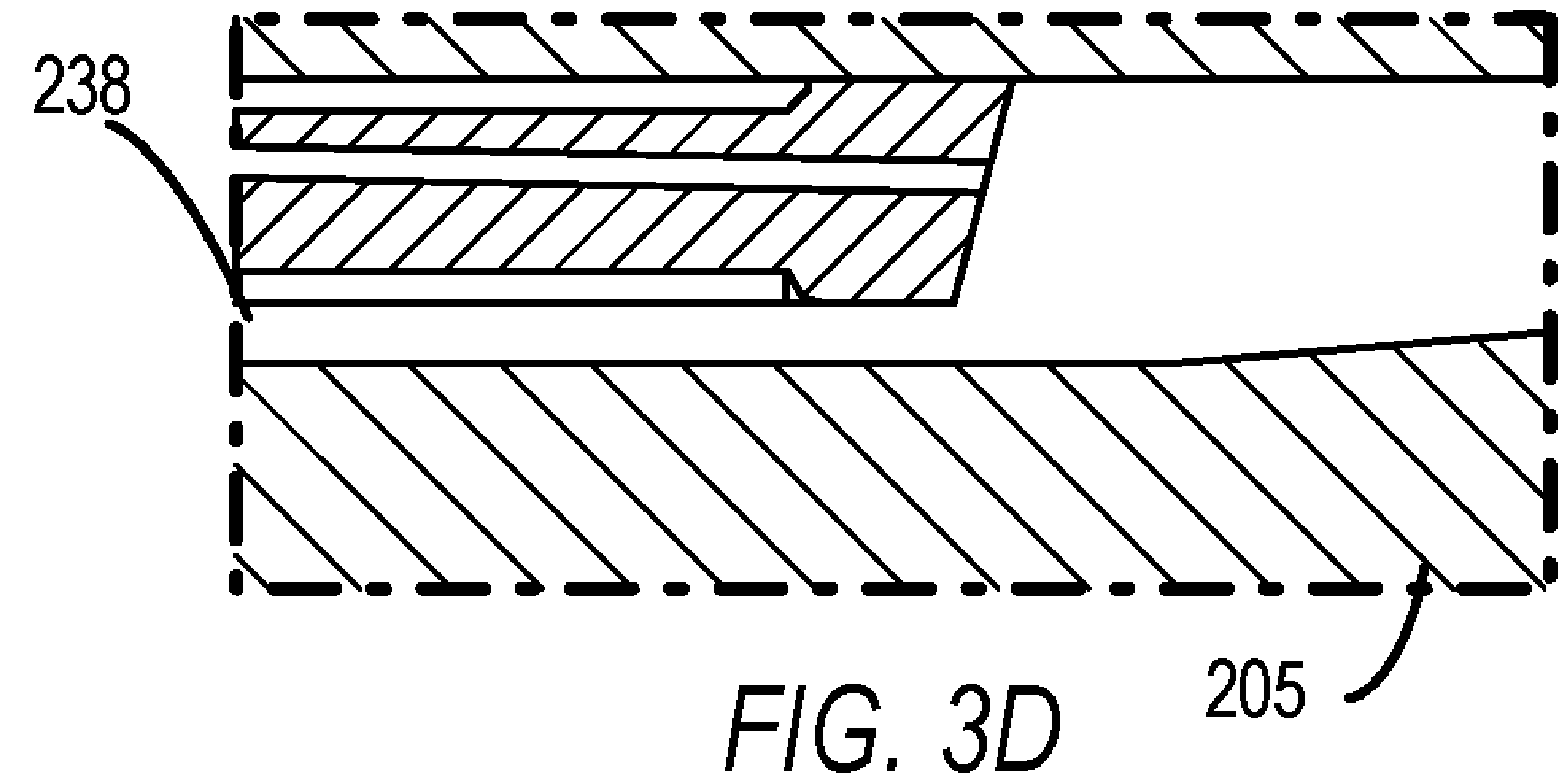


FIG. 3D

FIG. 4A

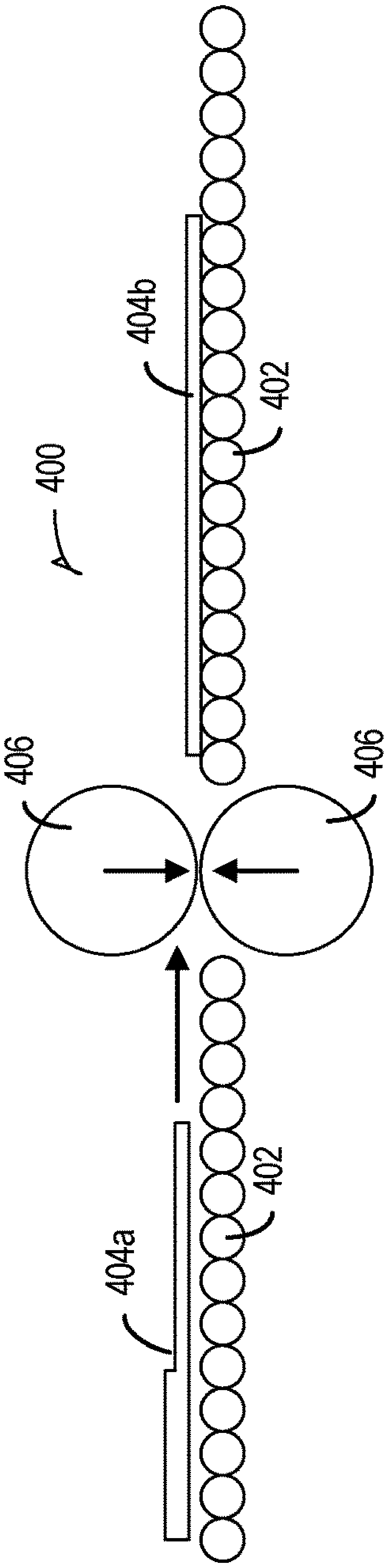
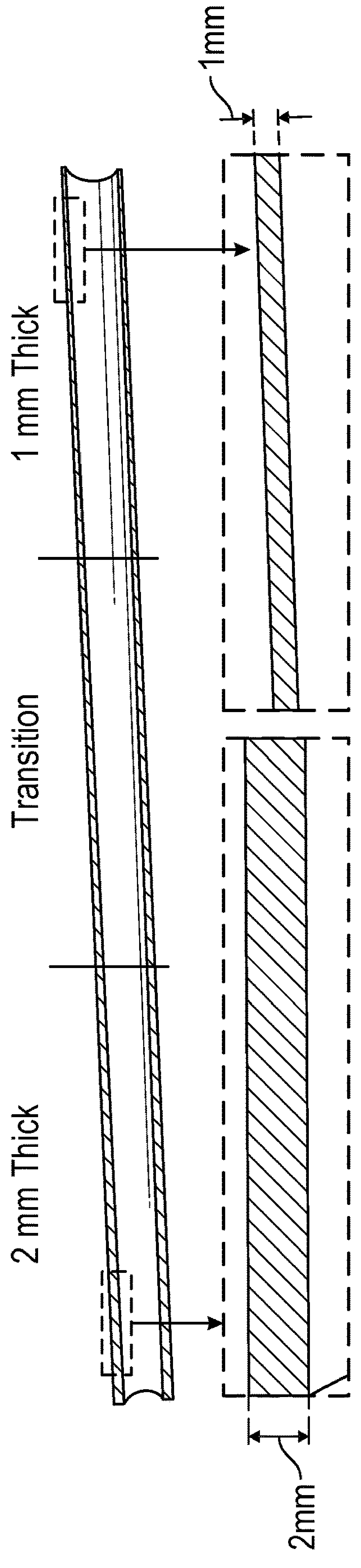

400
404a
404b
402
402
406
406

FIG. 4B


1 mm Thick
Transition
2 mm Thick
1mm
2mm

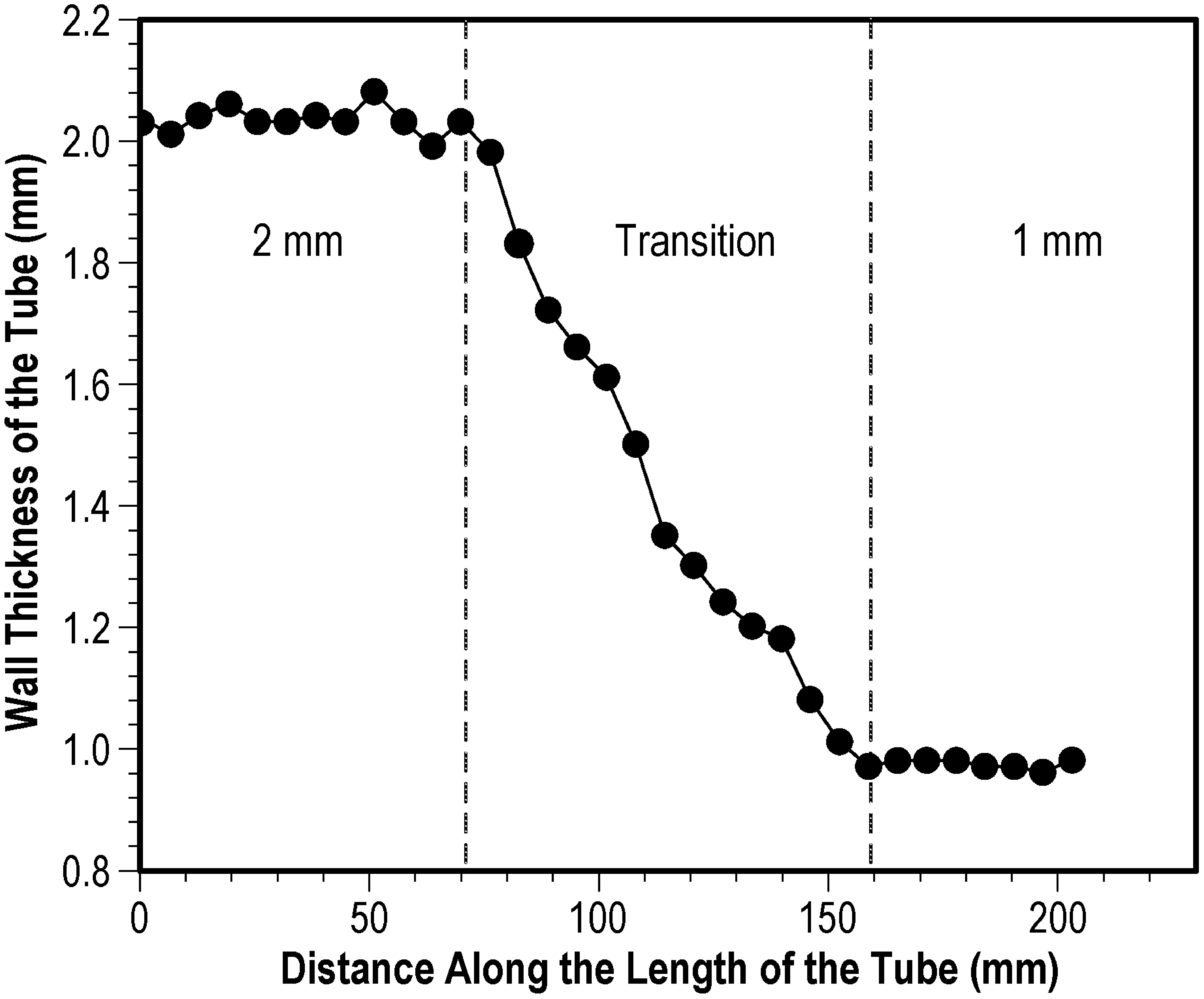

2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Wall Thickness of the Tube (mm)
2 mm
Transition
1 mm
0
50
100
150
200
Distance Along the Length of the Tube (mm)

