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(54) METHODS AND TOOLS FOR FRICTION EXTRUSION OF COMPOSITE EXTRUDATES

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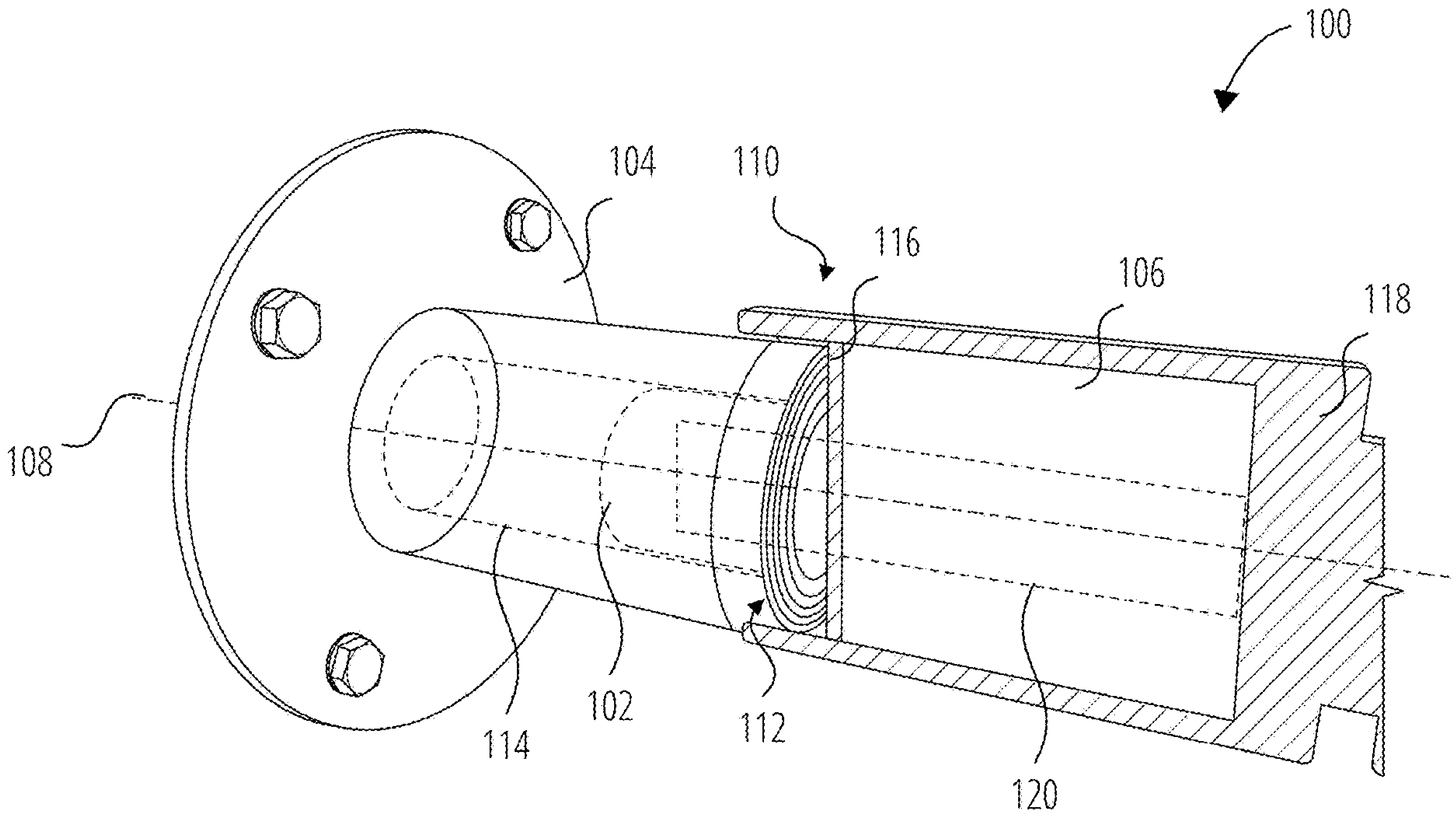
CPC ***B21C 23/04*** (2013.01)

(57) ABSTRACT

A tool assembly for friction extrusion can comprise a friction extrusion die. The friction extrusion die can include a distal face and a proximal end. The distal face can define at least one topographical ridge or groove feature to induce plasticization of a material in response to an axial force and a rotational force applied by the distal face to the material. The friction extrusion die can define a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces. The proximal end can define a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder. The faceted cross-sectional profile can be sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.



