US 20060208481A1

(19) United States
(12) Patent Application Publication (10) Pub. No.: US 2006/0208481 A1
Fischer et al. (43) Pub. Date: Sep. 21, 2006

(54) **ELECTROMAGNETIC PULSE WELDING OF FLUID JOINTS**

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(21) Appl. No.: **10/905,233**

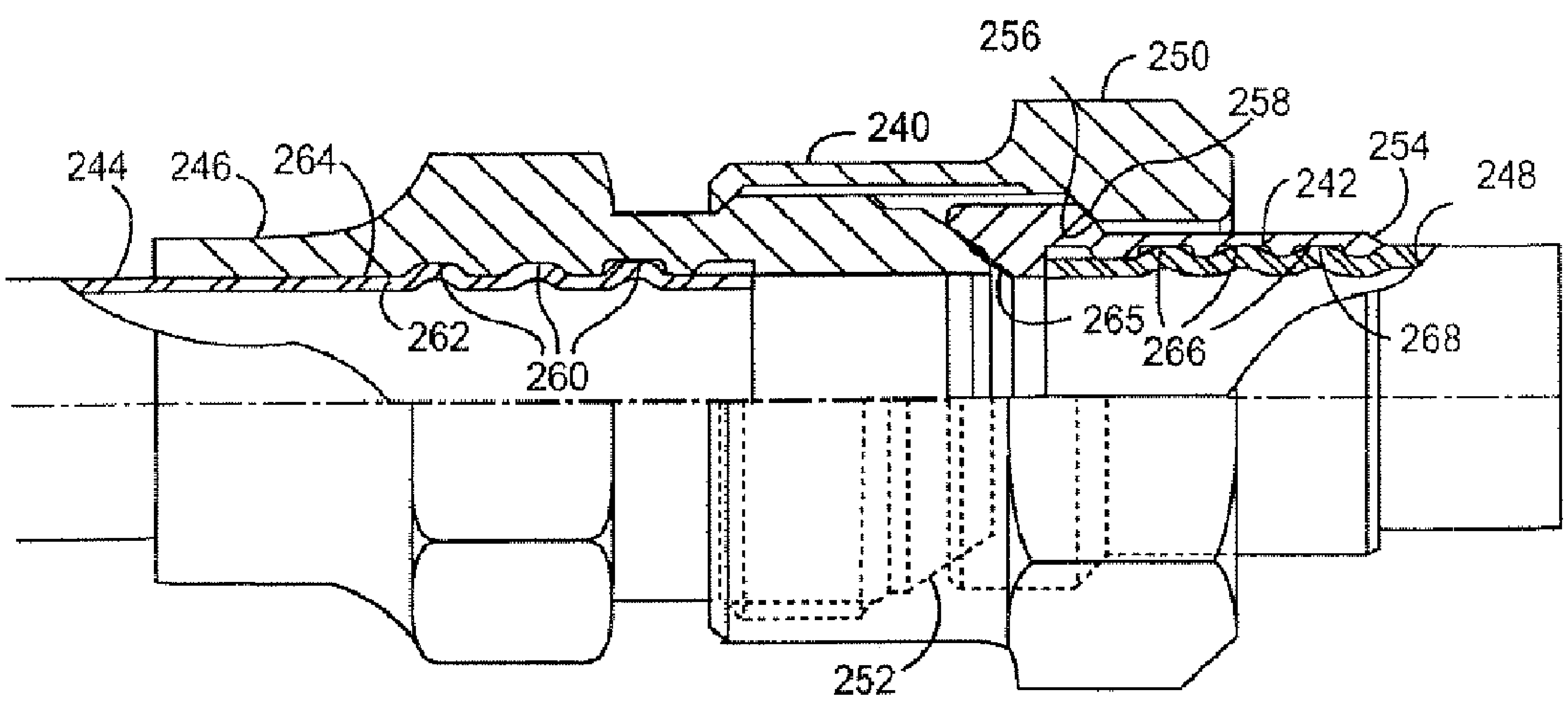
(22) Filed: **Dec. 22, 2004**

Publication Classification

(51) **Int. Cl.**
F16L 47/00 (2006.01)
(52) **U.S. Cl.** **285/258**

(57) **ABSTRACT**

A metallurgically formed fluid circuit joint includes a hollow fitting (**298**), a tubular conduit (**297**), and a metallurgically formed tube/fitting mesh (**296**). The tube/fitting mesh (**296**) includes a fitting portion of the hollow fitting (**298**) and a tube portion of the tubular conduit (**297**) that is electromagnetically formed with the fitting portion.