FIG. 4C

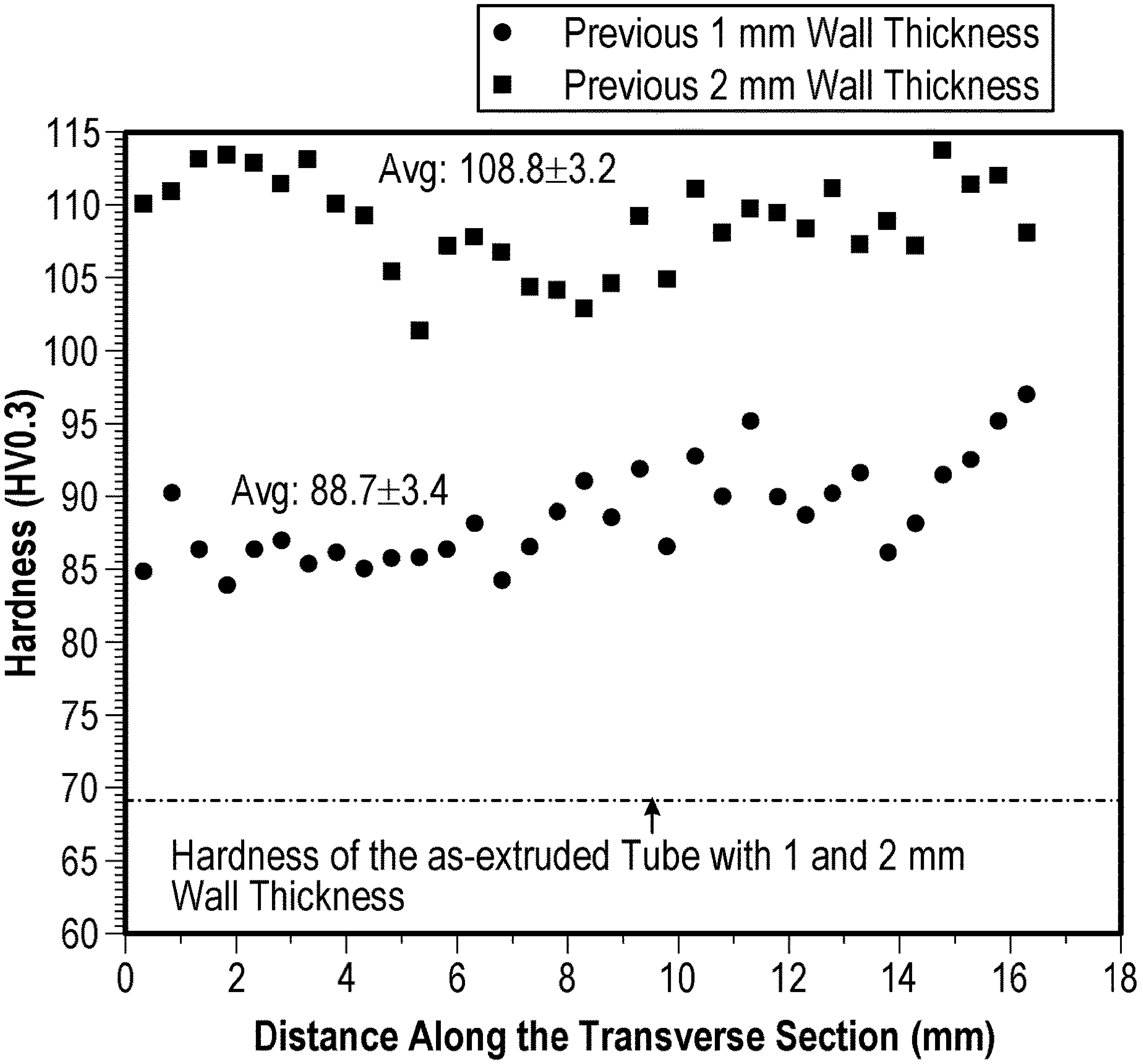

● Previous 1 mm Wall Thickness
■ Previous 2 mm Wall Thickness
Avg: 108.8±3.2
Avg: 88.7±3.4
Hardness of the as-extruded Tube with 1 and 2 mm Wall Thickness
Hardness (HV0.3)
115
110
105
100
95
90
85
80
75
70
65
60
0
2
4
6
8
10
12
14
16
18
Distance Along the Transverse Section (mm)

FIG. 5A

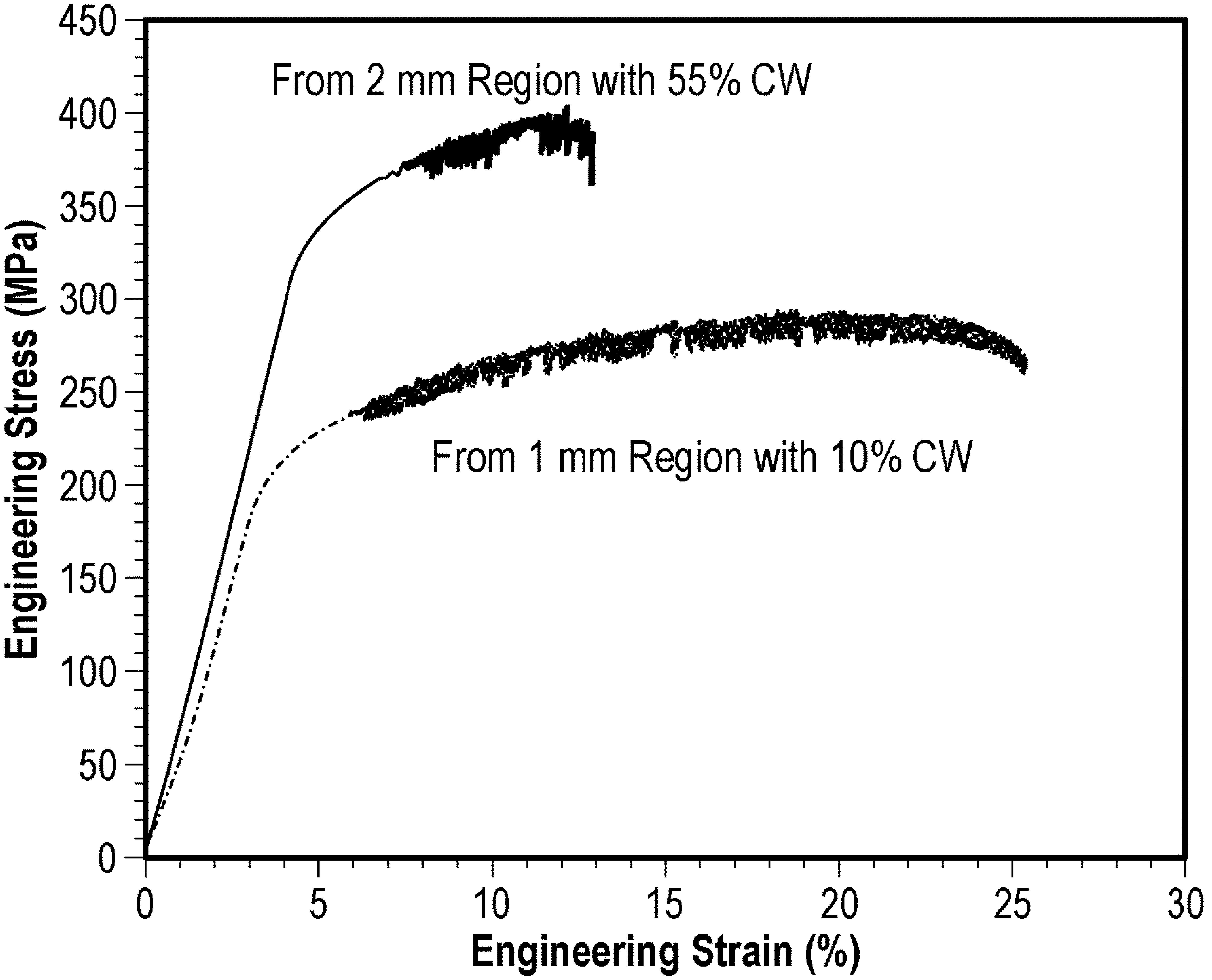

From 2 mm Region with 55% CW
From 1 mm Region with 10% CW
Engineering Stress (MPa)
Engineering Strain (%)
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25
30