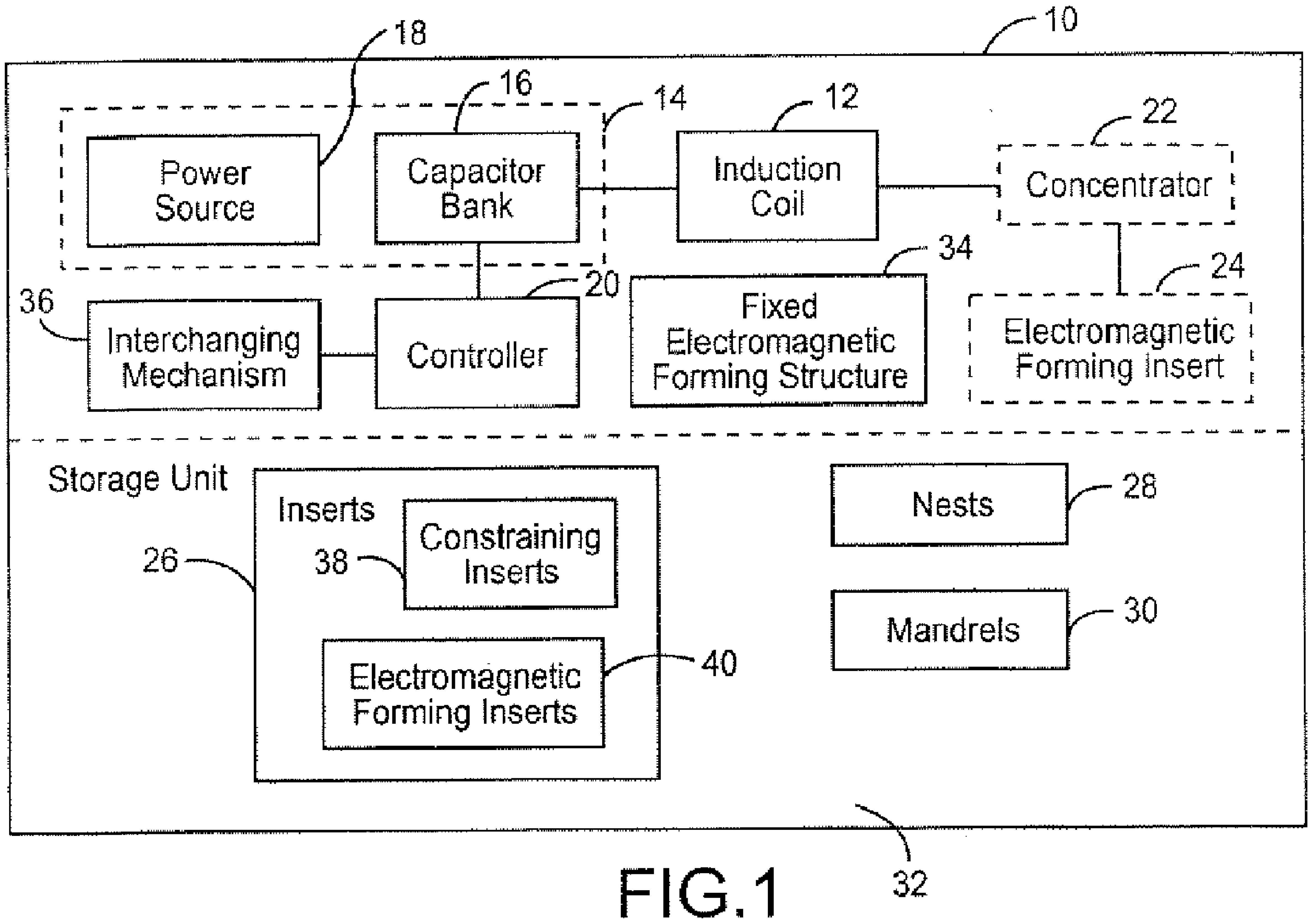


FIG.1

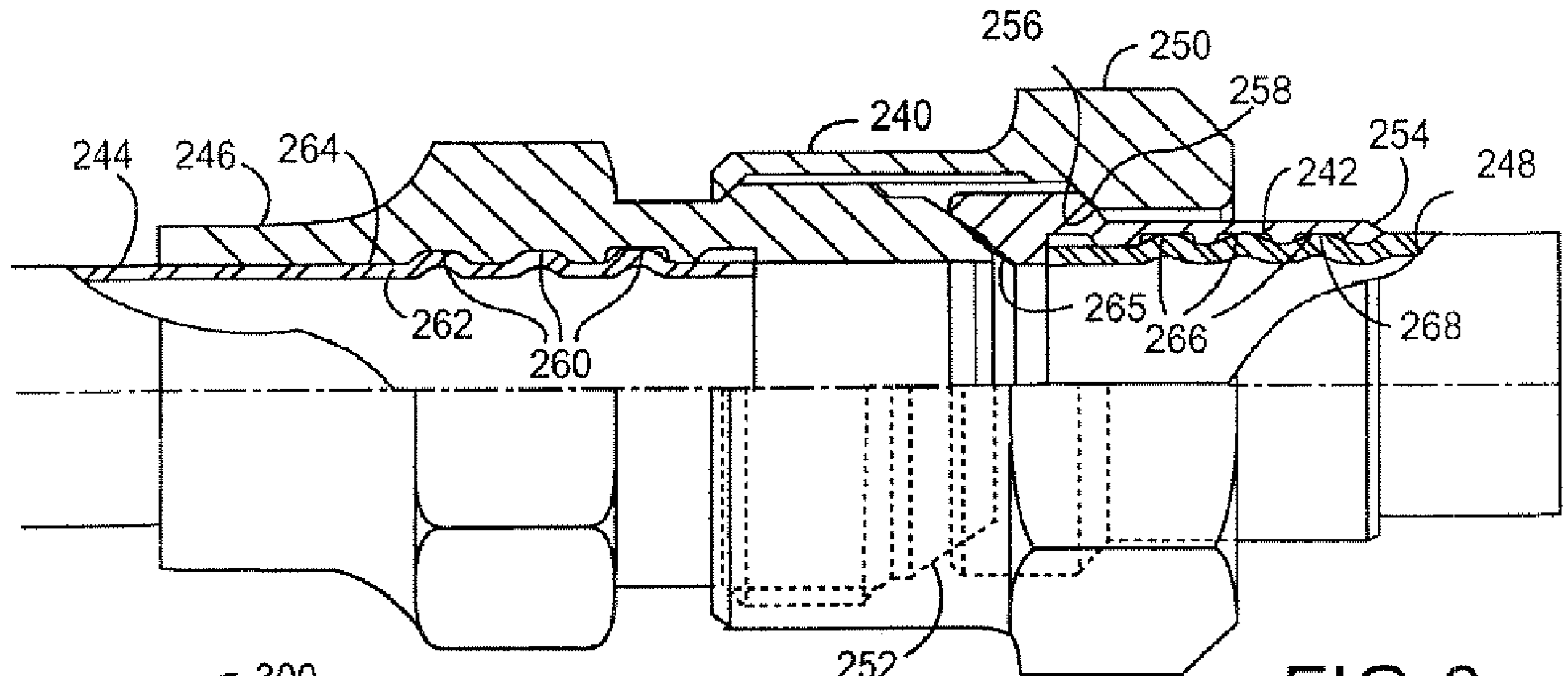


FIG.6

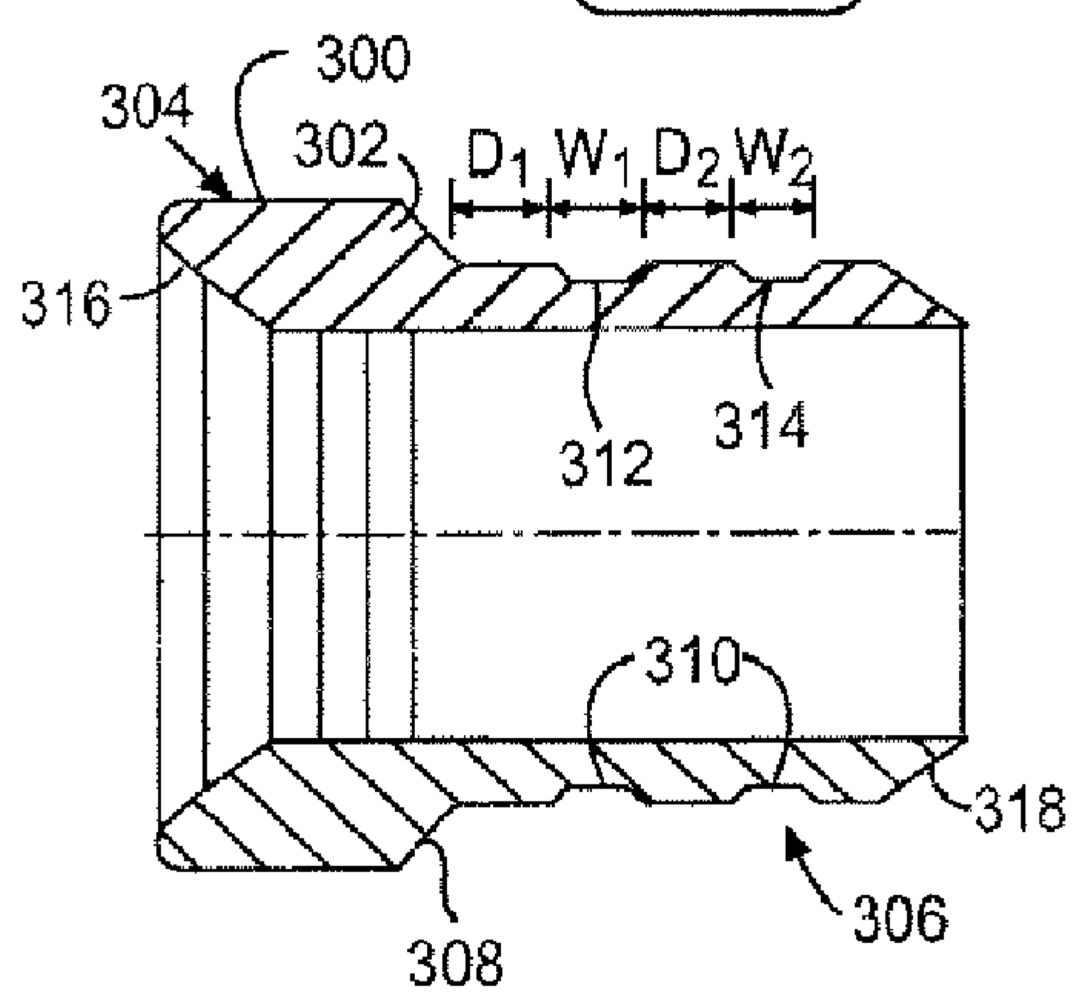


FIG.8

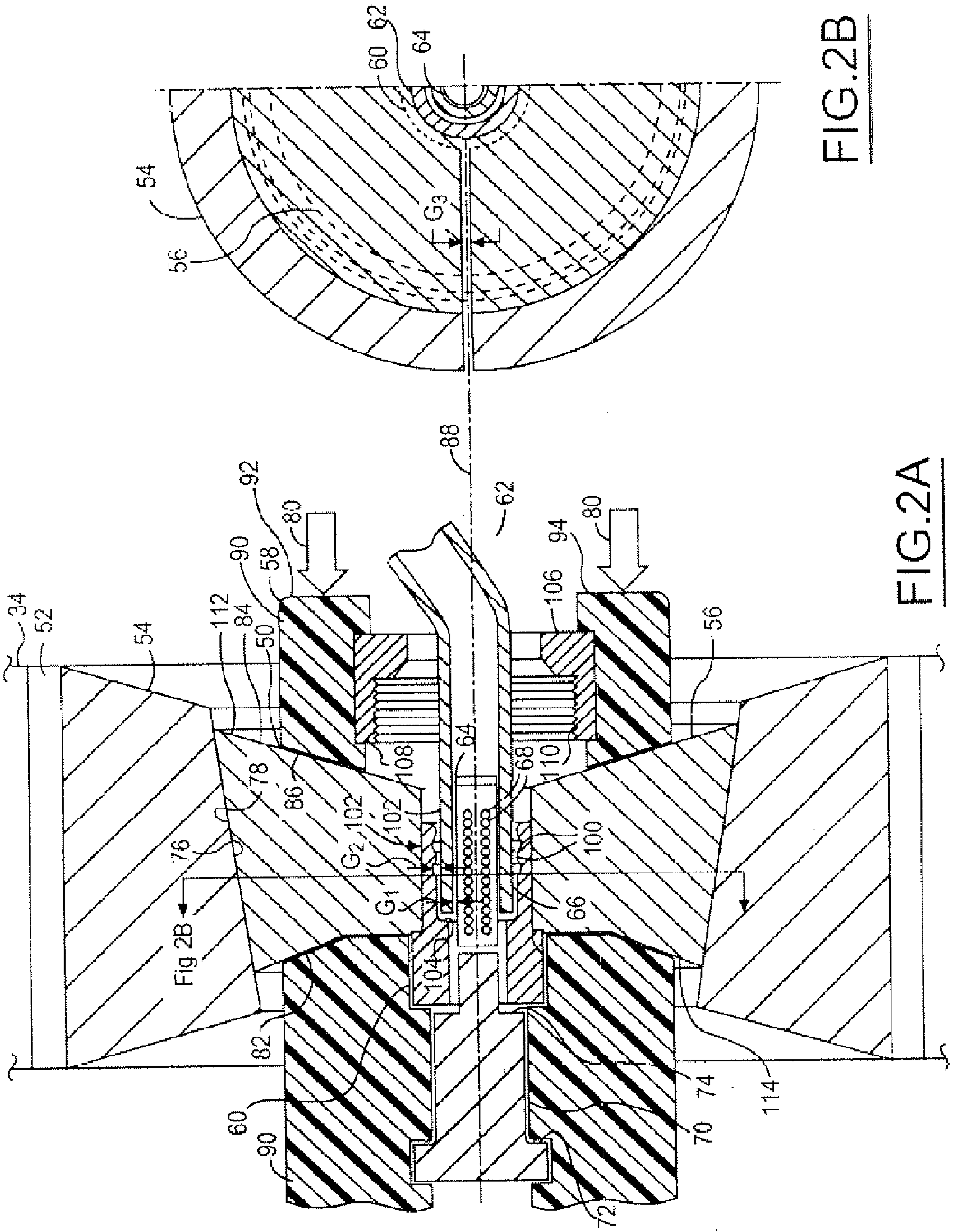


FIG.2A

FIG.2B

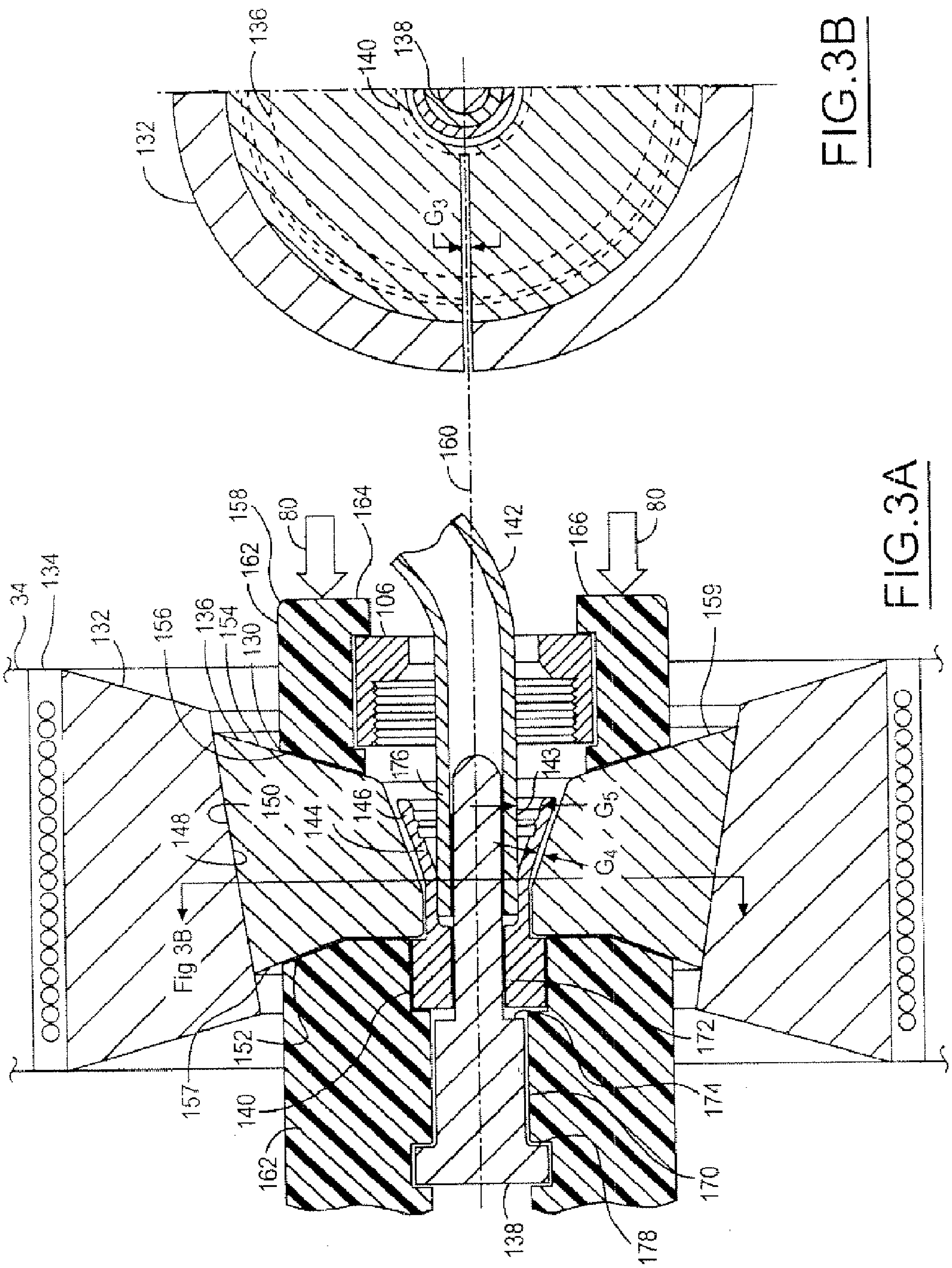

136
140
138
132
G_3
160
158
80
164
142
166
80
34
134
132
162
106
156
136
154
130
159
150
176
143
148
144
146
G_5
G_4
Fig 3B
172
152
157
140
174
162
170
138
178

FIG.3B

FIG.3A

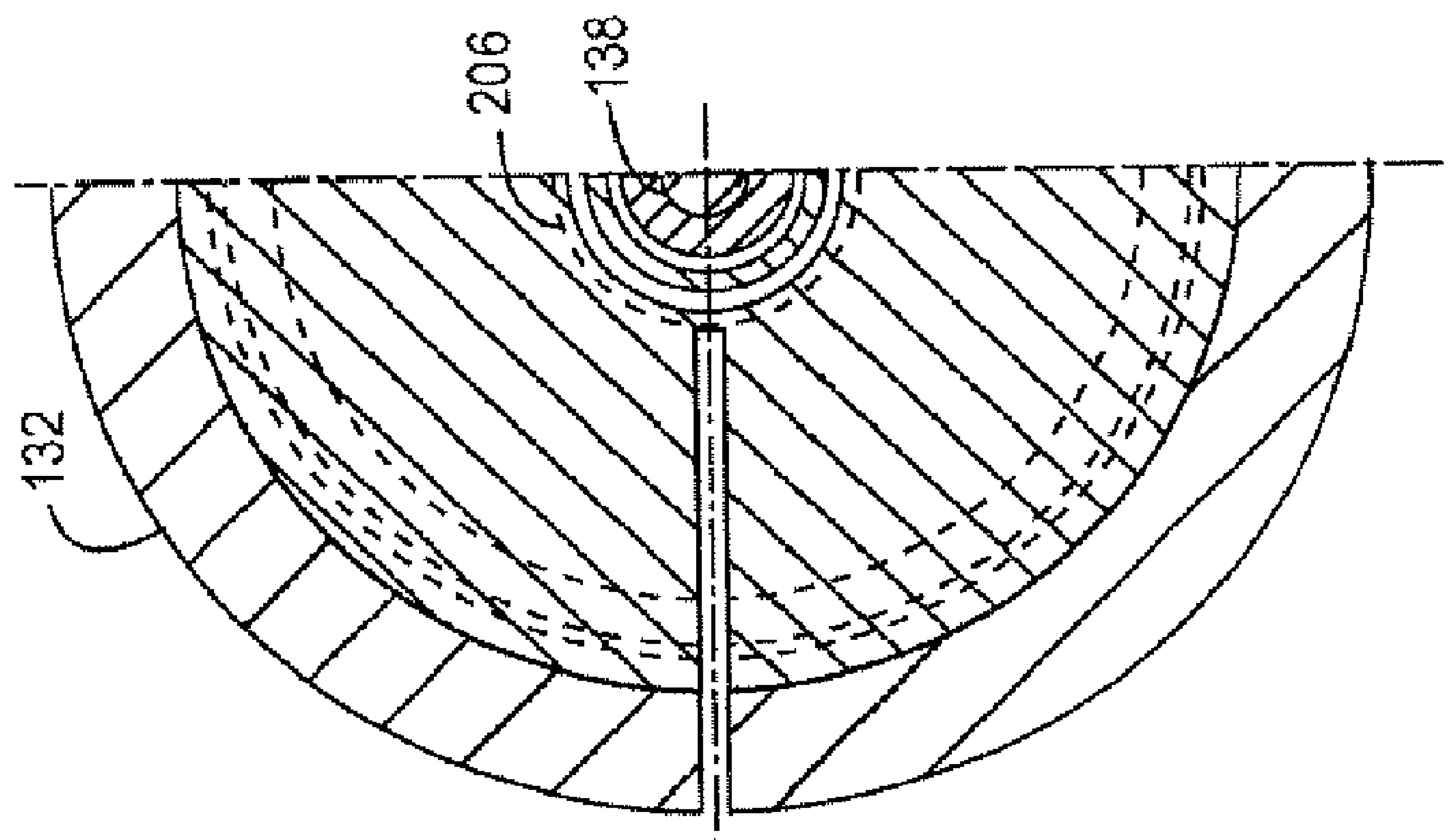

206
138
132

FIG.4B

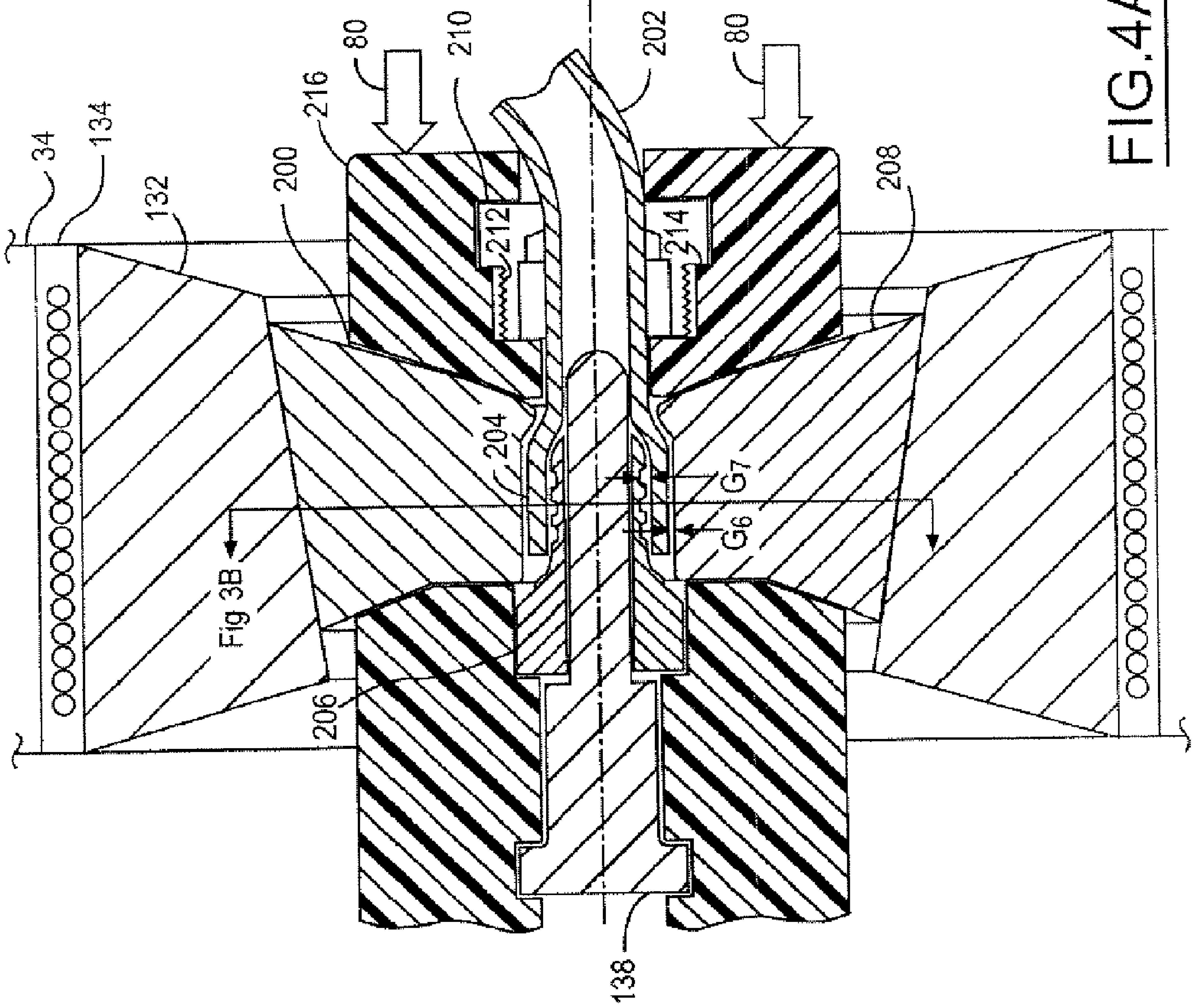

34
134
132
200
216
80
210
212
214
202
80
208
204
G7
G6
Fig 3B
206
138

FIG.4A

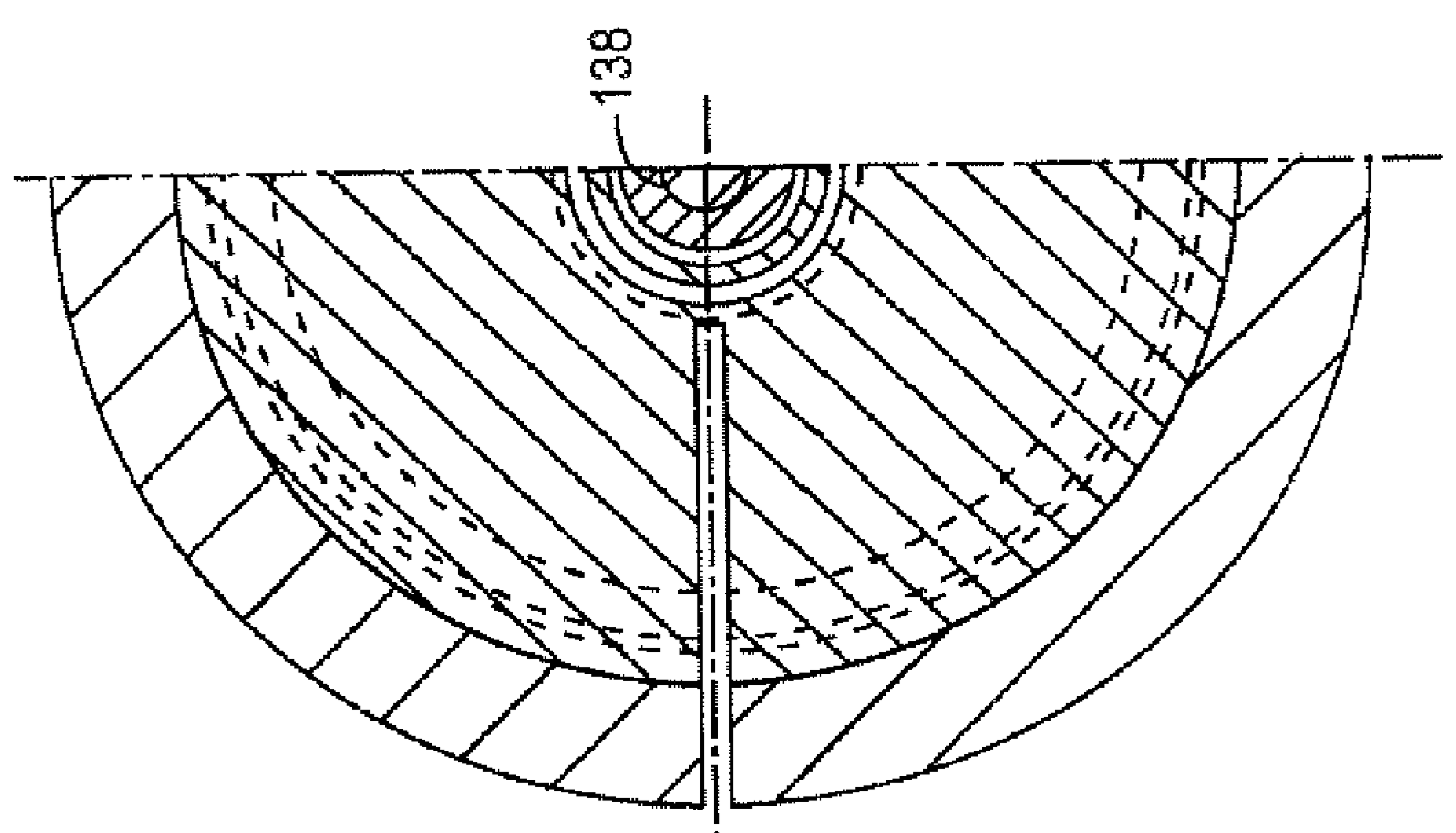


FIG.5B

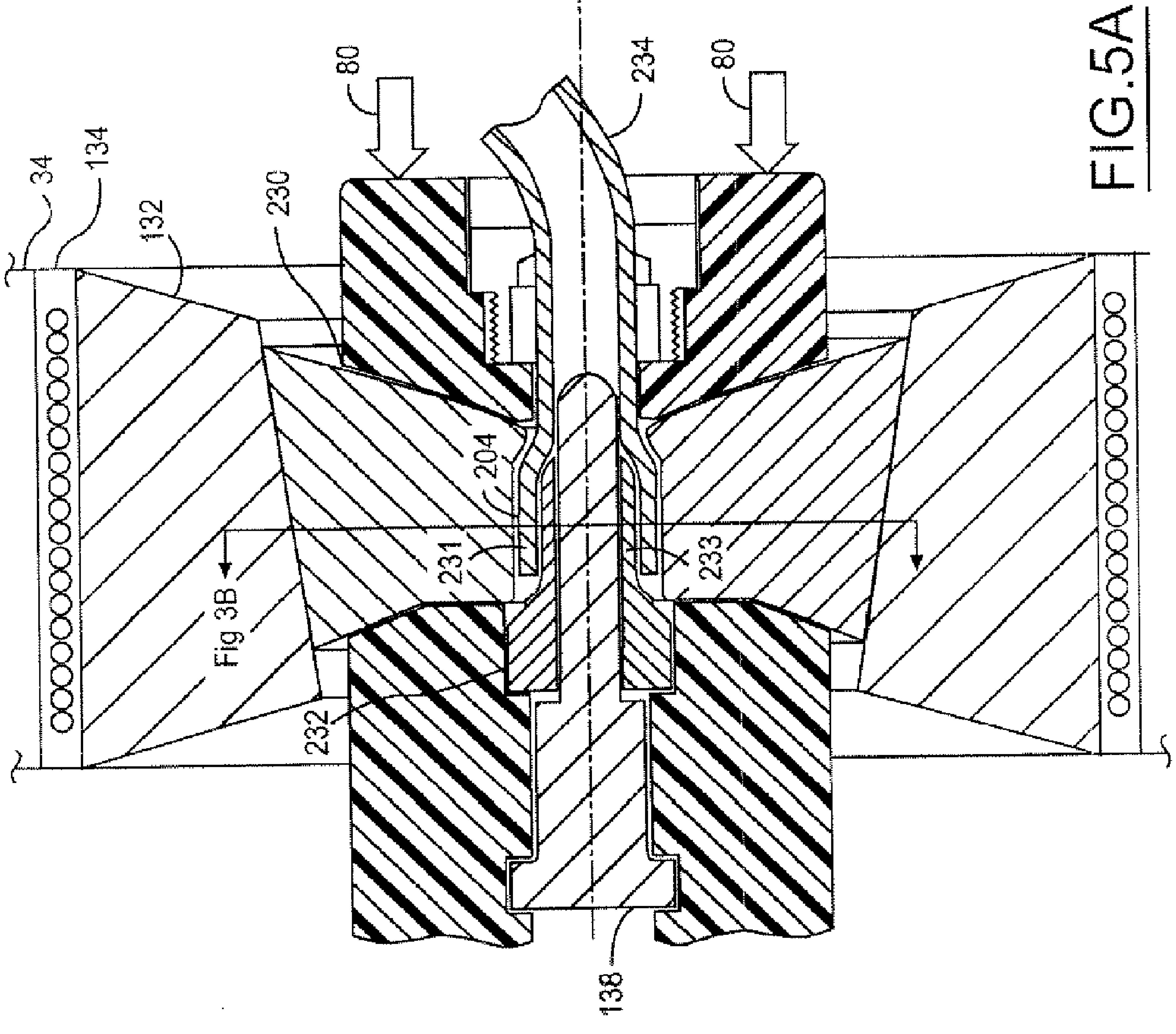


FIG.5A

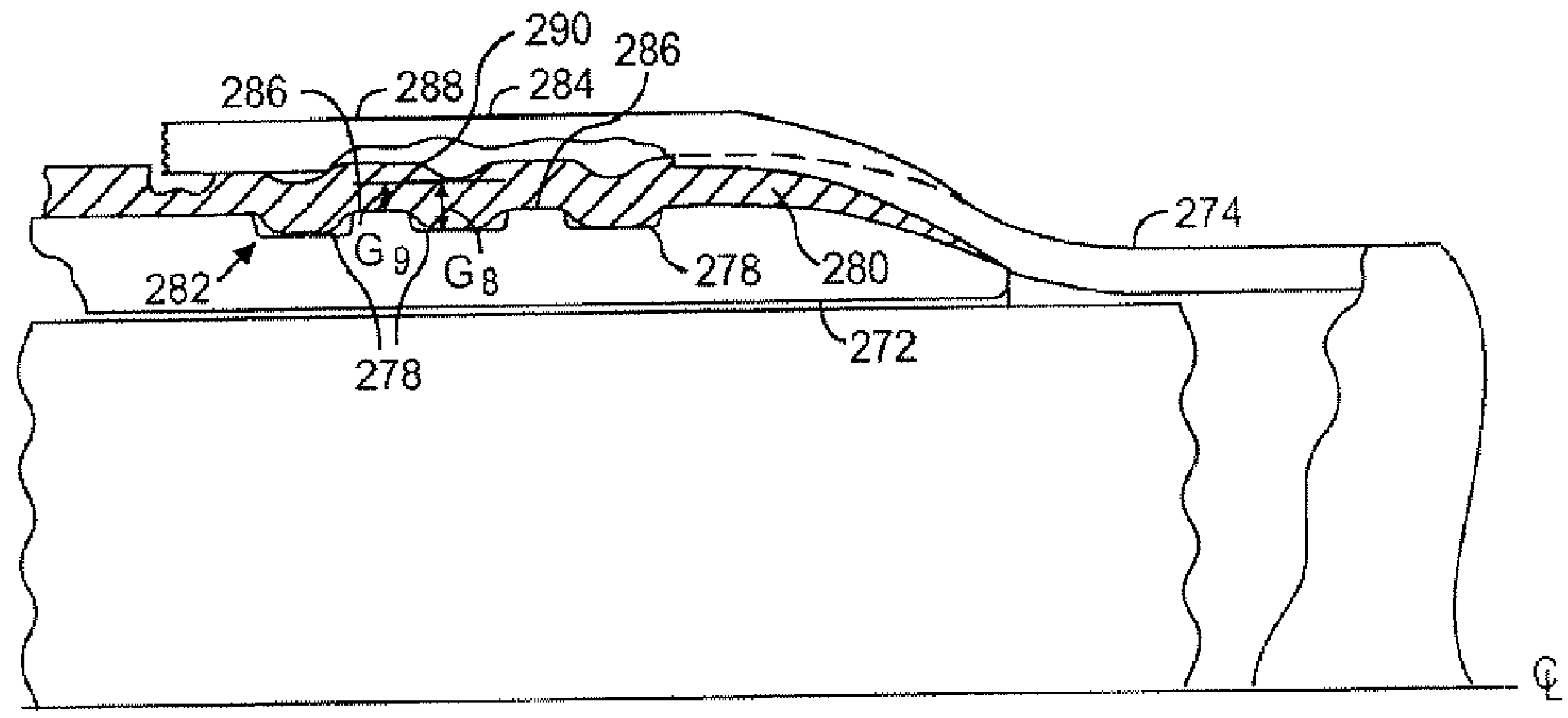


FIG.7A

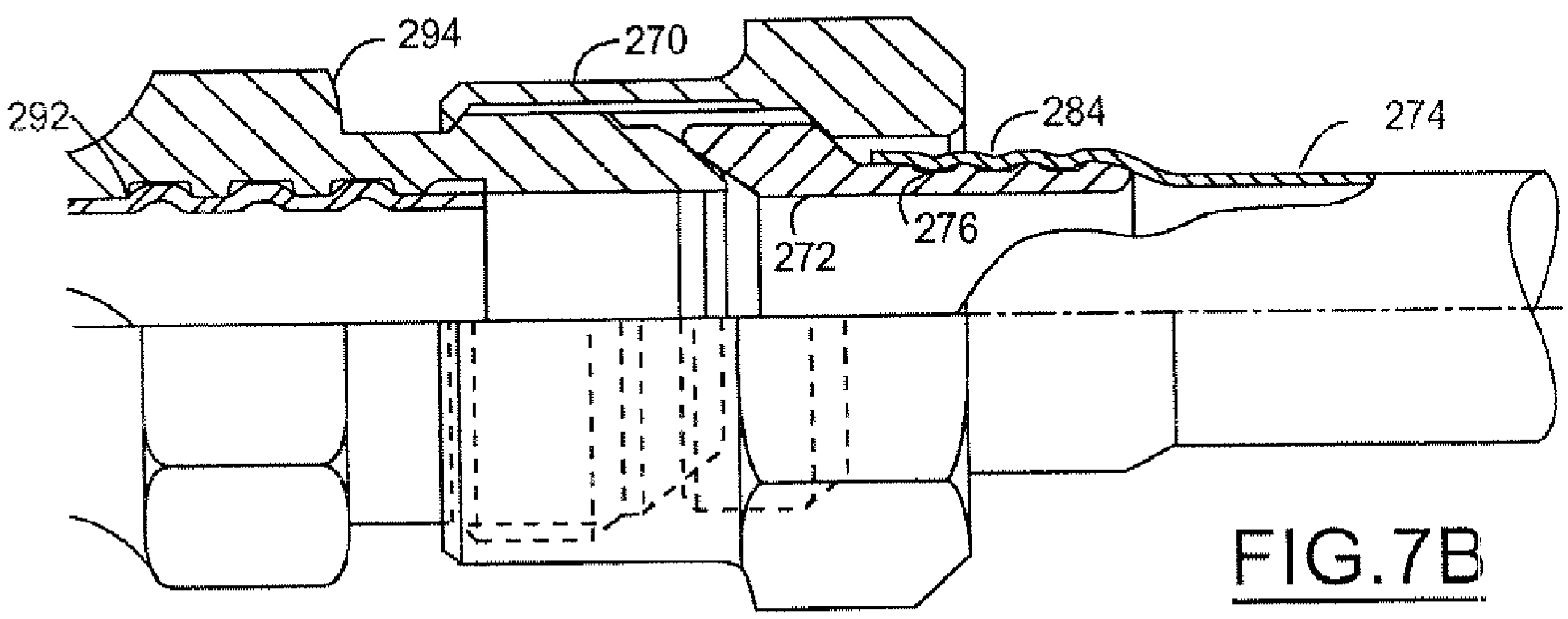


FIG.7B

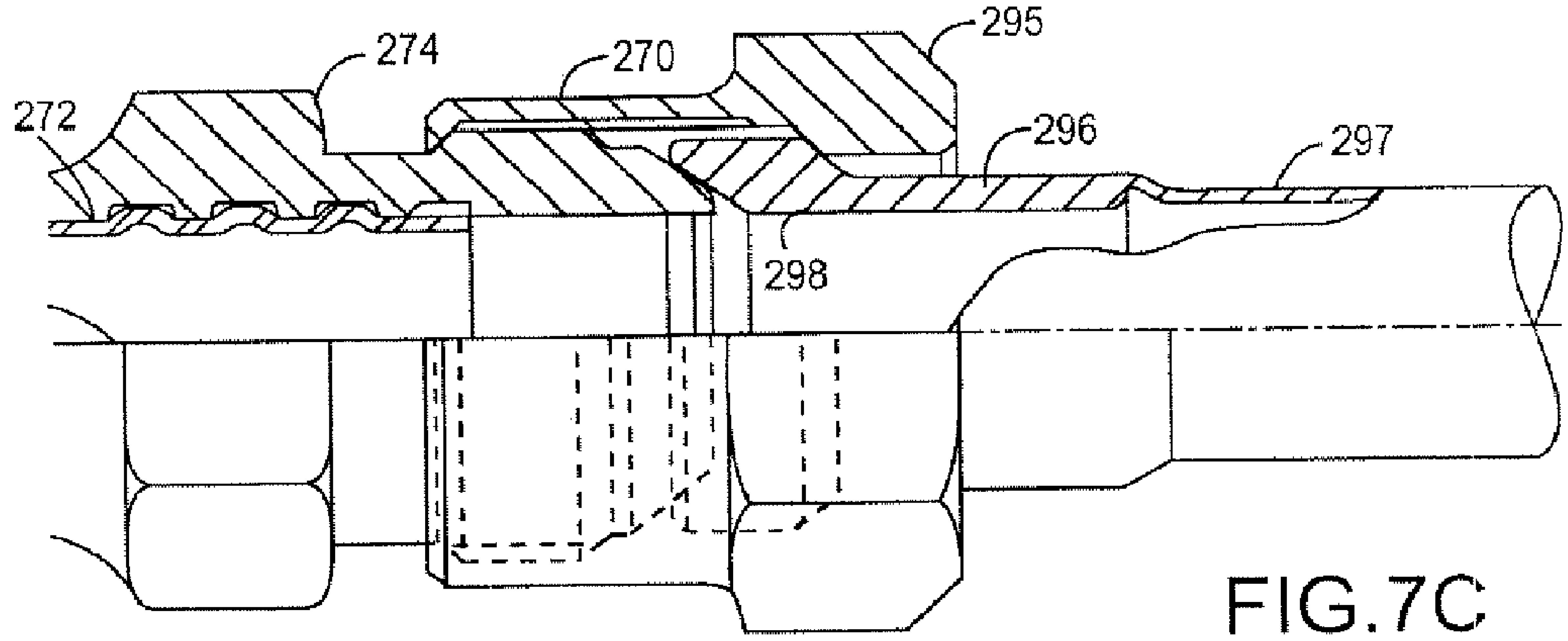


FIG.7C

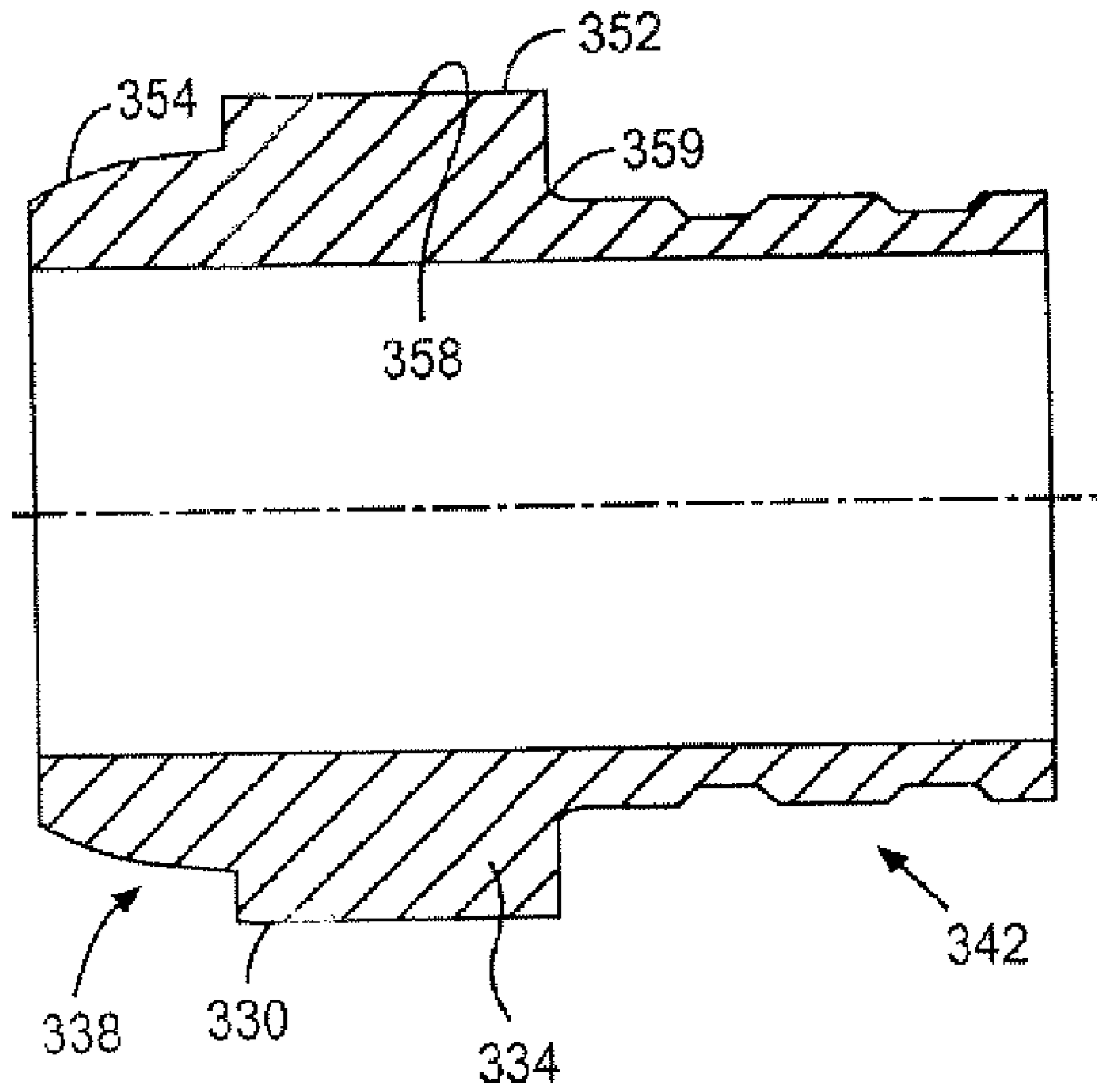


FIG.9

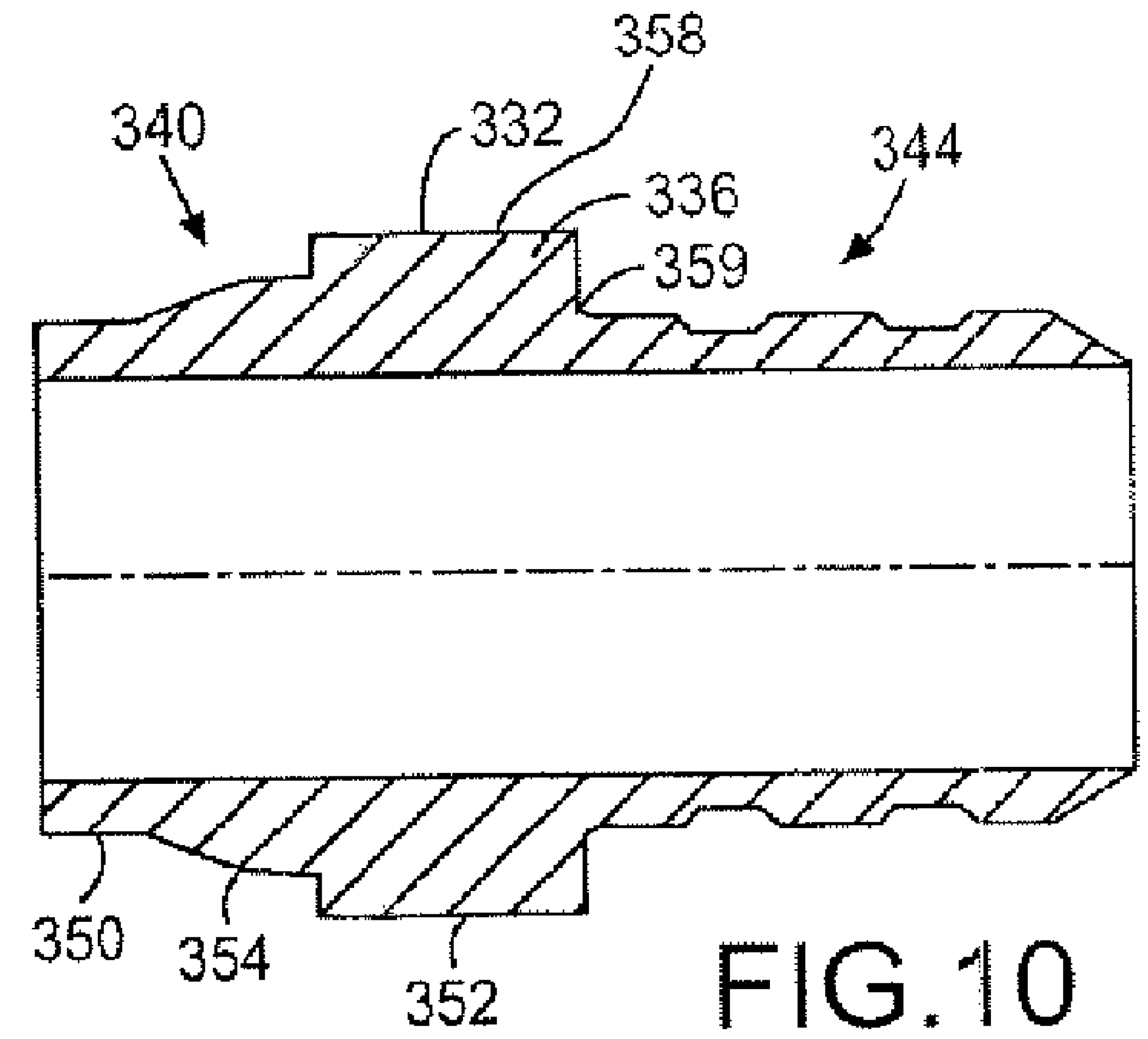


FIG.10

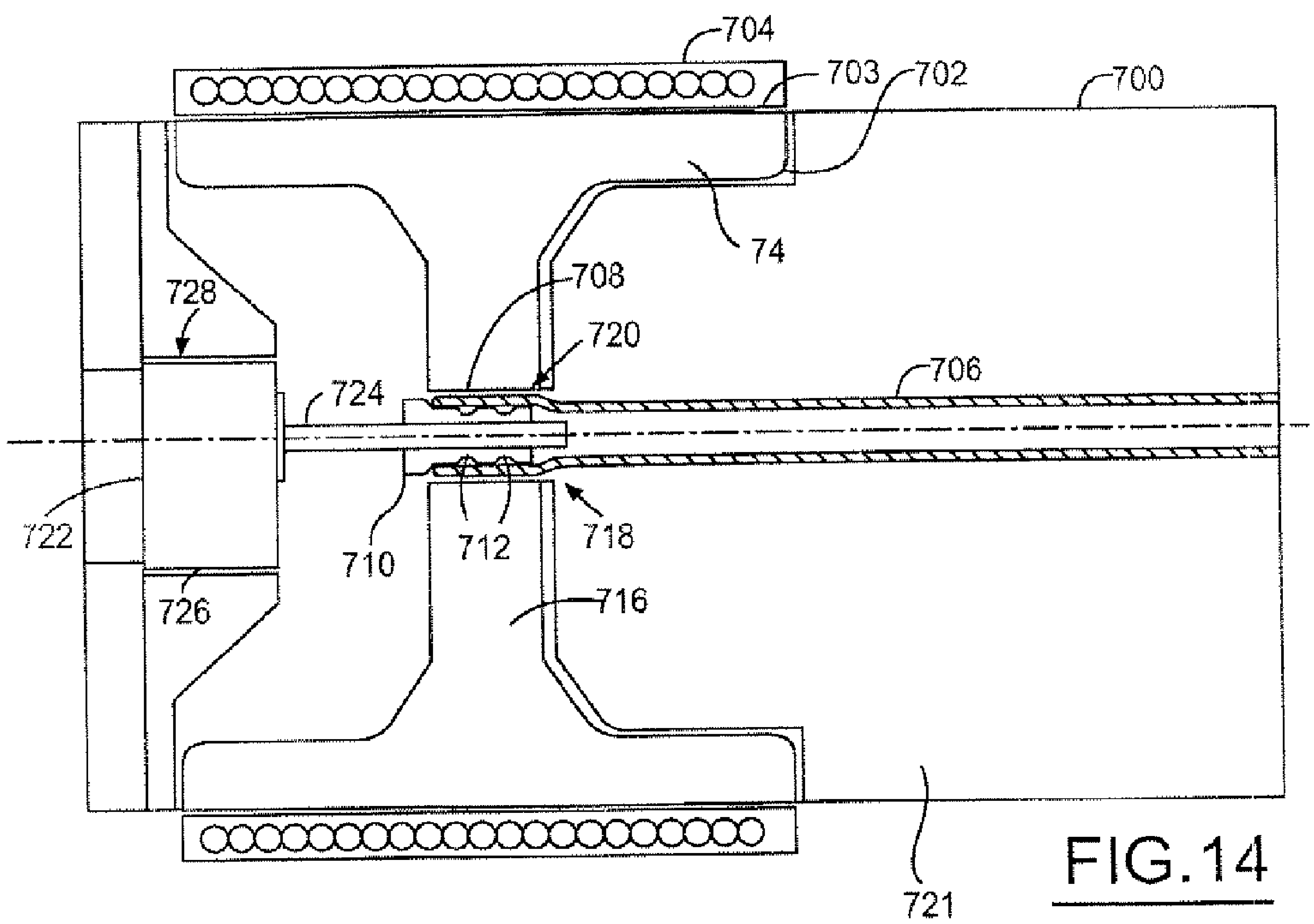


FIG.14

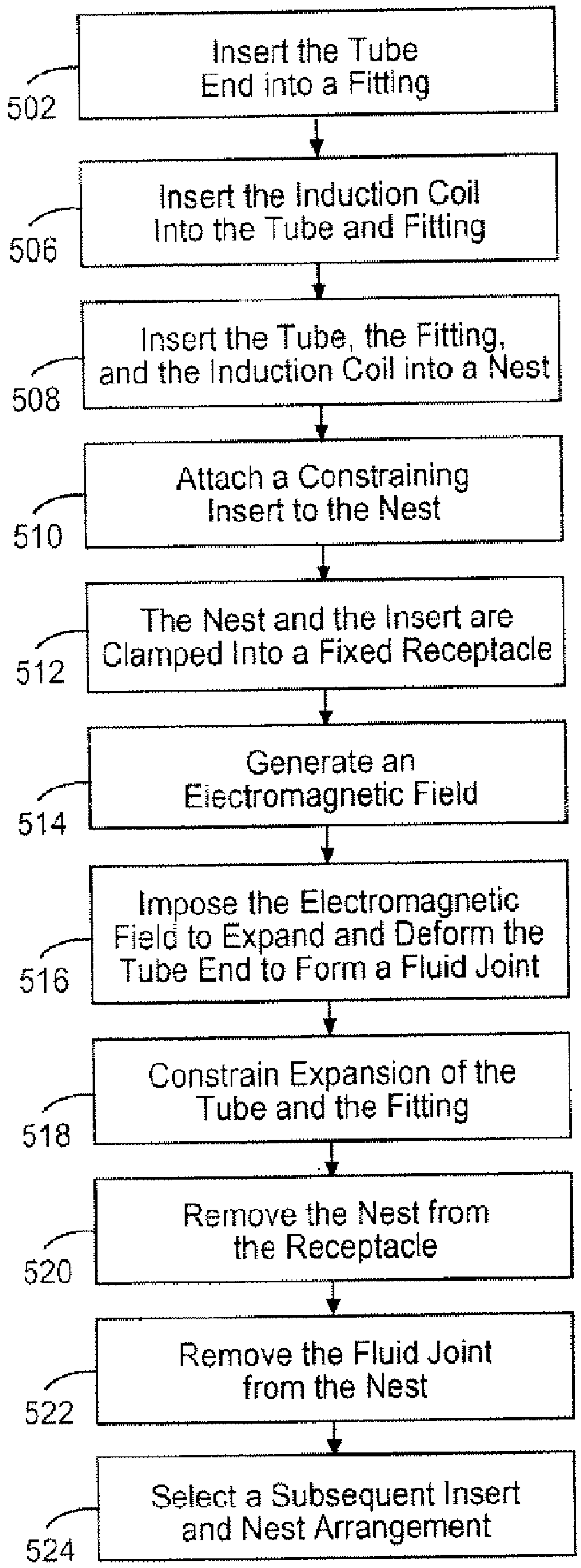

Insert the Tube End into a Fitting
502
Insert the Induction Coil Into the Tube and Fitting
506
Insert the Tube, the Fitting, and the Induction Coil into a Nest
508
Attach a Constraining Insert to the Nest
510
The Nest and the Insert are Clamped Into a Fixed Receptacle
512
Generate an Electromagnetic Field
514
Impose the Electromagnetic Field to Expand and Deform the Tube End to Form a Fluid Joint
516
Constrain Expansion of the Tube and the Fitting
518
Remove the Nest from the Receptacle
520
Remove the Fluid Joint from the Nest
522
Select a Subsequent Insert and Nest Arrangement
524

FIG.11

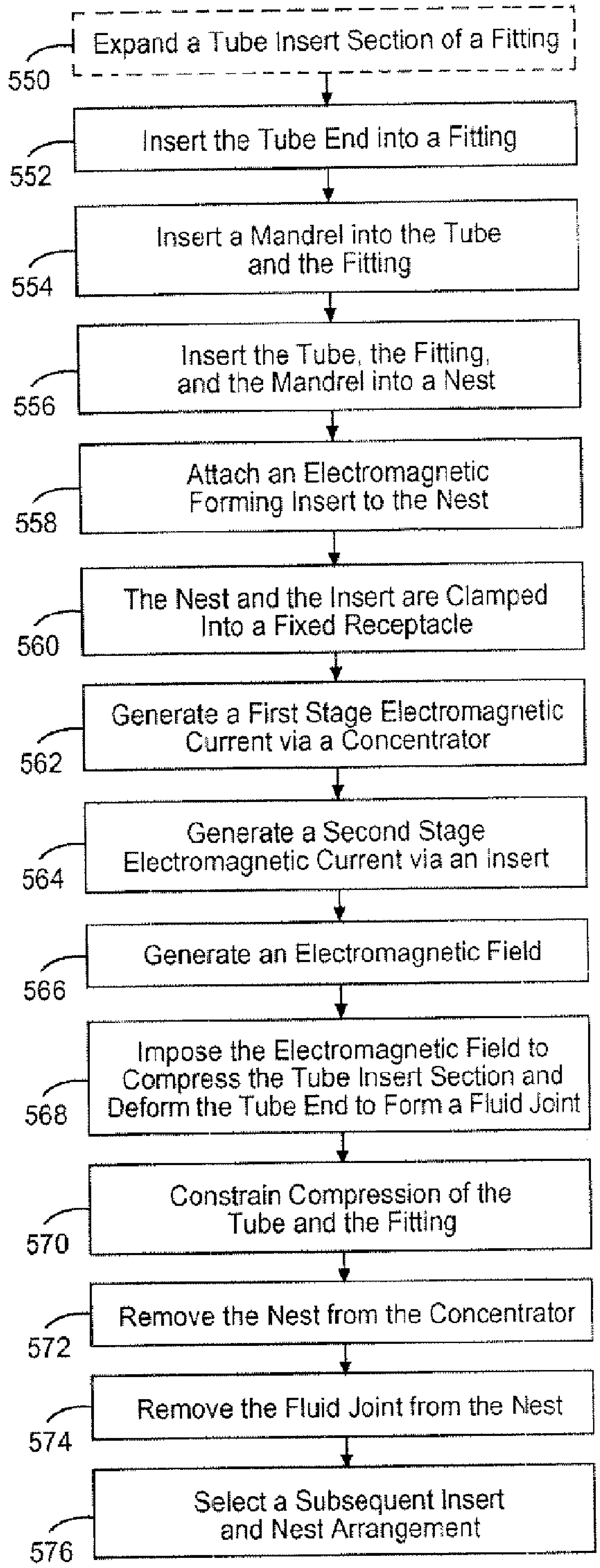

Expand a Tube Insert Section of a Fitting
550
Insert the Tube End into a Fitting
552
Insert a Mandrel into the Tube and the Fitting
554
Insert the Tube, the Fitting, and the Mandrel into a Nest