FIG. 5B

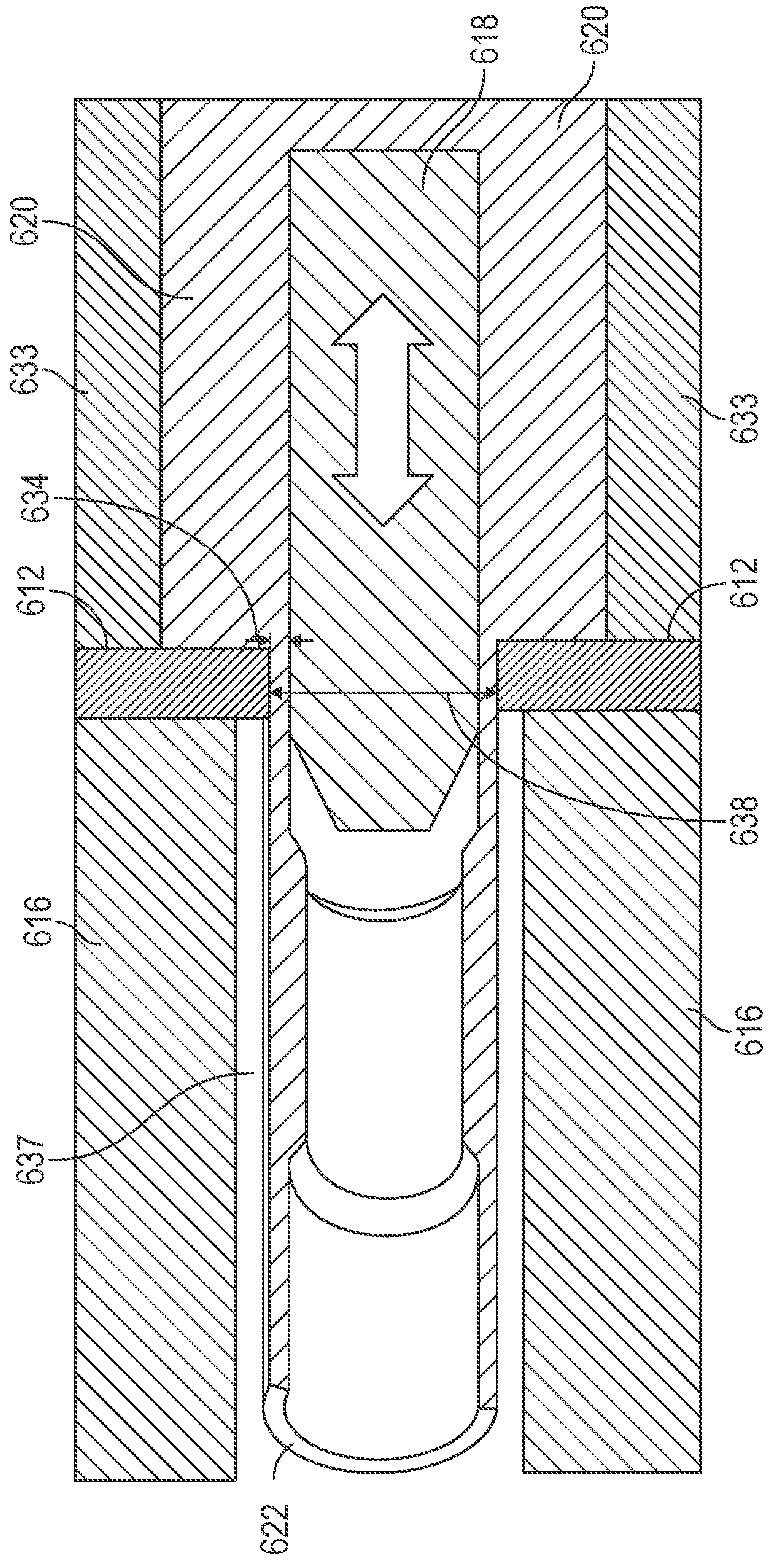


FIG. 6

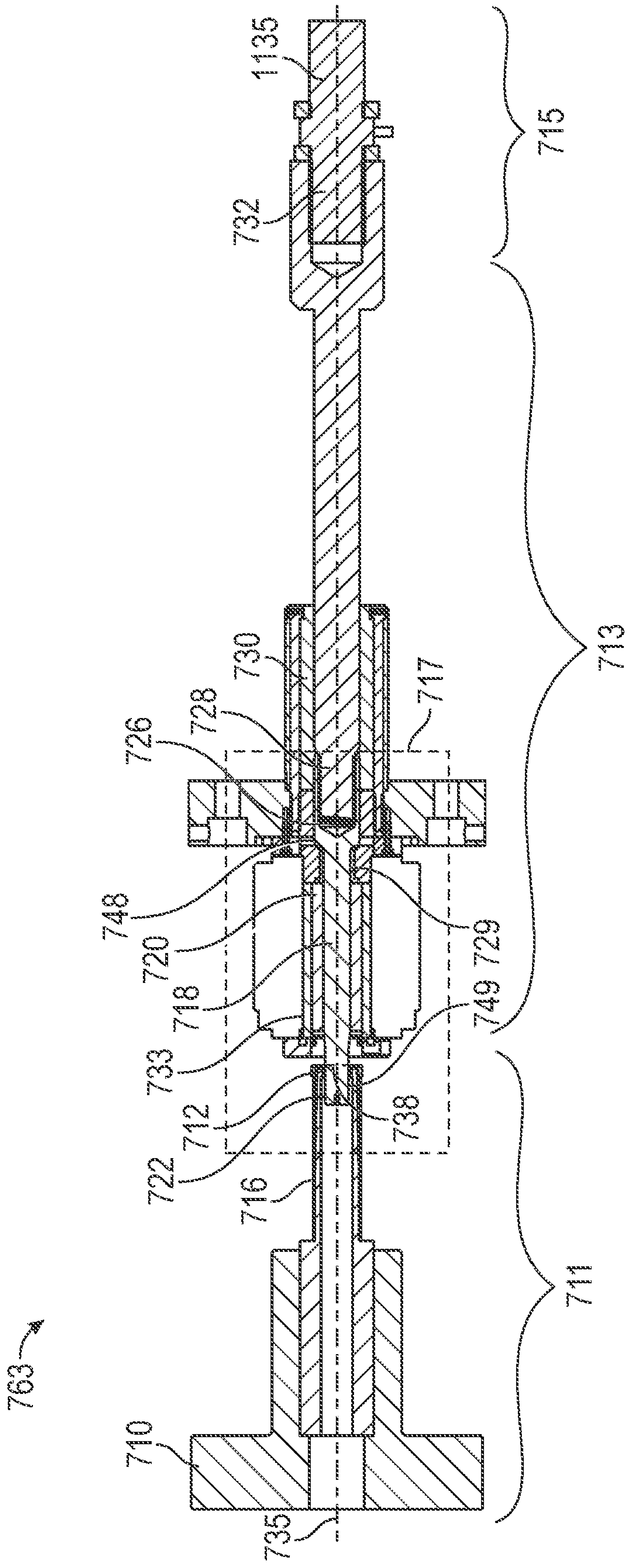

1135
715
732
713
730
717
728
726
748
720
729
718
749
733
712
738
722
716
711
763
710
735