556
Attach an Electromagnetic Forming Insert to the Nest
558
The Nest and the Insert are Clamped Into a Fixed Receptacle
560
Generate a First Stage Electromagnetic Current via a Concentrator
562
Generate a Second Stage Electromagnetic Current via an Insert
564
Generate an Electromagnetic Field
566
Impose the Electromagnetic Field to Compress the Tube Insert Section and Deform the Tube End to Form a Fluid Joint
568
Constrain Compression of the Tube and the Fitting
570
Remove the Nest from the Concentrator
572
Remove the Fluid Joint from the Nest
574
Select a Subsequent Insert and Nest Arrangement
576

FIG.12

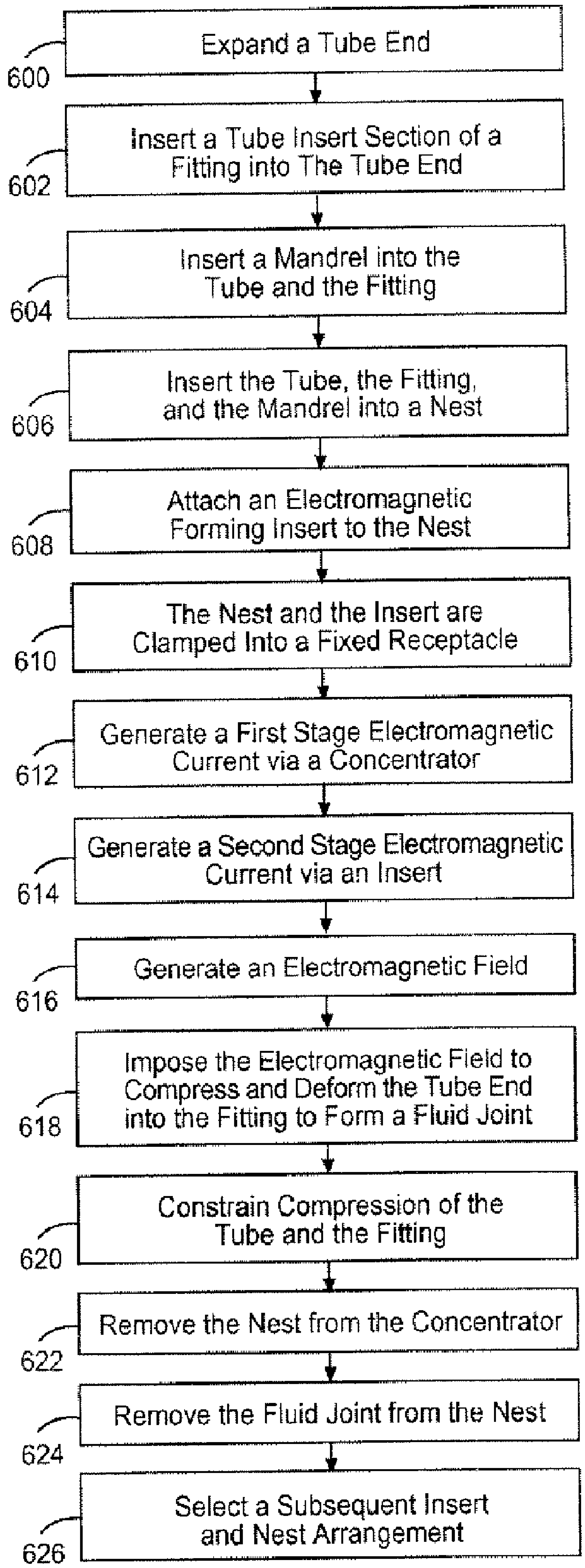

600
Expand a Tube End
602
Insert a Tube Insert Section of a Fitting into The Tube End
604
Insert a Mandrel into the Tube and the Fitting
606
Insert the Tube, the Fitting, and the Mandrel into a Nest
608
Attach an Electromagnetic Forming Insert to the Nest
610
The Nest and the Insert are Clamped Into a Fixed Receptacle
612
Generate a First Stage Electromagnetic Current via a Concentrator
614
Generate a Second Stage Electromagnetic Current via an Insert
616
Generate an Electromagnetic Field
618
Impose the Electromagnetic Field to Compress and Deform the Tube End into the Fitting to Form a Fluid Joint
620
Constrain Compression of the Tube and the Fitting
622
Remove the Nest from the Concentrator
624
Remove the Fluid Joint from the Nest
626
Select a Subsequent Insert and Nest Arrangement