FIG. 7

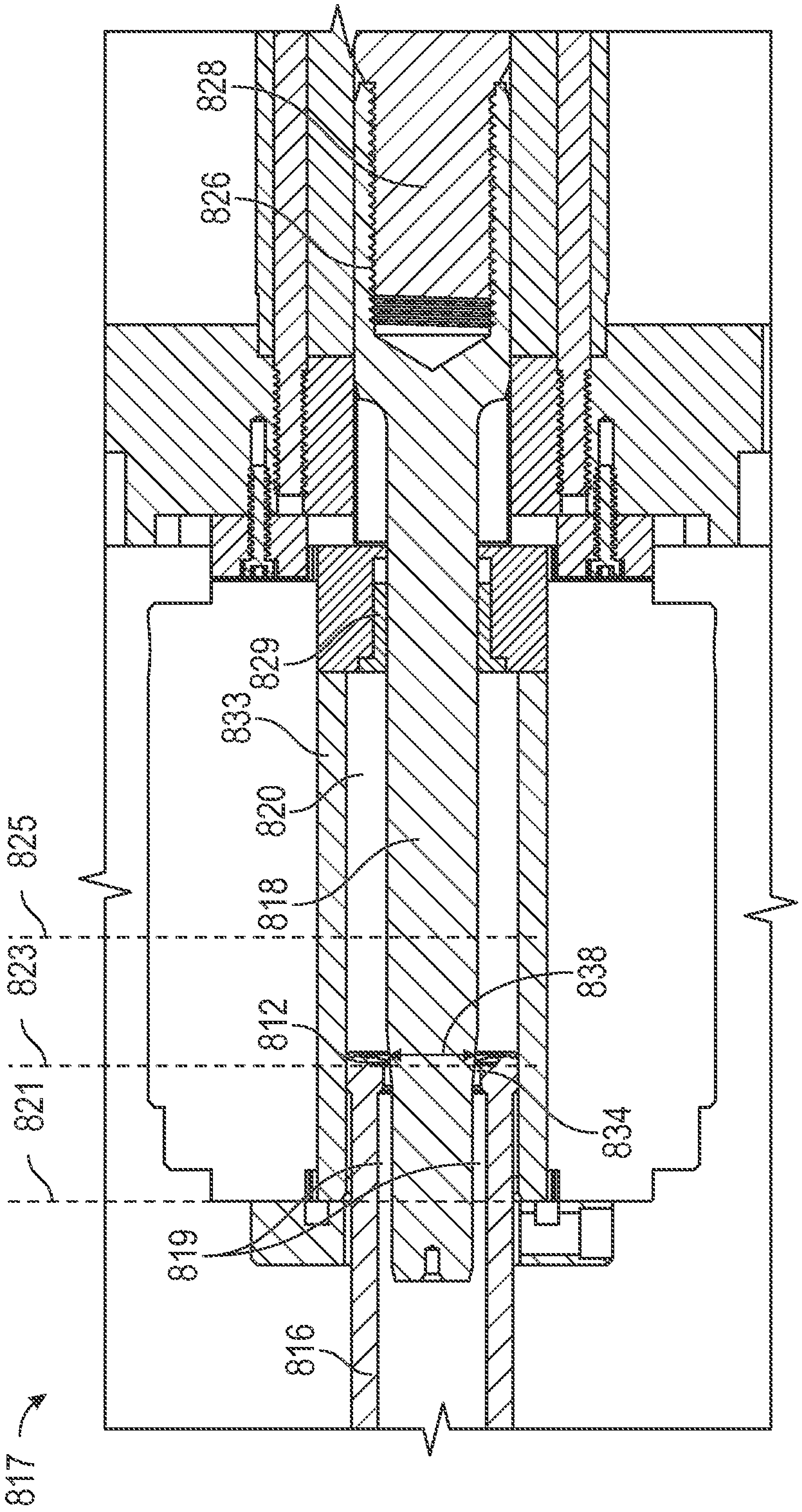


FIG. 8

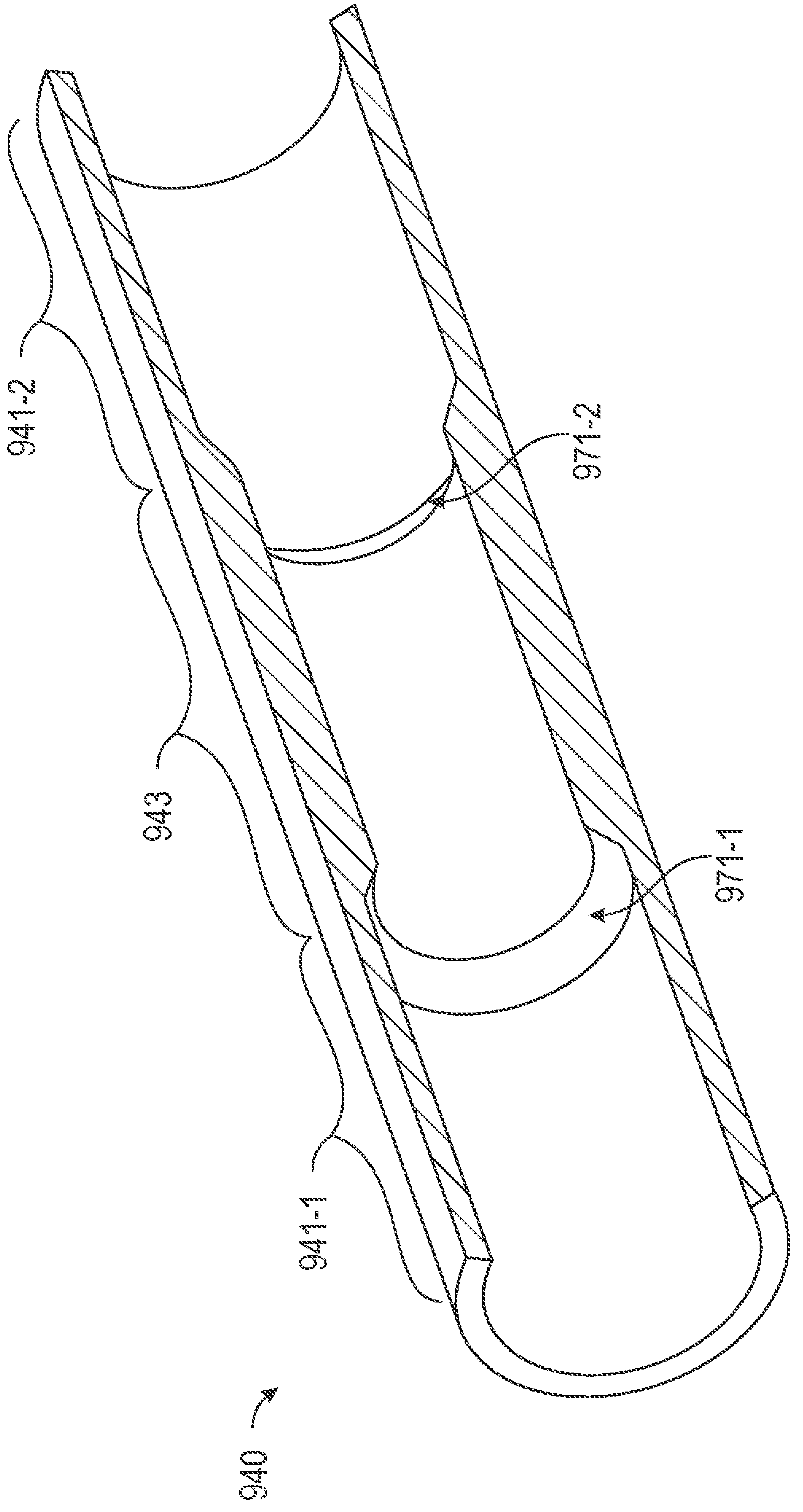


FIG. 9

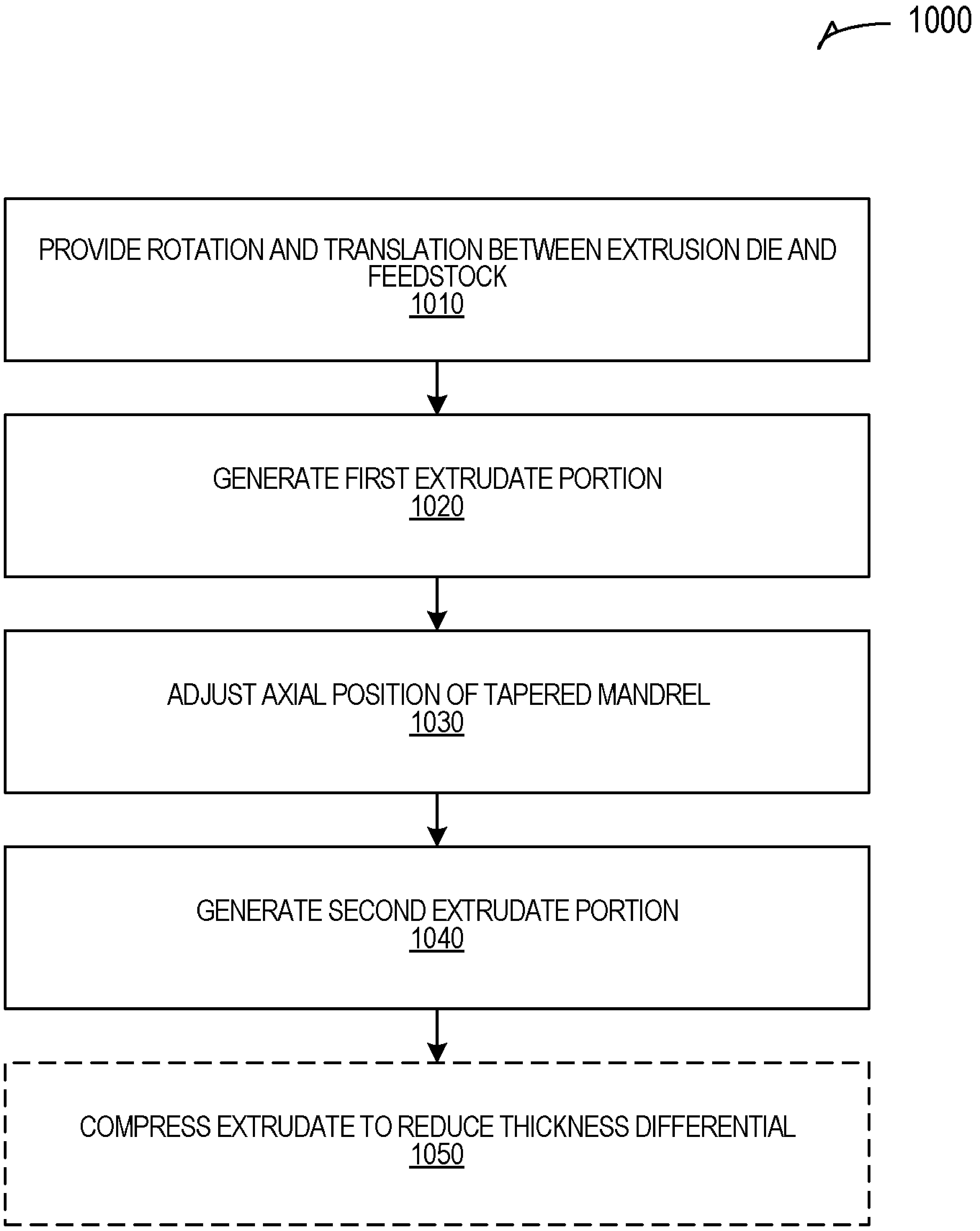

1000
PROVIDE ROTATION AND TRANSLATION BETWEEN EXTRUSION DIE AND FEEDSTOCK
1010
GENERATE FIRST EXTRUDATE PORTION
1020
ADJUST AXIAL POSITION OF TAPERED MANDREL
1030
GENERATE SECOND EXTRUDATE PORTION
1040
COMPRESS EXTRUDATE TO REDUCE THICKNESS DIFFERENTIAL
1050

FIG. 10

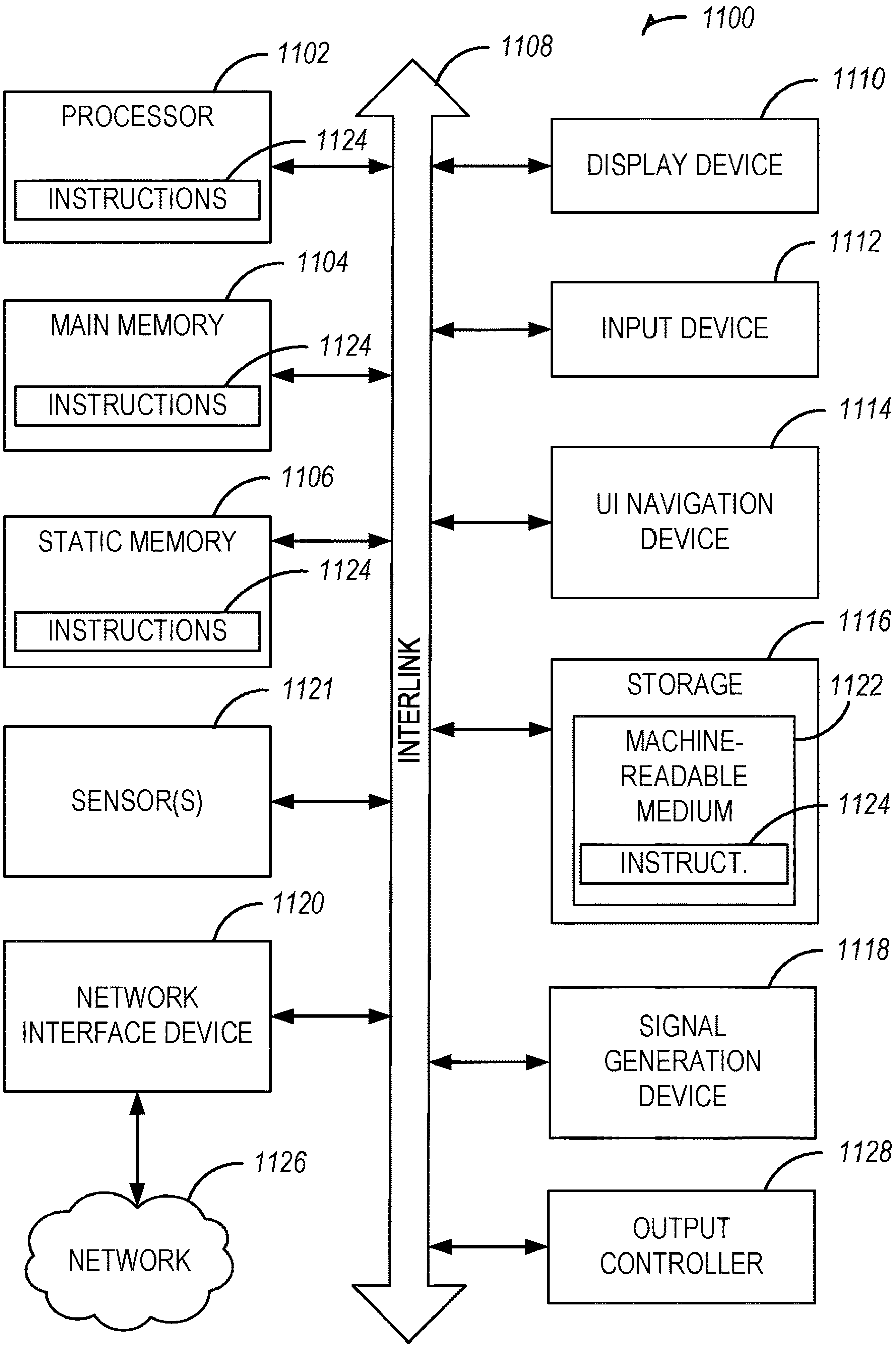

1100
1102
PROCESSOR
1124
INSTRUCTIONS
1108
1104
MAIN MEMORY
1124
INSTRUCTIONS
1106
STATIC MEMORY
1124
INSTRUCTIONS
1121
SENSOR(S)
1120
NETWORK INTERFACE DEVICE
1126
NETWORK
INTERLINK
1110
DISPLAY DEVICE
1112
INPUT DEVICE
1114
UI NAVIGATION DEVICE
1116
STORAGE
1122
MACHINE-READABLE MEDIUM
1124
INSTRUCT.
1118
SIGNAL GENERATION DEVICE
1128
OUTPUT CONTROLLER

FIG. 11

VARIABLE THICKNESS EXTRUSION FOR VARIABLE EXTRUDATE PRODUCT PROPERTIES

CLAIM OF PRIORITY

[0001] This application is a continuation-in-part of: (1) U.S. patent application Ser. No. 18/244,814 filed on Sep. 11, 2023, which claims priority to and the benefit of U.S. Provisional Application Ser. No. 63/405,664 filed on Sep. 12, 2022; and 2) U.S. Provisional Application Ser. No. 63/426,498 filed on Nov. 18, 2023 each of which is hereby incorporated herein by reference, and the benefit of priority of each of which is claimed herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with Government support under Contract DE-AC0576RL01830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

BACKGROUND

[0003] Metal extrusion is a manufacturing process involving pressing a feedstock against an extrusion die opening, e.g., using a hydraulic ram. The feedstock can deform plastically as it flows through the die opening, resulting in an extruded product with refined microstructure. Aluminum can be used as a feedstock in extrusion due to its light weight, high strength-to-weight ratio, and corrosion resistance. Aluminum extrusion can be used, for example, in manufacturing parts for aircraft and automobiles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. Various embodiments are illustrated by way of example in the figures of the accompanying drawings. Such embodiments are demonstrative and not intended to be exhaustive or exclusive embodiments of the present subject matter.