FIG. 13

ELECTROMAGNETIC PULSE WELDING OF FLUID JOINTS

RELATED APPLICATION

[0001] The present invention is related to U.S. Patent Application (Attorney Docket Numbers 03-0722) entitled "Magnetic Field Concentrator for Electromagnetic Forming and Magnetic Pulse Welding of Fluid Joints", U.S. Patent Application (Attorney Docket Numbers 04-1054/04-1055/90-79) entitled "Electromagnetic Mechanical Pulse Forming of Fluid Joints for Low-Pressure Applications", and U.S. Patent Application (Attorney Docket Number 04-0791) entitled "Electromagnetic Mechanical Pulse Forming of Fluid Joints for High-Pressure Applications", which are incorporated by reference herein.

TECHNICAL FIELD

[0002] The present invention generally relates to the solid state coupling of metallic tubes and fittings. More specifically, the present invention is related to a metallurgical coupling of the tubes and the fittings using magnetic interaction.

BACKGROUND ART

[0003] Metallic tubes are commonly used to carry fluid in the form of gas or liquid throughout various fluid circuits in many industries. This is especially true in the aerospace industry, due to the lightweight and strong mechanical features of the metallic tubes. For example, thin-walled aluminum and stainless steel tubing is often utilized within an aircraft to carry oxygen and hydraulic fluid for various applications, such as to breathing apparatuses and to and from vehicle brakes.

[0004] The fluid circuits typically contain a vast number of interlock joints, which reside between the tubing and the end fittings, such as ferrules. The current technique used to join the different sized tubes and ferrules, is referred to as a roller swaging process. During this process, a tube is inserted into a ferrule while the ferrule is constrained using a clamp. The tube is then expanded into the ferrule using a roller. The inner walls of the ferrule typically contain grooves within which the tube is expanded. An interlock is created between the tube and the ferrule due to the expansion and deformation of the tube against the inner walls and into the grooves of the ferrule.

[0005] Another technique that is commonly used to join metallic tubes to end fittings is referred to as Gas Tungsten Arc Welding (GTAW), which is a fusion welding process. The formed joints produced from fusion welding are often rejected by penetrant inspection, pressure testing, or by radiographic inspection and must be weld repaired. A weld formed joint may need to be repaired as many as three times, at significant costs.

[0006] A desire exists to increase the operating lifetime of a mechanical or fluid tight joint. Thus, there exists a need for an improved leak tight joint between a tube and a ferrule and a technique for forming the leak tight joint that may be applied to various fluid circuit applications. It is desirable that the improved technique be economical, have an associated quick production set-up time, and account for different sized tube and ferrule combinations.

SUMMARY OF THE INVENTION

[0007] The present invention satisfies the above-stated desires and provides a leak tight joint utilizing magnetic interactions to form a metallurgically formed tube/fitting mesh.

[0008] One embodiment of the present invention provides a metallurgically formed fluid circuit joint that includes a hollow fitting, a tubular conduit, and a metallurgically formed tube/fitting mesh. The tube/fitting mesh includes a fitting portion of the hollow fitting and a tube portion of the tubular conduit that is electromagnetically formed with the fitting portion.

[0009] The embodiments of the present invention provide several advantages. One such advantage is the provision of a metallugically formed fitting and tube joint. Metallurgical forming or welding of a fitting and a tube provides a single component tube/fitting joint, wherein wall portions of the tube and the fitting are combined into a single shared welded wall element. The single welded element is leak tight since it is formed by the metallurgical combination of the walls of the tube and of the fitting.

[0010] Furthermore, the present invention provides joint forming techniques with improved repeatability, with quick assembly times, that do not require lubrication to form, and that have low associated scrap rates. The scrap rates, as a result of the joint forming techniques, is approximately zero.

[0011] Other features, benefits and advantages of the present invention will become apparent from the following description of the invention, when viewed in accordance with the attached drawings and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **FIG. 1** is a block diagrammatic view of a magnetic forming system in accordance with an embodiment of the present invention.

[0013] **FIG. 2A** is a cross-sectional side view of a insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with an embodiment of the present invention.

[0014] **FIG. 2B** is a front half cross-sectional view of the insert/nest assembly of **FIG. 2A**.

[0015] **FIG. 3A** is a cross-sectional side view of a insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with another embodiment of the present invention.

[0016] **FIG. 3B** is a front half cross-sectional view of the concentrator/nest assembly of **FIG. 3A**.

[0017] **FIG. 4A** is a cross-sectional side view of a insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with still another embodiment of the present invention.

[0018] **FIG. 4B** is a front half cross-sectional view of the concentrator/nest assembly of **FIG. 4A**.

[0019] **FIG. 5A** is a cross-sectional side view of an insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with another embodiment of the present invention.

[0020] **FIG. 5B** is a front half cross-sectional view of the concentrator/nest assembly of **FIG. 5A**.

[0021] **FIG. 6** is a side cut-away view of a tube/fitting coupling incorporating a tube/fitting joint formed using the assemblies of **FIG. 2A** or 3A.

[0022] **FIG. 7A** is a half-side cross-sectional view of a tube/fitting coupling incorporating a tube/fitting joint prior and subsequent to magnetic formation using the assembly of **FIG. 4A**.

[0023] **FIG. 7B** is a side cut-away view of a tube/fitting coupling incorporating a tube/fitting joint subsequent to magnetic formation using the assembly of **FIG. 4A**.

[0024] **FIG. 7C** is a side cut-away view of a tube-fitting coupling subsequent to metallurgical formation using the assembly of **FIG. 5A**.

[0025] **FIG. 8** is a cross-sectional side view of a sample fluid carrying ferrule in accordance with an embodiment of the present invention.

[0026] **FIG. 9** is a cross-sectional side view of a sample hydraulic fluid carrying ferrule in accordance with an embodiment of the present invention.

[0027] **FIG. 10** is a cross-sectional side view of another sample hydraulic fluid carrying ferrule in accordance with another embodiment of the present invention.

[0028] **FIG. 11** is a first sample method of magnetically forming a fluid joint in accordance with an embodiment of the present invention.

[0029] **FIG. 12** is a second sample method of magnetically forming a fluid joint in accordance with another embodiment of the present invention.

[0030] **FIG. 13** is a third sample method of magnetically forming a fluid joint in accordance with still another embodiment of the present invention.

[0031] **FIG. 14** is a cross-sectional side view of another insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with still another embodiment of the present invention.

DETAILED DESCRIPTION

[0032] In each of the following Figures, the same reference numerals are used to refer to the same components. While the present invention is described with respect to a system for magnetically forming a fluid joint and to the joints formed therefrom, the present invention may be adapted for various applications, such as air, liquid, and fluid applications. The present invention may be applied to both low-pressure applications, i.e. less than approximately 2500 psi, and high-pressure applications of greater than approximately 5000 psi, as well as to applications therebetween. The present invention may be applied to fluid applications in the aerospace, automotive, railway, and nautical or watercraft industries, as well as to other industries where fluid tight joints are utilized.

[0033] In the following description, various operating parameters and components are described for one constructed embodiment. These specific parameters and components are included as examples and are not meant to be limiting.

[0034] Also, in the following description the term “fitting” may refer to a ferrule, a nut, a union, or other fitting known in the art. A fitting may be magnetically formed or magnetically welded to or with a tubular conduit, as is described below.

[0035] Referring now to **FIG. 1**, a block diagrammatic view of a magnetic forming system **10** in accordance with an embodiment of the present invention is shown. The magnetic forming system **10** includes an induction coil **12** that is utilized to magnetically form a fluid joint between fluid carrying tubes and fittings, some examples of fluid joints, fluid carrying tubes, and fittings are shown in **FIGS. 2A-10**.

[0036] In operation, the induction coil **12** receives current generated from a current supply circuit **14** and generates an electromagnetic field, which is utilized to mechanically form and/or weld portions of a tube and a corresponding fitting to form a fluid joint. The current supply circuit **14** may include a capacitor bank **16** and a power source **18**, as shown. A controller **20** is coupled to the capacitor bank **16**, via transmission lines and buses (not shown), and controls charge and discharge thereof via the power source **18**. The induction coil **12** may be coupled to a concentrator **22** and to an electromagnetic forming insert **24** for focusing electrical current within the induction coil **12**. Features of the insert **24** are described in greater detail below. The controller **20** prior to forming a fluid joint may select from various inserts **26**, nests **28**, and mandrels **30**, within a storage unit **32**, that correspond to a particular tube and fitting combination, as will become more apparent in view of the following description. The selected insert and nest are fastened within a fixed electromagnetic forming structure **34** prior to electromagnetic forming of a tube and/or a fitting.

[0037] The concentrator **22** and electromagnetic forming insert **24** are used to adapt a compression coil, such as the induction coil **12**, to a smaller diameter workpiece, having a smaller diameter than the induction coil. The concentrator **22** and the insert **24** concentrate the magnetically exerted pressure to a specific location on a tube and/or a fitting. When the capacitor bank **16** is discharged through the induction coil **12**, the induced current in the magnetic field produces a magnetic pressure on the conductive tube and/or fitting. The amount of discharged power produces a sufficient amount of magnetic compressive or expansive pressure to conform and deform the tube and/or fitting.

[0038] The magnetic forming system **10** may include an interchanging device **36** that is coupled to the controller **20** and to the power source **18**. The inserts **26**, nests **28**, and mandrels **30** may be manually selected or selected via the interchanging device **36** by the controller **20** for a particular fluid joint. The interchanging device **36** may be of various types and styles as known in the art for the selection, replacement, insertion, and coupling of the inserts **26**, nests **28**, and mandrels **30**, as well as various tubes and fittings within the magnetic forming system **10**. The interchanging device **36** may be in the form of an automated manufacturing system and have rails and motors for the selecting, rotating, coupling, inserting, sliding, and removing of inserts, nests, and mandrels during fluid joint production. The interchanging device **36** may be robotic in nature and have mechanical moving arms.

[0039] The controller **20** may be in the form of a control circuit and have switching devices for the control of the power settings utilized. The controller **20** may be microprocessor based such as a computer having a central processing unit, memory (RAM and/or ROM), and associated input and output buses. The controller **20** may be an application-specific integrated circuit or may be formed of other logic devices known in the art. The controller **20** may be a portion of a central main control unit, a control circuit, combined into a single integrated controller, or may be a stand-alone controller as shown.

[**0040**] The inserts **26** are generally toroidally shaped and include constraining inserts **38** and electromagnetic forming inserts **40**. The constraining inserts **38** prevent outward expansion of the fittings and the tubes being formed. The electromagnetic forming inserts **40** are utilized to generate electromagnetic fields to cause the deformation of a tube and/or fitting to form a fluid joint. The electromagnetic inserts **40** may also constrain or limit outward expansion of a tube and/or fitting.

[**0041**] Note that the sizes, materials, and current outputs of the components of the induction coil **12** and of the current supply circuit **14** are different depending upon whether electromagnetic mechanical forming or metallurgical welding is performed. For example, in performing metallurgical welding the size and capacity of the capacitor bank and the size of the induction coil are generally larger than those used to perform electromagnetic mechanical forming, due to the larger amount of energy exerted in metallurgical welding. An exerted energy example is provided below with respect to the embodiment of **FIGS. 2A and 2B**.

[**0042**] The below described embodiments of **FIGS. 2A-5B**, are sample embodiments that may be utilized in the electromagnetic forming of the walls of a fitting and of a tube to form a fluid tight joint.

[**0043**] Referring now to **FIGS. 2A and 2B**, a cross-sectional side view of an insert/nest assembly **50** that may be incorporated into the fixed structure **34** and a front half cross-sectional view of the insert/nest assembly **50** are shown in accordance with an embodiment of the present invention. The insert/nest assembly **50** is attached to the fixed structure **34** via a fixed base **52** and a fixed receptacle **54**. The base **52** is coupled within the fixed structure **34** and the receptacle **54** is coupled within the base **52**. The base **52** and the receptacle **54** may be of similar size and shape as the induction coils and concentrators of the embodiments of **FIGS. 3A-5B**. A removable split constraining insert **56** is axially clamped within the receptacle **54** and is coupled within a removable split nest **58**. The nest **58** holds a ferrule or fitting **60** and tube conduit **62** therein for magnetic forming thereof. An induction coil **64** resides within the tube **62**. The induction coil **64** is used to generate an electromagnetic field to expand and deform the end **66** of the tube **62**, such that a mechanically formed or metallurgically welded joint may be formed between the fitting **60** and the end **66**.

[**0044**] A separation gap G_1 exists between the tube **62** and the induction coil **64** for assembly clearance. A fly distance gap G_2 resides between the fitting **60** and the tube **62**, which allows for the acceleration of the material in the end **66** to be accelerated towards the fitting **60**. In one sample embodiment the gaps G_1 and $G_2$are approximately 0.05 inches in width.

[**0045**] The induction coil **64** has one or more coils **68** and may be of various sizes, shapes, and strengths and may be formed of various materials. For mechanical deformation of the end **66**, the induction coil **64** may generate a current pulse having approximately 2 kJ of energy. Of course, other current pulses having other amounts of energy may be utilized depending upon the materials utilized, the sizes of the fittings and the tubes utilized, and other known parameters. For metallurgical welding of the fitting **60** with the end **66**, the induction coil **64** may generate an energy pulse having approximately between 50-100 kJ. In one metallurgical welding embodiment of the present invention, the energy pulse is approximately 80 kJ. The induction coil **64** may have a handle portion **70** with a first step **72** and a second step **74**, which may abut the nest **58** and the fitting **60**, respectively.

[**0046**] The receptacle **54** and the insert **56** may be formed of various materials that allow for the outward constraining of the fitting **60** and the tube **62**. The receptacle **54** and the insert **56** may be formed of stainless steel and are used to prevent or limit the outward expansion of the fitting **60** and the tube **62**. The receptacle **54** includes a tapered inner surface **76** that corresponds with a tapered outer surface **78** of the insert **56**, which allow for the clamping and proper securing of the insert **56** within the receptacle **54**. Although the insert **60** is shown as having a tapered surface **76**, which is axially clamped within the receptacle **54**, the insert **60** may be coupled to the receptacle **54** utilizing other known coupling techniques. The axial clamping force applied to the insert **56** is represented by arrows **80**.

[**0047**] The nest **58** may be of various sizes, shapes, and styles, and may be formed of various non-metallic materials. In one embodiment, the nest **58** is formed of plastic. The nest **58** holds the fitting **60** and the tube **62** in alignment. The nest **58** also holds the induction coil **64** in place for proper alignment with the fitting **60** and the tube **62**.

[**0048**] The insert **56** also includes tapered sides **82** and **84** that correspond with an insert-angled channel **86** of the nest **58**. The tapered sides **82** and **84** converge towards a centerline **88** of the nest **58**. As the insert **56** is clamped into the receptacle **54**, inward force is exerted on the walls **90** of the nest **58**, which holds the upper half **92** and the lower half **94** of the nest **58** in place relative to each other. The left side **87** and the right side **89** of the nest **58** may be coupled to each other via fasteners extending therethrough in a circular pattern or via some other technique known in the art. The receptacle **54** and the insert **56** may be integrally formed as a single unit.

[**0049**] The fitting **60** and the tube **62** may be formed of various metallic materials, such as aluminum, stainless steel, and titanium. The fitting **60** includes grooves **100**, in a tube inlay section **101**, in which the wall **102** of the tube **62** is deformed therein. This deformation into the grooves **100** provides a non-sealant based fluid tight seal. Although a non-sealant based fluid tight seal may be formed as suggested, sealants known in the art may be utilized, for example, an O-ring or an adhesive may be utilized between the fitting **60** and the tube **62**. The tube end **66** may abut the fitting **60** at the inner step or tube-butting edge **104** of the fitting **60**. The tube **62** is shown having a nut **106** for coupling to a union. The threads **108** of the nut **106** may reside on an internal surface **110** of the nut **106**, as shown, or may reside on an external surface, as shown in **FIG. 4A**.

[**0050**] The insert **56** and nest **58** are split to provide ease in set-up and disassembling of the insert/nest assembly **50**.