[0005] FIG. **1**A depicts an example of a system for performing Shear Assisted Processing and Extrusion (ShAPE).

[0006] FIG. **1**B shows a process of manipulating an extrudate, e.g., produced by the system of FIG. **1**A, to derive a product including or exhibiting varying mechanical properties along a length of the product.

[0007] FIG. **2** depicts an example of portions of a system for performing Shear Assisted Processing and Extrusion (ShAPE).

[0008] FIG. **3**A depicts a cross-section view of the tooling used for a variable wall thickness extrusion.

[0009] FIG. **3**B depicts a cross-section view of the tooling used for a variable wall thickness extrusion.

[0010] FIG. **3**C depicts a cross-section view of the tooling used for a variable wall thickness extrusion.

[0011] FIG. **3**D depicts a cross-section view of the tooling used for a variable wall thickness extrusion.

[0012] FIG. **4**A depicts a roll press for compressing an extrudate or extrudate derivative.

[0013] FIG. **4**B depicts a cross section of an extrudate having varying wall thicknesses.

[0014] FIG. **4**C depicts such a transition portion as a function of wall thickness versus distance along an axial length of the extrudate tubing.

[0015] FIG. **5**A is a chart showing a hardness for two different compressed extrudate derivative portions along their respective lengths.

[0016] FIG. **5**B is a chart showing stress versus strain for each of the compressed extrudate derivative portions.

[0017] FIG. **6** illustrates a system for extruding hollow cross-section pieces using a tapered mandrel.

[0018] FIG. **7** illustrates a system for extruding hollow cross-section pieces using a mandrel that is tapered.

[0019] FIG. **8** illustrates a cutout of a portion of a system for extruding hollow cross-section pieces using a mandrel.

[0020] FIG. **9** illustrates an example of an extruded product.

[0021] FIG. **10** is a flowchart outlining the steps of an exemplary technique **1000** for shear-assisted extrusion.

[0022] FIG. **11** illustrates generally an example of a block diagram of a machine.

DETAILED DESCRIPTION

[0023] A metal extrusion manufacturing process can be useful in fabricating metal components including a controlled microstructure and having one or more specified mechanical properties. For example, the mechanical properties of an extrudate can depend at least in part on extrusion temperature, ram speed, die geometry, and alloy composition. Generally, extrusion temperature, opening size in the extrusion die, and ram speed can each affect the resulting strength and ductility of the resulting extrudate. Accordingly, one or more of the mechanical properties of the extrudate can be established by controlling these variables. Following extrusion, one or more of the physical properties of the extrudate can be further manipulated via downstream processing conditions, such as cooling sections, quenching, cutting, and tempering. In general, the physical properties of the extrudate can be tailored to meet specific design requirements of downstream applications in areas such as automotive, aerospace, and shipbuilding.

[0024] Certain approaches to extrusion involve preheating of the feedstock (e.g., a billet, powder, flake, or other similar material) or preheating of the extrusion die prior to commencing extrusion. For example, preheating the billet can help control temperature distribution of the billet, limiting extrusion defects due to thermal non-uniformity. In other approaches, rather than the billet or the die being preheated, the billet can be rapidly heated during the pressing and extrusion, with the heating uniformity and rate being important to the quality and properties of the extrudate. Whether preheating or rapidly heating the billet during extrusion, such approaches generally involve techniques in attempt to achieve a static, target set of operating parameters and to produce an extrudate having uniform properties.

[0025] It can be desirable to produce fabricated metal components having differing mechanical properties, such as varying along a length of an individual component. For instance, it can be desirable to fabricate automotive B-pillars such that a middle portion thereof has a relatively high strength to perform against impact while lateral portions each have a relatively high ductility (or "toughness") at the ends to promote energy absorption. It can be challenging to fabricate such a component having differing mechanical properties using certain extrusion techniques in which establishing each individual target set of operating parameters involves stopping and starting the extrusion (e.g., to preheat the billet while extrusion is stopped or paused). One approach to fabricating a part having varied or differing mechanical properties using extruded materials involves tailored welded blanks as feedstock. Here, a plurality of blanks can be extruded to each form respective portions of the part and can each exhibit different mechanical properties. The portions can be welded together and subjected to downstream processing conditions such as heat treating and quenching, thus forming the single fabricated component. Welding can involve expensive manufacturing steps and can complicate a geometry of the fabricated component. Another approach to fabricating a component having varied mechanical properties involves variable cooling of an extrudate, e.g., to induce martensite or bainite microstructures and thus localize one or both of strength or ductility along an extrudate. However, variable cooling temperature and cooling rate can make reproducibility difficult, thereby limiting application of such an approach. The present inventors have recognized a need for an improved manner of fabricating components having one or more differing mechanical properties along a length thereof using metal extrusion techniques.

[0026] One approach to creating varying mechanical properties of an extrudate can involve further processing the extrudate following extrusion. For example, a multi-pass method can involve further pressing or rolling of an extruded material to induce a change in structure. Differing mechanical properties of an extrudate can be achieved by i) producing an extrudate including first and second axial portions each having different form (e.g., size, shape, caused by varying a profile dimension along a length of an extrudate) from each other, and then ii) subjecting both the first and second axial portions to the same processing. This same processing (e.g., rolling, heating, cooling, etc.) can affect each of the first and second portions differently, by nature of their different form, to induce or expose different mechanical properties therebetween. It can be challenging, during an extrusion process, to vary a profile dimension along the length of an extrudate. For example, varying a profile dimension can involve stopping extrusion, changing an extrusion parameter (e.g., exchanging one extrusion die with another having a different opening), and resuming extrusion. Such stopping and resuming of extrusion can introduce variation of surface state (e.g., thermal non-uniformity) into an extrudate, which can, in certain circumstances, lead to defects in the finished product or can undesirably affect downstream processing steps.

[0027] The present disclosure describes an improved approach to produce extruded tubing, such as with tailored properties along the length. For example, this can involve providing relative rotation and translation between an extrusion die and a billet or other feedstock. The die can include an extrusion aperture, such as through which a tapered mandrel extends. Adjusting the axial position of the tapered mandrel relative to the die face during extrusion can facilitate modulation of the extrusion aperture, enabling extrusion deposition of extrudate portions with different inner diameters and wall thicknesses. For example, retracting the mandrel can increase wall thickness while advancing the mandrel can decrease wall thickness. An extrudate tube can be sliced to provide an intermediate product, and then evenly compressed, e.g., during one or more downstream processing steps from the extrusion. Here, applying such even compression to the intermediate product between the portions can affect the variable wall thickness regions such as to reduce the thickness differential therebetween. The compressed product, now having a substantially uniform thickness, can exhibit one or more different mechanical properties between the portions having previously being varied in wall thickness. This can be due, at least in part, to the fact that thicker wall extrudate-derivatives become relatively more compressed and the thinner wall extrudate-derivatives remain relatively less compressed, when subject to the same or even compression. This approach to creating a uniform thickness compressed from differing thicknesses to creating regions with different properties is especially effective in work-hardenable alloys, such as Al **5182**, where strengthening arises from the extent of cold working.

[0028] FIG. **1**A depicts an example of a system for performing Shear Assisted Processing and Extrusion (ShAPE). A ShAPE system **100** can include or use an extrusion die **110**, a feedstock **120**, and a tapered mandrel **105**. During extrusion, the extrusion die **110** and the feedstock **120** can be pressed against one another and rotated relative to one another such as to induce plastic deformation of the feedstock at a face of the extrusion die. The deformed feedstock **120** can travel through an extrusion aperture at an orifice or lumen of the extrusion die **110**. In an example, the tapered mandrel **105** can extend through the orifice of the extrusion die such as to at least partially impede, block, fill, or otherwise modify the extrusion aperture. "Aperture" as referred to herein can describe the orifice or lumen of the extrusion die **110** and can likewise describe an interface between the orifice and the mandrel **105**, when the mandrel **105** is present within the orifice. By nature of a taper of the mandrel **105**, adjusting an axial position of the tapered mandrel **105** relative to the face of extrusion die **110** can modify the aperture, such as to increase or decrease a distance between an inner extrusion diameter defined by the tapered mandrel **105** and an outer extrusion diameter defined by the orifice of the extrusion die **110**. Thereby, adjusting the axial position of the tapered mandrel **105** relative to the face of the extrusion die **110** can establish or adjust a wall thickness of extrudate extruded by the system **100**, and such adjustment can be carried out without requiring stopping, interrupting, or pausing the extrusion, if desired.

[0029] FIG. 1B shows a process of manipulating an extrudate, e.g., produced by the system of FIG. **1**A, to derive a product including or exhibiting one or more varying mechanical properties along a length of the product. In an example, an extrudate **150***a* can include a tube or tubing with a first axial region **152** and a second axial region **154** directly following extrusion from via the system **100**. For example, the first axial region **152** and the second axial region **154** can include different inner diameters from each other while including substantially similar outer diameters. Alternatively, the first axial region **152** and the second axial region **154** can include different outer diameters from each other while including substantially similar inner diameter. In an example, multiple different axial regions, e.g., repeating, alternating first and second axial regions **152** and **154**, can extend along a length of the extrudate **150***a*.

[0030] In an example, the extrudate **150***a* can be sliced via at least one lengthwise slice **155** to produce extrudate derivative **150***b*, such as an intermediate product. For example, the extrudate **150***a* can be sliced along a length of tubing and at least partially unfurled, unrolled, or flattened to produce the extrudate derivative **150***b*. The extrudate **150***a* can be halved (e.g., via two slices **155**), quartered, etc. and the extrudate derivative **150***b* can include only a part (e.g., a half or quarter) of the original extrudate **150***a*. As shown in FIG. **1**B, the first and second portions **152** and **154** of the extrudate derivative **150***b* can include different thicknesses by nature of the different inner/outer diameters discussed above with respect to the extrudate **150** in tube form. Optionally, the sliced extrudate derivative **150***b* can be flattened to produce extrudate derivative **150***c*, e.g., before downstream compression, or can instead be flattened via the compression.

[0031] Prior to compression, the extrudate derivative (**150***b* or **150***c*) can include first and second portions **152** and **154** having varying thickness along a length of the derivative. Such portions can otherwise have similar characteristics (e.g., alloy composition, hardness, etc.). Once subject to compression, the first and second portions **152** and **154** can be manipulated or altered such as to reduce a difference in thickness therebetween. For example, as depicted in FIG. **1**B, a thicker first portion **152** can be compressed toward an original thickness of a thinner second portion **154**. In an example, both the first portion **152** and the second portion **154** can be compressed such that each of their resulting thicknesses are less than their respective original thicknesses. As described further below with respect to FIG. **4**A, the first and second portions can be compressed via cold rolling, e.g., from a cold rolling mill. Alternatively or additionally, the first and second portions can be compressed via hot rolling, hammering, or pressing.

[0032] The first portion **152** of a resulting compressed extrudate derivative **150***d* along a first axial region extruded from the first portion of the feedstock can include one or more different physical properties than a second portion **154** of the compressed extrudate derivative **150***d* along a second axial region extruded from the second portion of the feedstock. Herein, "physical properties" can otherwise refer to one or more mechanical properties including, e.g., tensile strength, ductility, toughness, formability, yield strength, tensile elongation, fracture toughness, hardness, and fatigue resistance. For example, respective values of ductility between the first portion **152** and the second portion **154** of the compressed extrudate derivative **150***d* can differ by a percentage within a range of about 5% to about 25%, within a range of about 10% to about 20% or differ by about 15%. Also, respective values of tensile strength between the first portion **152** and the second portion **154** of the compressed extrudate derivative **150***d* can differ by a percentage within a range of about 5% to about 50%, within a range of about 15% to about 35%, or can differ by about 25%.

[0033] FIG. **2** depicts an example of portions of a system for performing Shear Assisted Processing and Extrusion (ShAPE). System **200** can be substantially similar to ShAPE system **100** as previously described with respect to FIG. **1**A. The components, structures, configurations, functions, etc. of the system **200** can therefore be the same as or substantially similar to that described in detail with respect to the ShAPE system **100**. The system **200** can include an extrusion die **210**, a container or other plasticization channel **215**, a driver **218**, at least one thermocouple **240** and a system controller **250**. As depicted in FIG. **2**, the die face **212** can define a die face orifice **238**, and a longitudinal axis (or "central longitudinal axis") **235** can be defined to extend through a center of the die face orifice **238**. The extrusion die **210** can include an outer diameter (OD), such as within a range of about 25 mm and about 35 mm, for example, an OD of about 31.7 mm. The extrusion die can include an inner diameter (ID) (e.g., defined by the die face orifice **238**) within a range of about 5 mm and about 28 mm, or an ID of about 12 mm. The extrusion die **210** can include a die face **212** that can be thrust against and into a billet material **220** (or other feedstock, e.g., powder or flake). For example, the billet material **220** can be fed into the plasticization channel **215** and pressed against the die face **212**, such as by being compressed or moved via a driver **218**. In an example, the driver **218** can include a piston, a hydraulic ram, a screw mechanism, or another mechanism for applying compressive or extrusion forces to the billet or feedstock. The driver **218** can provide a specified amount of force at a target speed, to push or thrust the billet material **220** in an axial extrusion direction a and through an die orifice **238** or a porthole or other opening of the die face **212**. Alternatively or additionally, the driver **218** can move or press the extrusion die **210** toward the billet material **220** to supply thrust of the die face **212** against the billet material **220**, and to push the billet material **220** in the axial extrusion direction a and through the die orifice **238**. The driver **218** can be arranged to regulate a rate at which the billet material **220** and the die face are pressed against each other.

[0034] Concurrent with the thrust of the billet material **220** in the extrusion direction a and through the die orifice **238**, the system **200** can include a motor that can be arranged to rotate at least one of the die face **212** or the billet material **220** relative to the other. The motor can be disposed at or within a rotating unit, e.g., a rotating collet, a rotating material handling device, a rotating arm, a spindle, a rotating platform, a chuck or other gripping component, a bearing, another suitable rotating device, or one or more combinations thereof. In an example, a thermocouple can be embedded or otherwise positioned proximal to a contact region between the die face **212** and the billet material **220** such as to measure an indication a temperature at an extrusion die-billet interface (e.g., at the die face **212**) during extrusion.

[0035] Following plastic deformation of the billet material **220** and extrusion through the orifice **238** of the die face **212**, a die bearing surface **224** can facilitate reconstitution of the plasticized material into an arrangement that can exhibit a more refined grain size and texture control at the microscopic level as compared with the raw billet material **220** before extrusion. As such, the extrusion die **210** can facilitate forming the extrudate **222**, such as can include one or more desired characteristics.

[0036] The mandrel **205** can extend through the die orifice **238**. In an example, together with a die face orifice **238** in the die face **212**, the mandrel **205** can define an annular extrusion aperture **234** through which the plasticized extrusion material is extruded to form the extruded product **222**. The annular extrusion aperture **234** can include the die orifice **238**, being further defined or constricted by the tapered mandrel **205** during extension of the mandrel **205** through the die face orifice **238** in the die face **212**.

[0037] In an example, the system **200** can include or use a mandrel driver configured to establish or adjust an axial position of the mandrel **205** relative to the die face **212**, e.g., axially along the central longitudinal axis **235**. By moving a tapered portion **248** of the mandrel **205** along a longitudinal axis **235** with respect to the die face orifice in the die face **212** (or vice versa), a cross-sectional profile width of the annular extrusion aperture **234** can be adjusted. This can result in an adjustably specifiable inner lumen diameter or even a variable inner lumen diameter of the extruded product **222**. In addition to modifying various parameters such as feed rate, heat, pressure and spin rates of the process, various mechanical elements, such as varying an annulus width of an extrusion aperture and/or rotationally fixing the mandrel **205** while allowing for linear translation of a tapered portion **248** of the mandrel **205**, can achieve various desired results. A similar system including a moveable mandrel for extrusion is described in U.S. patent application Ser. No. 18/244,514, which is incorporated by reference herein in its entirety.

[0038] In an example, the die face **212** can include one or more scrolls **214** (e.g., spiral structures protruding outward that direct plasticized material inward as the die face **212** rotates relative to the billet material **220**). The die face **212** can include other surface morphology features, or alternatively can be planar. Rotational shear force (via the die face **212**) and the longitudinal axial compressive force of the die face **212** and the die shank **216** can each contribute toward plasticizing the billet material **220** at the interface between the die face **212** and the billet material **220**. In an example, a rotation of the die face **212** relative to the billet material **220** can be within a range of about 300 millimeters per minute (mm/min) and about 400 mm/min, or about 360 mm/min. Such a rotation, when combined with pressing the billet material **220** against the die face **212**, can establish a temperature at a billet-die interface within a range of about 300° C. and about 550° C., or toward a maximum temperature of about 500° C.

[0039] The system controller **250** can receive information provided by the mandrel driver **219**, the motor, the thermocouple or other control or sensing systems or devices. The controller **250** can receive sensor data or other information from the mandrel driver **219** to determine an axial position of the mandrel along the central longitudinal axis **235**. The controller **250** can receive sensor information and accordingly issue control instructions (e.g., "commands") to regulate an output of the mandrel driver **219**, the driver **218** (e.g., to establish a thrust rate relative to the billet material **220**) and/or to regulate an output of the motor (e.g., to adjust a rotation speed of the extrusion die **210** or the billet material **220**). This control can be coordinated in accordance with specified shear assisted extrusion parameters.

[0040] In an example, the system controller **250** can, contemporaneously with the establishing or adjusting the rotation of the die face **212** relative to the billet material **220** and contemporaneously with pressing the die face **212** and the billet material against each other, establish or adjust (via the mandrel driver **219**) an axial position of the mandrel **205** relative to the die face. For example, the system controller **250** can perform retracting and extending of the mandrel **205** during an extrusion operation.

[0041] The system controller **250** can also facilitate, via establishing and/or adjusting relative i) an amount of axial force of the billet material **220** toward the die face **212** and ii) a rate of rotation of the die face **212** to apply shear force between the die face **212** and the billet material **220**, such as to help provide extrusion of varying material properties along the extrusion length. Here, contact between the rotating die face **212** and the billet material **220** can generate heat at the die-billet interface, e.g., caused by friction and heat from within the billet material **220** caused by plastic deformation of the billet material **220**. The extent of heat generation can be controlled by regulating rotational speed, ram speed, or both. Such a configuration for heating the billet material **220** can be facilitated without requiring that the billet material is pre-heated.

[0042] In an example, the billet material **220** can be aluminum. Alternatively or additionally, the billet material **220** can include one or more other metals such as copper, steel, or titanium. In an example, the billet material **220** can be selected such that it includes an aluminum alloy, e.g., as 2-series (2xxx), 5-series (5xxx) 6-series (6xxx), or 7-series (7xxx) aluminum alloy. In an example, the billet material **220** can include an Al **5182** alloy.

[0043] FIG. **3**A, FIG. **3**B, FIG. **3**C. and FIG. **3**D each depict a cross-section view of the tooling used for a variable wall thickness extrusion. As shown in FIG. **3**A, the mandrel **205** can include a non-uniform in cross section, such as tapering e.g., from a larger diameter to a smaller diameter. As depicted through FIG. **3**B, FIG. **3**C, and FIG. **3**D, the mandrel **205** can be slidingly axially translatable through the die orifice **238**. The orifice **238** can determine an outer diameter of an extrudate tubing, while the tapered mandrel **205** can vary an internal diameter (and resulting wall thickness of the extrudate. In an example, the extrusion die can be formed from H13 steel and can include an inner diameter of about 20 mm and an outer diameter of about 34.9 mm. In an example, the mandrel **205** can be formed from H13 steel, and can include a maximum outer diameter within a range of about 10 mm and about 45 mm. For example a minimum outer diameter of the mandrel **205** (such as at an tapered end of the mandrel **205**) can be within a range of about 10 m to about 18 mm (e.g., about 14 mm, 16 mm or 18 mm) the maximum outer diameter of the mandrel (such as at an opposite end of the mandrel **205**) can be within a range of about 8 mm to about 55 mm (e.g., about 10 mm, 20 mm, or 40 mm). In an example, the mandrel **205** can be coated with a diamond like coating (DLC), such as to help reduce or mitigate friction between the mandrel **205** and the fillet material.

[0044] FIG. **4**A depicts a roll press for compressing an extrudate or extrudate derivative. In an example, the roll press **400** can include a conveyer **402** and one or more rollers **406**. An extrudate or extrudate derivative in a first form **404*a*** can be fed against the one or more rollers **406** and compressed thereagainst. For example, the roll press **400** can include a pair of rollers **406**, and the pair of rollers can define a specified compression window therebetween. For example, the compression window can be within a range of about 0.25 mm and about 5 mm, or within a range of about 1 mm and about 2 mm. The extrudate or extrudate derivative in the first form **404*a*** can be fed through the compression window and can be manipulated by the roll press **400** into a second form **404*b***. For example, the second form **404*b*** can include a substantially uniform thickness. Herein, substantially uniform (or substantially the same thickness) can refer to thicknesses varying no more than 10%.