The insert **56** includes an insert upper half **112** and an insert lower half **114**. The nest **58**, as stated above, includes the nest upper half **92** and the nest lower half **94**. A gap G_3 resides between the upper halves **92** and **112** and the lower halves **94** and **114** for magnetic reaction.

[0051] Referring now to **FIGS. 3A and 3B**, a cross-sectional side view of a insert/nest assembly **130** that may be incorporated into the fixed structure **34** and a front half cross-sectional view of the insert/nest assembly **130** are shown in accordance with another embodiment of the present invention. The insert/nest assembly **130** is coupled within a permanent or fixed concentrator **132**, which in turn is coupled within a permanent or fixed induction coil **134**. The insert/nest assembly **130** includes an electromagnetic forming insert **136** that resides within the concentrator **132**. An inward constraining mandrel **138** resides within the fitting **140** and the tube **142**.

[0052] A gap G_3' resides between the upper halves **157** and **164** and the lower halves **159** and **166** for magnetic reaction. An assembly clearance gap G_4 resides between the insert **136** and the tube end **143**. A fly distance gap G_5 resides between the fitting **140** and the tube **142**, which allows for the material in the expanded portion **144** to be accelerated towards the tube **142**.

[0053] In operation, current within the induction coil **134** is focused by the concentrator **132** and the insert **136** to generate an electromagnetic field, which is imposed on the fitting **140**. The expanded portion **144** of the exterior wall **146** of the fitting **140** is compressed and accelerated towards the tube **142**. The mandrel **138** limits the inward displacement of the fitting and the tube **142**.

[0054] The concentrator **132** and the insert **136** may be formed of beryllium copper BeCu or the like. The concentrator **132** also has a tapered inner surface **148** that corresponds with a tapered outer surface **150** of the insert **136**. The tapered surfaces **148** and **150** and the coupling therebetween allow for the clamping and the proper securing of the insert **136** within the concentrator **132**. The tapered surfaces **148** and **150** assure a solid contact between the concentrator **132** and the insert **136**, such that there is no arcing therebetween and also provides for proper operation of the associated magnetic forming system. The concentrator **132** and the insert **136** may be integrally formed as a single unit.

[0055] Like the insert **56**, the insert **136** also includes tapered sides **152** and **154** that correspond with an insert-angled channel **156** of the nest **158**. The tapered sides **152** and **154** converge towards a centerline **160** of the nest **158**. As the insert **136** is clamped into the concentrator **132**, inward force is exerted on the walls **162** of the nest **158**, which holds the upper and lower halves **164** and **166** of the nest **158** in place relative to each other. The insert **136** includes an insert upper half **157** and an insert lower half **159**.

[0056] The mandrel **138** has a handle portion **170** and an insert portion **172** with a step **174** therebetween. The insert portion **172** may be slightly tapered, although not shown, and is inserted within the fitting **140** and the tube **142**. The outer edges **176** of the insert portion **172**, when tapered, are tapered inward towards the centerline **160** away from the handle portion **170**. The mandrel **138** may abut the nest **158** or the fitting **140** via the first step **178** or the second step **174**, respectively. The mandrel **138** may, as an example, be formed of stainless steel and plastic.

[0057] Referring now to **FIGS. 4A and 4B**, a cross-sectional side view of a insert/nest assembly **200** that may be incorporated into the fixed structure **34** and a front half cross-sectional view of the insert/nest assembly **200** are shown in accordance with still another embodiment of the present invention. The configuration of the insert/nest assembly **200** is similar to that of the insert/nest assembly **130**. However, in the example embodiment of **FIGS. 4A and 4B** a tube **202** having an expanded end **204** is compressed onto a fitting **206**, as opposed to a fitting being compressed onto a tube. Fitting features are described with respect to the embodiments of **FIGS. 8-10**. Thus, the electromagnetic forming insert **208** has a different shape than the insert **136** to accommodate for this difference in the tube/fitting relationship.

[0058] An assembly clearance gap G_6 resides between the tube **202** and the insert **208**. A fly distance gap G_7 resides between the tube **202** and the fitting **206**, respectively, which allows for the acceleration of the material in the expanded end **204** to be accelerated towards the fitting **206**.

[0059] Note that the nut **210** on the tube **202** has threads **212** on an exterior side **214** as opposed to an interior side, as with the nut **106**. There is no correlation between the overlap relationship of the fitting **206** and the tube **202** and the location of the threads **212**. The threads **212** are shown on the exterior side **214** to illustrate another possible embodiment and another example as to the different internal shape of a nest. The nest **216** is shaped to accommodate the insert **208** and the nut **210**.

[0060] Referring now to **FIGS. 5A and 5B**, a cross-sectional side view of an insert/nest assembly **230** that may be incorporated into the fixed structure **34** and a front half cross-sectional view of the insert/nest assembly **230** are shown in accordance with another embodiment of the present invention. In operation, the insert/nest assembly is used to metallurgically combine the tube wall portion **231** and the fitting wall portion **233** to form a tube/fitting mesh, as shown in **FIG. 7C**.

[0061] The embodiment of **FIGS. 5A and 5B** is similar to that of **FIGS. 4A and 4B**. However, the fitting **232** does not include grooves. Although metallurgical welding may be applied to any of the configurations of **FIGS. 2A-5B**, **FIG. 5A and 5B** illustrate that since the walls of a fitting and of a tube are metallurgically combined, that fittings and tubes without grooves may be utilized in the metallurgical welding process to form fluid tight joints.

[0062] The fittings **140**, **206** and **232** and the tubes **142**, **202**, and **234** may be formed of similar materials as the fitting **60** and the tubes **62**.

[0063] Referring now to **FIG. 6**, a side cut-away view of a tube/fitting coupling **240** is shown, incorporating a tube/fitting fluid joint **242** formed using one of the insert/nest assemblies **50** and **130**. The fluid joint **242** is a non-sealant based fluid tight seal, as well as other fluid joints herein described. The tube/fitting coupling **240** includes a first tube **244** having a union **246** residing thereon and a second tube **248** having a nut **250**. In connecting the first tube **244** to the second tube **248** the nut **250** is threaded onto the union **246**. The tip **252** of the union **246** is pressed into the ferrule **254** due to the coupling between the nut **250** and the ferrule **254** and the threading of the nut **250** onto the union **246**. The nut **250** includes a ferrule-chamfered surface **256** that corresponds with a middle tapered exterior surface **258** of the ferrule **254**. As the nut **250** is threaded onto the union **246** the nut **250** pulls the union **246** into the ferrule **254**.

[0064] The union **246** may include grooves **260** on an interior surface **262**. A first end **264** of the first tube **244** may be expanded and formed into the grooves **260** using a magnetic forming or magnetic welding process as described herein. The ferrule **254** resides between the nut **250** and the union **246** and is coupled to the second tube **248** via a magnetic forming or magnetic welding process of the present invention, such as that described in the embodiments of **FIGS. 2A-3B**.

[0065] The ferrule **254** includes a union chamfered surface **264** in which the tapered tip **252** resides when coupled to the ferrule **254**. The ferrule **254** also includes multiple grooves **266** on an interior side **268** for forming of the second tube **248** therein.

[0066] Referring now to **FIGS. 7A and 7B**, a half-side cross-sectional view of a tube/fitting coupling **270** is shown prior and subsequent to magnetic formation using the assembly of **FIG. 4A**, along with a side cut-away view of the tube/fitting coupling **270** subsequent to magnetic formation.

[0067] The tube/fitting coupling **270** includes a first tube **292** and a second tube **274**. The second tube **274** is coupled to a fitting **272** via a fluid tight joint **276** therebetween. The fitting **272** includes multiple grooves **278** that are located on an exterior side **280** of the fitting **272** in a tube overlap region **282**. The tube **274** has an end portion **284** that overlaps the fitting **272**. The end portion **284** is expanded prior to being slid over the overlap region **282**. Fly distance gaps G_8 and G_9 exist between the overlap region **282** and the end portion **284**. The fly distance gaps G_8 and G_9 exist between the grooves **278** and the end portion **284** and between the end portion **284** and the ribs **286**, respectively.

[0068] In **FIG. 7A**, the end portion **284** is shown in a first position **288**, representing the end portion **284** prior to magnetic forming, and in a second position **290**, representing the end portion **284** subsequent to magnetic forming. During magnetic forming the end portion **284** is formed into the grooves **278**. The bent sections of the end portion **284** may be referred to as electromagnetic field formed wall deformations. Three such sections **291** are shown.

[0069] In **FIG. 7B**, the tube/fitting coupling **270** is shown illustrating the union coupling between the first tube **292** and the second tube **274**. The tube/fitting coupling **270** includes the first tube **292** and the union **294**, which are similar to the first tube **244** and the union **246**. The first tube **292** and the union **294** are coupled to the second tube **274** and to the ferrule **272**.

[0070] Referring now to **FIG. 7C**, a side cut-away view of a tube/fitting coupling **295** subsequent to metallurgical formation. The tube/fitting coupling **295** includes a tube/fitting mesh **296** that is a metallurgically formed fluid circuit joint, which is in the form of a shared wall section between a tube **297** and a ferrule **298**. The tube/fitting mesh **296** includes materials from wall portions of the tube **297** and the ferrule **298**.

[0071] Although metallurgical welding may be applied to any of the configurations of **FIGS. 2A-4B**, since the walls of the fitting and of the tube are metallurgically combined, a fitting and a tube that do not contain any grooves may be utilized in the metallurgical welding process to form a fluid tight joint.

[0072] The embodiments of **FIGS. 2A-5B** may be applied to low-pressure fluid applications to form the tube/fitting joints of **FIGS. 6-7C**. The tube/fitting joints of **FIGS. 6-7C** when containing thin-walled tubes and/or fittings are capable of withstanding internal fluid pressures of approximately equal to or less than 2500 psi and thus have a fluid pressure rating as such. An example of a thin-walled tube is one in which the thickness of the tube wall is approximately less than 0.1 multiplied by the average radius of the tube.

[0073] Referring now to **FIG. 8**, a cross-sectional side view of a sample fluid-carrying ferrule **300** in accordance with an embodiment of the present invention is shown. The fluid-carrying ferrule **300** includes a wall **302** having a fluid-union coupling region **304** and a tube overlap region **306**. A tube end, not shown, may reside over the overlap region **306** and abut the step **308** of the wall **302**.

[0074] The overlap region **306** includes multiple grooves **310**. Although two grooves are shown having a particular shape and size, any number of grooves, having various sizes and shapes may be utilized, depending upon the application. Each groove **310** provides an additional fluid tight transition for additional leak prevention.

[0075] In the embodiment shown, the overlap region **306** includes a first groove **312** and a second groove **314**. The first groove **312** is slightly wider than the second groove **314**. There is approximately equal distance between the step **308** and the first groove **312** as between the first groove **312** and the second groove **314**. The widths W_1 and W_2 of the grooves **310** may be approximately equal to the separation distances D_1 and D_2 between the step **308** and the grooves **310**.

[0076] The ferrule **300** also includes a chamfered inner surface **316** for coupling to a union, such as unions **246** and **294**. The ferrule **300** further includes, within the overlap region **306** a break edge **318**, which allows for easy insertion into a tubular conduit.

[0077] Referring now to **FIGS. 9 and 10**, cross-sectional side views of sample hydraulic fluid carrying ferrules **330** and **332** are shown in accordance with an embodiment of the present invention. The hydraulic ferrules **330** and **332** include walls **334** and **336** having hydraulic union coupling regions **338** and **340** and tube overlap regions **342** and **344**.

[0078] The hydraulic-coupling regions **338** and **340** are different than that of the air-coupling region **304** to accommodate for the different application. The hydraulic-coupling regions **338** and **340** may include a standard wall section **350**, steps **352**, and arched sections **354**. The steps **352** also include radius edges **359** that are associated with an end of a tubular conduit (not shown).

[0079] The tube overlap regions **342** and **344** are similar to the tube overlap region **306**. The tube overlap regions **342** and **344** may or may not have a break edge.

[0080] In the methods of **FIGS. 11-13**, the material compositions of the tubes and the fittings utilized can affect the ability of the tubes and or the fittings to be deformed. As an example, when it is desired for a fitting to be deformed as opposed to a tube, the material composition of the fitting may be adjusted and/or have less tensile strength than that of the tube to allow for such deformation. The thickness of the tube and fitting walls may also be adjusted to provide various degrees of tensile strength. In addition, the electromagnetic current pulses utilized may also be adjusted to provide the desired deformation in the tube and the fitting.

[0081] Referring now to **FIG. 11**, a first sample method of magnetically forming a fluid joint in accordance with an embodiment of the present invention is shown.

[0082] In step **502**, the current tube is inserted into the current fitting. The tube may be inserted into the fitting manually or through use of the interchanging device **36**. In step **506**, the induction coil is inserted into the current tube.

[0083] In step **508**, inserting the current tube, the current fitting, and the induction coil into a nest. The current tube, the current fitting, and the induction coil are placed on a first half of a selected nest, such as the nest half **92**. The nest may be selected from the nests **28**. The second half of the nest, such as the nest half **94**, is placed over the first half covering the fitting, the tube, and the induction coil.

[0084] In step **510**, an insert, such as one of the constraining inserts **38** or the constraining insert **56**, is attached and/or inserted into the nest.

[0085] In step **512**, the nest and the insert are clamped into a fixed receptacle, such as the receptacle **54**. The insert is press fitted into the receptacle using techniques known in the art.

[0086] In step **514**, a controller, such as the controller **20**, via a capacitor bank and the induction coil generates an electromagnetic field. An electromagnetic current is discharged from the capacitor bank into the induction coil in response to a current pulse signal generated from the controller **20**.

[0087] In step **516**, the induction coil in generating the electromagnetic field imposes the electromagnetic field upon the tube. The electromagnetic field accelerates the end of the tube toward the fitting, thereby expanding the end of the tube within the fitting and deforming the end into the grooves, such as the grooves **100**, of the fitting. The fly distance gap, such as the gap G_2, between the tube and the fitting allow for the acceleration of the tube end. The expansion and deformation of the tube end against the fitting forms a pressure tight fluid joint.

[0088] Electrical current from the capacitor bank is passed through the induction coil, which generates an intense electromagnetic field and creates high magnitude eddy currents in the tube end. The opposing magnetic fields that are directly generated by the induction coil and that are generated by the eddy currents accelerate the tube end towards the fitting. When electromagnetic mechanical forming is performed the tube end is deformed into the grooves of the fitting. When electromagnetic welding is performed the tube end is metallurgically welded with the fitting.