[0045] FIG. **4**B depicts a cross section of an extrudate having varying wall thicknesses. In an example, by altering of the axial position of the mandrel (as described with respect to FIG. **2** and FIG. **3**A, FIG. **3**B, FIG. **3**C, and FIG. **3**D), the resulting extrudate tubing can include a first portion, a second portion, and a transition portion located therebetween. In an example, the transition portion can exhibit a gradual increase in wall thickness from the first portion (e.g., about 2 mm thick) toward the second portion (e.g., about 1 mm thick). FIG. **4**C depicts such a transition portion as a function of wall thickness versus distance along an axial length of the extrudate tubing.

[0046] FIG. **5**A is a chart showing a hardness for two different compressed extrudate derivative portions along their respective lengths. For example, a hardness of the compressed extrudate derivative resulting from a previous 1 mm wall thickness can be within a range of about 80 Vickers hardness value (HV0.3) and about 100 HV0.3, or at an average of about 89 HV0.3. A hardness of the compressed extrudate derivative resulting from a previous 2 mm wall thickness can be within a range of about 100 HV0.3 and about 115 HV0.3, or at an average of about 109 HV0.3.

[0047] FIG. **5**B is a chart showing stress versus strain for each of the compressed extrudate derivative portions (1 mm & 2 mm) as described with respect to FIG. **5**A.

[0048] FIG. **6** illustrates a system for extruding hollow cross-section pieces using a tapered mandrel **618**. The system in FIG. **6** includes a die shank **616**, and a die face **612**. The die shank **616** and the die face **612** can be rotated about a longitudinal axis. The die face **612** can be brought into close proximity to a container **633** holding billet material **620** that encircles a mandrel **618**. The rotation of the die face **612** in close proximity and/or engaged with the billet material **620**, can cause the billet material **620** to plasticize, as described herein.

[0049] The mandrel **618** can include a tapered tip portion having a variable outer diameter or other outer lateral dimension. For example, the mandrel **618** can include a first diameter and a second diameter and a portion between the first diameter and the second diameter that has a tapered diameter from the first to the second diameter. The tapered tip portion of the mandrel **618** can create an extrusion aperture **634** that can have a specifiably-fixed or even a variable inner diameter based on a position (indicated by the illustrated double-sided arrow) of the mandrel **618** along the longitudinal axis, as it is moved distally away from or proximally toward the die face **612**. The mandrel **618** can be tapered to have a smaller lateral profile toward a tip of the mandrel that extends distally into a die face orifice **638** than a lateral profile of a more proximal portion of the mandrel **618**. In this way, the billet material **620** can be extruded through the extrusion aperture **634**, resulting in an extruded product **622** with an inner lumen wall of variable diameter. In order to do this, as will be described further below, the mandrel **618** can move longitudinally along the longitudinal axis but can be inhibited or prevented from rotating about the longitudinal axis, such as by using an anti-rotation device that engages the mandrel and inhibits rotation even when the die face is rotating. This is in contrast to prior approaches of linear extrusion where an anti-rotation device is not used due to a lack of a rotational component to the force and therefore no use for preventing spinning of the mandrel. A gap **637** between the die shank **616** and the extruded product **622** can be present due to a lip in the die face **612** at the extrusion aperture **634**. This gap **637** can be provided to help inhibit or prevent the extruded product **622** from scraping or riding along a side of the die shank **616**. The mandrel **618** can be configured to extrude a first portion of plasticized billet material through the extrusion aperture **634** in response to the mandrel **618** being at a first position that corresponds to a first extrusion aperture dimension.

[0050] In some embodiments, the mandrel **618** can be moved to a desired location with respect to the die face orifice **638**, and the billet **620** is extruded in a fixed, and not variable, diameter. In this example, the mandrel **618** may not move with the billet **620** and does not move longitudinally with respect to the container, but is moveable and fixable to specify the desired size of the die face orifice **638** to result in a specifiable fixed inner diameter of the extrudate. Further, in the example of the variable (e.g., undulating) inner diameter or fixed inner diameter of the extrusion aperture **634**, the mandrel **618** is able to move independently of the container **633** that in turn moves the billet **620**. In some examples, a control system can include a controller and circuitry and/or hardware or firmware to adjust the longitudinal position of the mandrel **618**. Adjustment of the longitudinal position of the mandrel **618** can achieve the desired inner diameter of the extrusion aperture **634** (and therefore the diameter of the extruded product) and/or to fix the position of the mandrel **618** during extrusion once the desired position is achieved, thereby causing a uniform and straight inner lumen wall of the extruded product. Further, the control system can adjust the position of the mandrel **618** during extrusion to cause a tapered diameter along the inner diameter of the extruded product, as will be described in association with FIG. **9** below.

[0051] FIG. **7** illustrates a system **763** including a die portion **711**, a tailstock portion **713**, and a linear actuation device **715** for extruding hollow cross-section pieces using a mandrel **718** that is tapered. The die portion **711** includes a rotating die holder **710**, a die shank **716**, and a die face **712**. The rotating die holder **710**, the die shank **716**, and the die face **712** can each be fixedly coupled to each other and rotate about a longitudinal axis **735** of the rotating die portion **711**.

[0052] The tailstock portion **713** can include a container **733** used to hold a billet material **720**. The mandrel **718** can be encircled by the billet material **720** and move longitudinally along the longitudinal axis **735** while being prevented from rotating about the longitudinal axis **735**. The mandrel **718** can move independent of the container **733** when moving longitudinally along the longitudinal axis **735**, and therefore also independent of the billet material **720**. The mandrel **718** can include a threaded or other connector portion **726** used to connect the mandrel **718** to a stem **728**. The mandrel **718** can be in contact with a linear bearing **730** or other anti-rotation mechanism that inhibits the mandrel **718** from rotating about the longitudinal axis **735** while still moveable distally away from or proximally toward a die face **712** along the longitudinal axis **735**. The linear bearing **730** can provide support for the stem **728** and other structures in contact with or close proximity to the linear bearing **730** in addition to preventing rotation of the mandrel **718**. The tailstock portion **713** can include a sleeve bearing **729** in contact with the mandrel **718** and the billet material **720**, as illustrated. The sleeve bearing **729** is a bearing structure that is in contact with the mandrel **718** and container **733**, allowing for the mandrel **718** to translate without allowing billet material **718** to reverse-extrude in an undesirable direction.

[0053] A linear actuation device **715** can be in contact with the stem **728** such as through a shaft that is used to move the mandrel **718** along the longitudinal axis **735**. Optionally a force measurement device **732** can be used to couple the linear actuation device **715** to the stem **728** and provide process force measurements. The mandrel **718** can be engaged with the linear actuation device **715** at a first end **748** of the mandrel **718** opposite a second end **749**. The second end can be configured to be in contact with the billet material **720**. The linear actuation device **715** can be controlled and/or operated by control circuitry used to determine a position of the mandrel **718** in particular a position of a tapered portion of the mandrel that is located within a die face orifice **738** and defining a corresponding inner diameter of the extrusion aperture.

[0054] FIG. **8** illustrates a cutout **817** of a portion of a system for extruding hollow cross-section pieces using a mandrel **818**. The cutout **817** illustrates a die shank **816**, and a die face **812**, which are analogous to the die shank **716** and die face **712** in FIG. **7**. The container **833** is used to hold a billet material within a billet region **820**. The mandrel **818** can be encircled by the billet material in the billet region **820** and can move longitudinally along the longitudinal axis **735** while being prevented from rotating about the longitudinal axis **735**. The mandrel **818** can include a connector portion **826** used to connect the mandrel **818** to a stem **828**. A sleeve bearing **829** can be in contact with the mandrel **718** and the billet material **720**, as illustrated.

[0055] While applying a rotational shearing force by the die face **812** on the billet material in the billet region **820**, a plasticized extrusion material can be extruded through the extrusion aperture **834** to form the extrusion product **819**. The extrusion aperture **834** can have an intermediate inner diameter as the die face **812** is positioned in proximity to the mandrel **818** at a taper of the mandrel **818** between a first location **821** of the mandrel **818** with a smaller diameter and a second location **825** of the mandrel **818** with a larger diameter. As an example, the inner diameter of the extrusion aperture **834** is adjustable by moving the mandrel **818** longitudinally along the longitudinal axis (e.g., such as longitudinal axis **735** in FIG. **7**) to move the die face **812** into closer proximity to a specific location on a tapered portion of the mandrel **818** that causes a specified inner diameter of the extrusion aperture.

[0056] The outer diameter of the extrusion aperture **834** can be defined by the location of the die face **812**, or rather the inner diameter of the die face orifice **838**, which can remain constant in this example. While two diameters with a tapered portion of the mandrel **818** are illustrated, any number of diameters and progression from one diameter to another diameter can be implemented, such as a linear taper, a non-linear taper, etc.

[0057] FIG. **9** illustrates an example extruded product **940**. The example shear-assisted extrusion product **940** can include portions of varying diameters. For example, a first set of portions **204-1**, **204-2** can be a first thickness (e.g., 1 mm between an inner diameter and an outer diameter) and a second set of portions **943** can be a second thickness (e.g., 2 mm between an inner diameter and an outer diameter). The first set of portions **941-1**, **941-2** can be produced while an extrusion aperture, such as the extrusion aperture **834** in FIG. **8**, is smaller in diameter than when the second set of portions **943** is produced. A respective transition region **971-1**, **971-2** between the first set of portions **941-1/941-2** and second set of portions **943** exists, which may be either gradual or abrupt.

[0058] These increasing and decreasing tapering portions can be beneficial for creating extrusion products with "crumple zones" or similar specified locations of particular strength and other specified locations of weaknesses. As an example, the shear-assisted extrusion product **942** can preferentially crumple at the specified locations of differing stiffness upon receiving pressure at a particular end of the extruded product, which can help absorb at least some impact energy received at one end of the extruded product such that the impact energy is attenuated at the other end of the extruded product or otherwise dissipated through deformation. Each of the portions with a lesser thickness may collapse prior to the portions with greater thickness, providing an advantage to the structure, particularly in the automotive and aeronautical industries. Such preferential crumpling or deformation can help to dissipate energy in vehicular collisions or reduce a likelihood of penetration of an occupied region of a vehicle cab during a collision, or both.

[0059] The shear-assisted extrusion product **942** can include a tube **949** defining an inner lumen having a length, as illustrated. The tube **949** can have a fixed outer diameter and the inner lumen can define a varying inner diameter along the length of the inner lumen. The shear-assisted extrusion product **942** can include at least one of aluminum, an aluminum alloy, magnesium, a magnesium alloy, or a combination thereof. The tube **942** can include a wall thickness including alternating relatively thinner and thicker portions, as illustrated.

[0060] FIG. **10** is a flowchart outlining the steps of an exemplary technique **1000** for shear-assisted extrusion. The technique **1000** can be implemented using one or more devices or systems described herein, such as the system controller of FIG. **2**, the processor of FIG. **11**, etc.