[0089] A high current pulse of short duration, approximately between about 10 and 100 microseconds, is introduced to the coils of the induction coil, which generates the electromagnetic field to instantaneously deform the tube radially outward towards the insert, resulting in the crimping or metallurgical welding of the tube to the fitting to form the fluid joint. The pulse is strong enough to induce magnetic forces above the yield strength of the material in the tube.

[0090] In step **518**, the insert and the receptacle, during electromagnetic forming of the tube, constrain or limit the expansion of the tube and the fitting. Steps **514**-**518** are substantially performed simultaneously.

[0091] In step **520**, upon completion of steps **514**-**518** the current nest is removed from the receptacle containing the fluid joint. In step **522**, the fluid joint is removed from the current nest. The first half and the second half of the current nest are separated to allow for the removal of the fluid joint.

[0092] In step **524**, it is determined whether the current setup and configuration of the current tube and the current fitting is to be reused or replaced. The controller may determine whether to form another tube/fitting coupling using the current insert and nest arrangement or to select a replacement insert and nest. The replacement insert and nest may have different internal dimensions as compared with the current insert and nest and may be selected from the constraining inserts **38** and the nests **28**. The different internal dimensions may correspond to a tube/fitting coupling of different size, to a tube/fitting coupling having a different tube/fitting configuration, to a tube/fitting coupling formed using a different electromagnetic forming or electromagnetic welding technique, or to other known tube/fitting related differences known in the art. Steps **520**-**524** may be performed via the interchanging mechanism **36**. Upon selection of a second or replacement tube, a second or replacement fitting, a replacement insert, and a replacement nest, the controller **20** returns to step **502**.

[0093] Referring now to **FIG. 12**, a second sample method of magnetically forming a fluid joint in accordance with another embodiment of the present invention is shown.

[0094] In step **550**, a tube insert section or portion of a current fitting, such as the portion **144**, may be expanded also via an end-forming device or originally machined with a tapered shape. In step **552**, a tube end of a current tube, such as the tube end **143**, is inserted into the fitting. In step **554**, a temporary mandrel is selected, such as the mandrel **176**, and is inserted into the tube and the fitting. The mandrel is inserted into the tube to prevent excessive tube-wall collapse.

[0095] In step **556**, the tube, the fitting, and the mandrel are inserted into a current nest, such as the nest **166**. The tube, the fitting, and the mandrel are placed on a first half of the nest. The second half of the nest is placed over the first half covering the fitting, the tube, and the mandrel. In step **558**, an insert, such as one of the electromagnetic forming inserts **40** or the electromagnetic forming insert **136**, is attached and/or inserted into the nest.

[0096] In step **560**, the nest and the insert are clamped into a fixed concentrator, such as the concentrator **132**. The insert is press fitted into the concentrator using techniques known in the art.

[0097] In step **562**, the controller **20**, via a capacitor bank and an induction coil, such as the induction coil **134**, generates a first stage electromagnetic current that is passed into the concentrator via coupling between the concentrator and the induction coil. An electromagnetic current is discharged from the capacitor bank into the induction coil, which is then passed into the concentrator. In step **564**, a field concentrator focuses the first stage electromagnetic current to form a second stage electromagnetic current, which is passed into the insert via the coupling between the concentrator and the insert. In step **566**, the insert focuses the second stage electromagnetic current and forms an electromagnetic field.

[0098] In step **568**, the electromagnetic field is imposed upon the exterior of the fitting and accelerates and compresses the tube insert section onto the tube. In accelerating and compressing the fitting onto the tube, the tube end is deformed into the grooves of the fitting. The fly distance gap, between the insert and the tube, such as the gap G_5, allows for the acceleration of the tube insert section of the fitting. The compression of the fitting and the deformation of the tube form a fluid joint. In step **570**, the mandrel constrains or limits the compression of the fitting and the tube during electromagnetic formation. Steps **562-570** are substantially performed simultaneously.

[0099] In step **572**, upon completion of steps **562-570** the current nest is removed from the concentrator containing the fluid joint. In step **574**, the fluid joint is removed from the current nest. The first half and the second half of the current nest are separated to allow for the removal of the fluid joint.

[0100] In step **576**, it is determined whether the current setup and configuration of the current tube and the current fitting is to be reused or replaced, similar to step **524** above. The controller may determine whether to form another tube/fitting coupling using the current insert and nest arrangement or to select a replacement insert and nest. Steps **572-576** may be performed via the interchanging mechanism. Upon selection of a second or replacement tube, a second or replacement fitting, a replacement insert, and a replacement nest, the controller returns to step **550**.

[0101] Referring now to **FIG. 13**, a third sample method of magnetically forming a fluid joint in accordance with still another embodiment of the present invention is shown.

[0102] In step **600**, a current tube end, such as the tube end **204**, is expanded using an end-forming device. In step **602**, a current fitting, such as the fitting **206** or the fitting **272**, is inserted into the tube end. In step **604**, a mandrel, such as the mandrel **138**, is inserted into the tube and the fitting.

[0103] In step **606**, the tube, the fitting, and the mandrel are inserted into a current nest, such as the nest **216**. The tube, the fitting, and the mandrel are placed on a first half of the nest. The second half of the nest is placed over the first half covering the fitting, the tube, and the mandrel.

[0104] In step **608**, an insert, such as one of the electromagnetic forming inserts **40** or the electromagnetic forming insert **208**, is attached and/or inserted into the nest. In step **610**, the nest and the insert are clamped into a fixed concentrator, such as the concentrator **132**. The insert is press fitted into the concentrator using techniques known in the art.

[0105] In step **612**, the controller **20**, via the capacitor bank and the induction coil, such as the induction coil **134**, generates a first stage electromagnetic current that is passed into the concentrator via coupling between the concentrator and the induction coil. An electromagnetic current is discharged from the capacitor bank into the induction coil, which is then passed into the concentrator. In step **614**, the field concentrator focuses the first stage electromagnetic current to form a second stage electromagnetic current, which is passed into the insert via the coupling between the concentrator and the insert. In step **616**, the insert focuses the second stage electromagnetic current and forms an electromagnetic field.

[0106] In step **618**, the electromagnetic field is imposed upon the exterior of the tube and accelerates and compresses the tube end onto the fitting, similar to step **568** above. In accelerating and compressing the tube onto the fitting, the tube end is deformed into the grooves of the fitting. The fly distance gap between the insert and the tube, such as the gap G_7, allows for the acceleration of the tube end. The compression and deformation of the tube end forms a fluid joint. In step **620**, the mandrel constrains or limits the compression of the fitting and the tube during electromagnetic formation. Steps **612-620** are substantially performed simultaneously.

[0107] In step **622**, upon completion of steps **612-620** the current nest is removed from the concentrator containing the fluid joint. In step **624**, the fluid joint is removed from the current nest. The first half and the second half of the current nest are separated to allow for the removal of the fluid joint.

[0108] In step **626**, it is determined whether the current setup and configuration of the current tube and the current fitting is to be reused or replaced, similar to steps **524** and **576** above. The controller may determine whether to form another tube/fitting coupling using the current insert and nest arrangement or to select a replacement insert and nest. Steps **612-626** may be performed via the interchanging mechanism. Upon selection of a second or replacement tube, a second or replacement fitting, a replacement insert, and a replacement nest, the controller returns to step **600**.

[0109] Note that the above methods may be performed without the use of lubrication, which minimizes steps involved and can eliminate the need for cleaning of the fittings, tubes, and fluid tight joints.

[0110] The above-described steps in the methods of **FIGS. 11-13** are meant to be illustrative examples; the steps may be performed sequentially, synchronously, simultaneously, or in a different order depending upon the application.

[0111] Referring now to **FIG. 14**, a cross-sectional side view of another insert/nest assembly that may be incorporated into the system of **FIG. 1** in accordance with still another embodiment of the present invention is shown. The insert/nest assembly **700** utilizes a field shaper **702** as opposed to a concentrator and an insert, as described above. The insert/nest assembly includes a first half (shown) as well as a second half (not shown), which is a mirror image of the first half. The field shaper **702** is coupled to an induction coil **704**. An insulation layer **703** may reside between the field shaper **702** and the induction coil **704**. The induction coil **704** generates an electromagnetic field, which is imposed on the tube **706** via the field shaper **702**. The electromagnetic field accelerates the end **708** of the tube **706** toward the fitting **710**, thereby compressing the end **708** within the grooves **712** of the fitting **710**.

[0112] The field shaper **702** may be formed of materials similar to that of the field concentrators and inserts described above. The cross-section of the field shaper **702** is "I"-shaped. The field shaper includes an outer ring **714** and a main center disc **716** that extends inward toward a tube/fitting forming region **718**. The center disc **716** has a semi-circular opening **720** in the tube/fitting forming region **718**. The field shaper **702** resides within a nest **721**, which has internal dimensions and geometry that correspond to that of the field shaper **702** such that the field shaper **702** is held fixed in place during electromagnetic forming. The nest **721** may be formed of the nest materials stated above, such as plastic.

[0113] A mandrel **722** resides within the nest **721** and includes a stem **724**, which is inserted into the tube **706** and the fitting **710** through the tube/fitting forming region **718**. The stem **724** is coupled to a handle **726**, which resides in a recessed portion **728** of the nest **721**. In one example embodiment, the stem **724** is formed of stainless steel and the handle **726** is formed of plastic.

[0114] The present invention provides fluid tight leak joints with reduced scrap rate. Further, because the insert/nest assemblies are quickly and easily inserted and removed from a fixed structure, a large quantity of tubular joints may be quickly formed. The above stated reduces costs associated with manufacturing down times.

[0115] The present invention reduces manufacturing processing steps as compared to conventional welding and roller swaging or elastomeric processes. The present invention also reduces inspection process steps, cost of production, and provides a highly reproducible manufacturing process to maintain consistent quality.

[0116] While the invention has been described in connection with one or more embodiments, it is to be understood that the specific mechanisms and techniques which have been described are merely illustrative of the principles of the invention, numerous modifications may be made to the methods and apparatus described without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A metallurgically formed fluid circuit joint comprising:

a hollow fitting;

a tubular conduit; and

metallurgically formed tube/fitting mesh comprising;

fitting portion of said hollow fitting; and

tube portion of said tubular conduit electromagnetically formed with said fitting portion.

2. A fluid circuit joint as in claim 1 wherein said tubular conduit is received at least partially within said hollow fitting.

3. A fluid circuit joint as in claim 1 wherein said tubular conduit is received at least partially over said hollow fitting.

4. A fluid circuit joint as in claim 1 wherein said hollow fitting prior to electromagnetic forming comprises a plurality of grooves.

5. A fluid circuit joint as in claim 1 wherein said hollow fitting and said tubular conduit are formed of at least one material selected from stainless steel, aluminum, and titanium.

6. A fluid circuit joint as in claim 1 wherein the hollow fitting prior to electromagnetic forming thereof comprises:

a tube inlay section comprising;

a tube-butting edge associated with an end of said tubular conduit; and

a plurality of internal grooves.

7. A fluid circuit joint as in claim 1 wherein the hollow fitting prior to electromagnetic forming comprises:

a tube overlap region comprising;

an radius edge associated with an end of the tube;

a plurality of grooves; and

a break edge guiding insertion of the fitting into the tube.

8. A magnetic forming system for creating a fluid circuit joint between a tube and a fitting comprising:

an induction coil forming an electromagnetic current; and

a field concentrator assembly electrically coupled to said induction coil and forming a electromagnetic field in response to said electromagnetic current, said field concentrator assembly comprising:

field concentrator focusing said electromagnetic current to form said electromagnetic field; and

nest configured to contain the tube at least partially positioned within the fitting;

aid field concentrator imposing said electromagnetic field on the fitting to metallurgically weld the fitting to the tube to form the fluid circuit joint.

9. A system as in claim 8 wherein said field concentrator imposes said electromagnetic field to compress the fitting on the tube to form the fluid circuit joint.

10. A system as in claim 8 wherein said nest resides at least partially within said field concentrator.

11. A system as in claim 8 further comprising a mandrel residing within the tube and inwardly constraining the tube and the fitting.

12. A system as in claim 8 further comprising:

a controller generating a current pulse signal; and

a current supply circuit generating an energy pulse in response to said current pulse signal;

said induction coil generating said electromagnetic field in response to said current pulse.

13. A system as in claim 8 wherein said field concentrator imposes said electromagnetic field to compress said fitting prior to metallurgical welding thereof.

14. A method as in claim 8 further comprising:

an end-forming device expanding said fitting prior to insertion of said tube into said fitting; and

said field concentrator imposing said electromagnetic field on said fitting to metallurgically weld said fitting with said tube to form said fluid circuit joint.

15. A system as in claim 8 further comprising an insert electrically coupled to said field concentrator and imposing said electromagnetic field on said fitting to form said fluid circuit joint.

16. A system as in claim 15 wherein said field concentrator is external to said nest and said insert is coupled at partially within said nest.

17. A magnetic forming system for creating a fluid circuit joint between a tube and a fitting comprising:

an end former expanding at least a portion of the tube;

an induction coil forming an electromagnetic current; and

a field concentrator assembly electrically coupled to said induction coil and forming a electromagnetic field in response to said electromagnetic current, said field concentrator assembly comprising:

a concentrator focusing said electromagnetic current to form said electromagnetic field; and

a nest configured to contain the fitting at least partially positioned within said portion;

said field concentrator imposing said electromagnetic field on the tube to metallurgically weld the tube to the fitting to form the fluid circuit joint.

18. A system as in claim 17 wherein said field concentrator imposes said electromagnetic field to compress said portion on the fitting to form the fluid circuit joint.

19. A system as in claim 17 wherein the fitting comprises a tube overlap region having at least one groove.

20. A system as in claim 17 wherein the fitting comprises:

a tube overlap region comprising;

a radius edge associated with an end of the tube;

a plurality of grooves; and

a break edge guiding insertion of the fitting into the tube.

21. A system as in claim 17 further comprising a mandrel residing within the fitting and inwardly constraining the tube and the fitting.

22. A system as in claim 17 further comprising:

a controller generating a current pulse signal; and

a current supply circuit generating a current pulse in response to said current pulse signal;

said induction coil generating said electromagnetic field in response to said current pulse.

23. A system as in claim 17 wherein said field concentrator imposes said electromagnetic field to compress said tube prior to metallurgical welding thereof.

24. A system as in claim 17 further comprising an insert electrically coupled to said field concentrator and imposing said electromagnetic field on said tube to form said fluid circuit joint.

25. A system as in claim 24 wherein said field concentrator is external to said nest and said insert is coupled at partially within said nest.

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