[0061] At **1010**, relative rotation and translation can be provided between an extrusion die and a billet or other feedstock. As noted above, the extrusion die includes an aperture through which a tapered mandrel extends.

[0062] At **1020**, a first extrudate portion can be generated via the aperture. The outer dimension of the first extrudate portion is established by the inner dimension of the aperture. The inner dimension of the first extrudate portion is established by the outer dimension of the mandrel.

[0063] At **1030**, the axial position of the tapered mandrel can be adjusted relative to the die face during the relative rotation and translation. This modulates the size of the extrusion aperture. In an example, the mandrel can be retracted or advanced as needed to modulate the aperture and wall thickness.

[0064] At **1040**, adjusting the mandrel position allows generation of a second extrudate portion having a different inner dimension compared to the first extrudate portion. This varies the wall thickness between the first and second portions. In an example, minimal variation in outer diameter can be maintained between portions, for example less than 2% difference.

[0065] After **1040**, the process may optionally proceed to **1050**, where the extrudate portions are sliced lengthwise and compressed, for example using a rolling mill, to reduce the thickness differential while maintaining the tailored microstructures and properties. For example, this can facilitate production of extrudate portions with controlled differences in ductility, tensile strength, or other attributes.

[0066] FIG. **11** illustrates generally an example of a block diagram of a machine **1100** upon which any one or more of the techniques (e.g., methodologies) discussed herein may perform in accordance with some examples. In alternative embodiments, the machine **1100** may operate as a standalone device or may be connected (e.g., networked) to other machines. In a networked deployment, the machine **1100** may operate in the capacity of a server machine, a client machine, or both in server-client network environments. In an example, the machine **1100** may act as a peer machine in peer-to-peer (P2P) (or other distributed) network environment. The machine **1100** may be a personal computer (PC), a tablet PC, a set-top box (STB), a personal digital assistant (PDA), a mobile telephone, a web appliance, a network router, switch or bridge, or any machine capable of executing instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein, such as cloud computing, software as a service (SaaS), other computer cluster configurations.

[0067] Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms. Modules are tangible entities (e.g., hardware) capable of performing specified operations when operating. A module includes hardware. In an example, the hardware may be specifically configured to carry out a specific operation (e.g., hardwired). In an example, the hardware may include configurable execution units (e.g., transistors, circuits, etc.) and a computer readable medium containing instructions, where the instructions configure the execution units to carry out a specific operation when in operation. The configuring may occur under the direction of the execution units or a loading mechanism. Accordingly, the execution units are communicatively coupled to the computer readable medium when the device is operating. In this example, the execution units may be a member of more than one module. For example, under operation, the execution units may be configured by a first set of instructions to implement a first module at one point in time and reconfigured by a second set of instructions to implement a second module.

[0068] Machine (e.g., computer system) **1100** may include a hardware processor **1102** (e.g., a central processing unit (CPU), a graphics processing unit (GPU), a hardware processor core, or any combination thereof), a main memory **1104** and a static memory **1106**, some or all of which may communicate with each other via an interlink (e.g., bus) **1108**. The machine **1100** may further include a display unit **1110**, an alphanumeric input device **1112** (e.g., a keyboard), and a user interface (UI) navigation device **1114** (e.g., a mouse). In an example, the display unit **1110**, alphanumeric input device **1112** and UI navigation device **1114** may be a touch screen display. The machine **1100** may additionally include a storage device (e.g., drive unit) **1116**, a signal generation device **1118** (e.g., a speaker), a network interface device **1120**, and one or more sensors **1121**, such as a global positioning system (GPS) sensor, compass, accelerometer, or another sensor. The machine **1100** may include an output controller **1128**, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR), near field communication (NFC), etc.) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.).

[0069] The storage device **1116** may include a machine readable medium **1122** that is non-transitory on which is stored one or more sets of data structures or instructions **1124** (e.g., software) embodying or utilized by any one or more of the techniques or functions described herein. The instructions **1124** may also reside, completely or at least partially, within the main memory **1104**, within static memory **1106**, or within the hardware processor **1102** during execution thereof by the machine **1100**. In an example, one or any combination of the hardware processor **1102**, the main memory **1104**, the static memory **1106**, or the storage device **1116** may constitute machine readable media.

[0070] While the machine readable medium **1122** is illustrated as a single medium, the term "machine readable medium" may include a single medium or multiple media (e.g., a centralized or distributed database, or associated caches and servers) configured to store the one or more instructions **1124**.

[0071] The term "machine readable medium" may include any medium that is capable of storing, encoding, or carrying instructions for execution by the machine **1100** and that cause the machine **1100** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding or carrying data structures used by or associated with such instructions. Non-limiting machine-readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of machine-readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks.

[0072] The instructions **1124** may further be transmitted or received over a communications network **1126** using a transmission medium via the network interface device **1120** utilizing any one of a number of transfer protocols (e.g., frame relay, internet protocol (IP), transmission control protocol (TCP), user datagram protocol (UDP), hypertext transfer protocol (HTTP), etc.). Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks (e.g., cellular networks), Plain Old Telephone (POTS) networks, and wireless data networks (e.g., Institute of Electrical and Electronics Engineers (IEEE) 1002.11 family of standards known as Wi-Fi®, IEEE 1002.16 family of standards known as WiMax®), IEEE 1002.15.4 family of standards, peer-to-peer (P2P) networks, among others. In an example, the network interface device **1120** may include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the communications network **1126**. In an example, the network interface device **1120** may include a plurality of antennas to wirelessly communicate using at least one of single-input multiple-output (SIMO), multiple-input multiple-output (MIMO), or multiple-input single-output (MISO) techniques. The term "transmission medium" shall be taken to include any intangible medium that is capable of storing, encoding or carrying instructions for execution by the machine **1100**, and includes digital or analog communications signals or other intangible medium to facilitate communication of such software.

[0073] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to generally as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0074] In the event of inconsistent usages between this document and any documents so incorporated by reference, the usage in this document controls.

[0075] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In this document, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc., are used merely as labels, and are not intended to impose numerical requirements on their objects.

[0076] Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Such instructions can be read and executed by one or more processors to enable performance of operations comprising a method, for example. The instructions are in any suitable form, such as but not limited to source code, compiled code, interpreted code, executable code, static code, dynamic code, and the like.

[0077] Further, in an example, the code can be tangibly stored on one or more volatile, non-transitory, or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

[0078] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

[0079] The above detailed description is intended to be illustrative, and not restrictive. The scope of the disclosure should, therefore, be determined with references to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. A method for solid phase processing (SPP) of a billet or other feedstock, the method comprising:

providing relative rotation and translation between an extrusion die and a feedstock, the die including an extrusion aperture through which a tapered mandrel extends;

generating a first extrudate portion via the aperture, a first outer dimension of the first extrudate portion established by an inner dimension of the aperture, and a first inner dimension of the first extrudate portion established by an outer dimension of the mandrel; and

adjusting an axial position of the tapered mandrel, relative to a face of the die, during the providing the relative rotation and translation to generate a second extrudate portion having a second inner dimension that is different from the first inner dimension of the first extrudate portion to thereby vary a wall thickness between the first extrudate portion and the second extrudate portion.

2. The method of claim **1**, comprising:

slicing the first and second extrudate portions, lengthwise; and

compressing at least part of each of the lengthwise-sliced first and second extrudate portions to reduce a difference in wall thickness therebetween.

3. The method of claim **2**, wherein the compressing is such that the sliced and compressed first and second extrudate portions differ from each other in at least one mechanical property.

4. The method of claim **3**, wherein the first and second extrudate portions differ in ductility by at least 15%.

5. The method of claim **4**, wherein the first and second extrudate portions differ in tensile strength by at least 25%.

6. The method of claim **1**, wherein the second extrudate portion has an outer dimension that is within 2% of an outer dimension of the first extrudate portion.

7. The method of claim **6**, wherein the second extrudate portion is deposited from the extrusion die including a tubing wall thickness with a value greater than 150% a wall tubing wall thickness of the first extrudate portion.

8. The method of claim **1**, wherein adjusting the axial position of the tapered mandrel includes retracting the tapered mandrel an opposite direction of the extrusion.

9. The method of claim **8**, comprising axially advancing, following the retracting of the tapered mandrel in an opposite direction of the extrusion, the tapered mandrel toward the extrusion die and in a direction of the extrusion, the axially advancing performed during the providing relative rotation and translation.

10. The method of claim **1**, comprising placing the tapered mandrel into the extrusion aperture, including axially advancing the tapered mandrel in a direction of the extrusion, such that a maximum outer diameter of the mandrel is disposed within the aperture and at the face of the extrusion die.

11. A processed, shear-assisted extrusion product, comprising:

at least a portion of unfurled, flattened extrudate tubing, the at least a portion including:
  a first axial region extruded from a first portion of a feedstock; and
  a second axial region extruded from a second portion of a same feedstock;
  wherein:
    the first and second axial regions have a substantially similar thickness; and
    the first region comprises different physical properties than the second region.

12. The extrusion product of claim **11**, wherein the first and second axial regions differ in ductility by at least 15%.

13. The extrusion product of claim **11**, wherein the first and second axial regions differ in tensile strength by at least 25%.

14. A system for solid phase processing (SPP) of a billet or other feedstock, the system comprising:

an extrusion die including:
  a die face configured to have relative rotational motion relative to a feedstock material; and
  a die orifice arranged to establish an outer dimension of an extrudate tubing;
a first driver configured to apply an axial extrusion force to drive the feedstock material and the die face together, during the relative rotational motion;
a tapered mandrel extending through the die orifice and slidingly translatable therethrough, the tapered mandrel configured to establish an inner dimension of an extrudate tubing; and
a system controller configured to establish or adjust the rotation of the die face relative to the feedstock material and contemporaneously establish or adjust an axial position of the tapered mandrel, relative to a face of the die modulate an extrusion aperture defined between the die orifice and the tapered mandrel to thereby vary a wall thickness between a first extrudate portion and a second extrudate portion.

15. The system of claim **14**, comprising an extrudate compressor configured to compress at least part of the first and second extrudate portions to reduce a difference in wall thickness therebetween.

16. The system of claim **15**, wherein the extrudate compressor includes a rolling mill.

17. The system of claim **14**, wherein the system is configured to extrude the first and second extrudate portions such that the second extrudate portion has an outer dimension that is within 2% of an outer dimension of the first extrudate portion.

18. The system of claim **17**, wherein the system is configured to extrude the first and second extrudate portions such that the second extrudate portion is deposited from the extrusion die including a tubing wall thickness with a value greater than 150% a wall tubing wall thickness of the first extrudate portion.

19. The system of claim **14**, wherein the system controller is configured to retract the tapered mandrel an opposite direction of the extrusion.

20. The system of claim **19**, wherein the system controller is configured to axially advance, following the retracting of the tapered mandrel in an opposite direction of the extrusion, the tapered mandrel toward the extrusion die and in a direction of the extrusion.

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