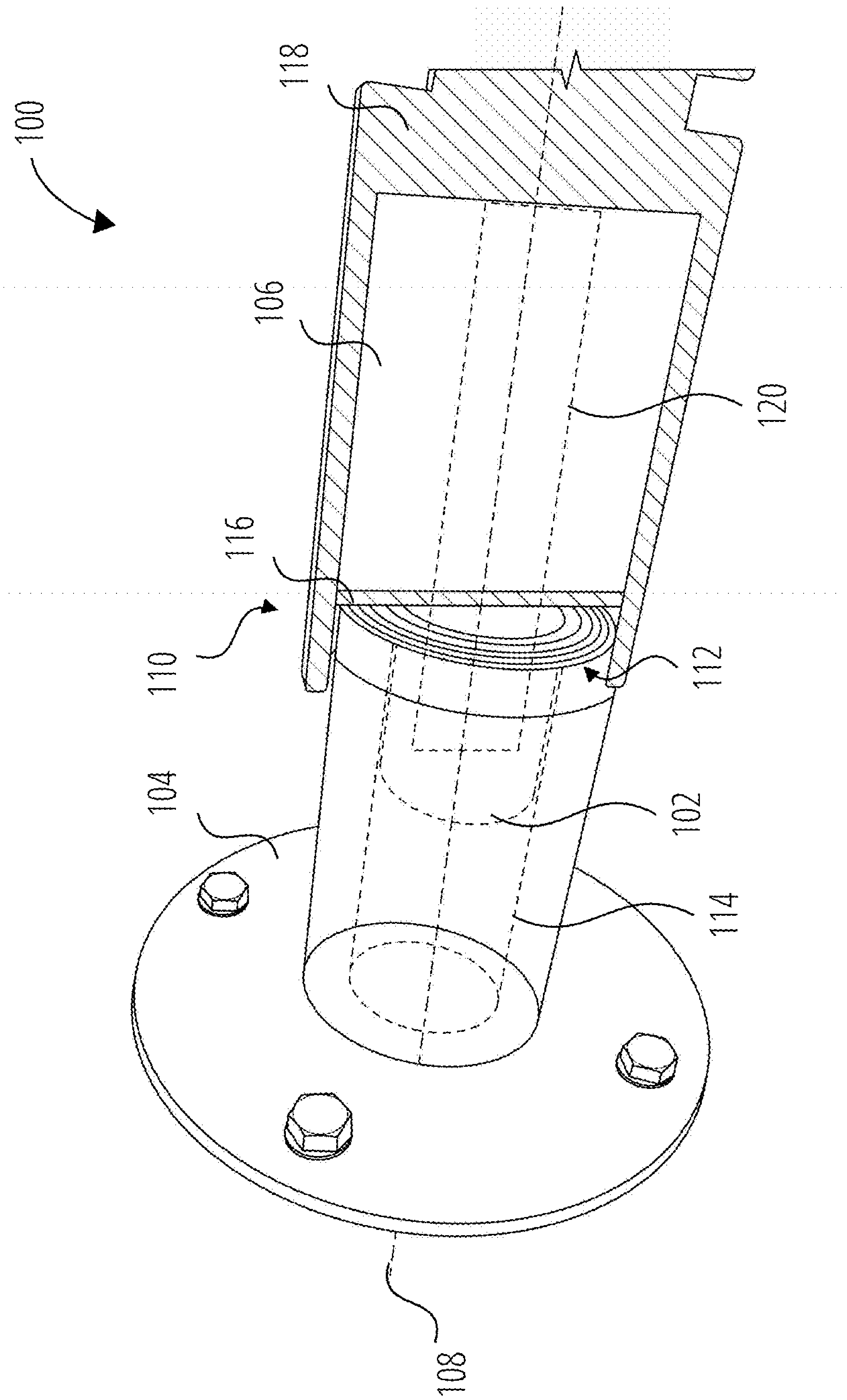


FIG. 1A

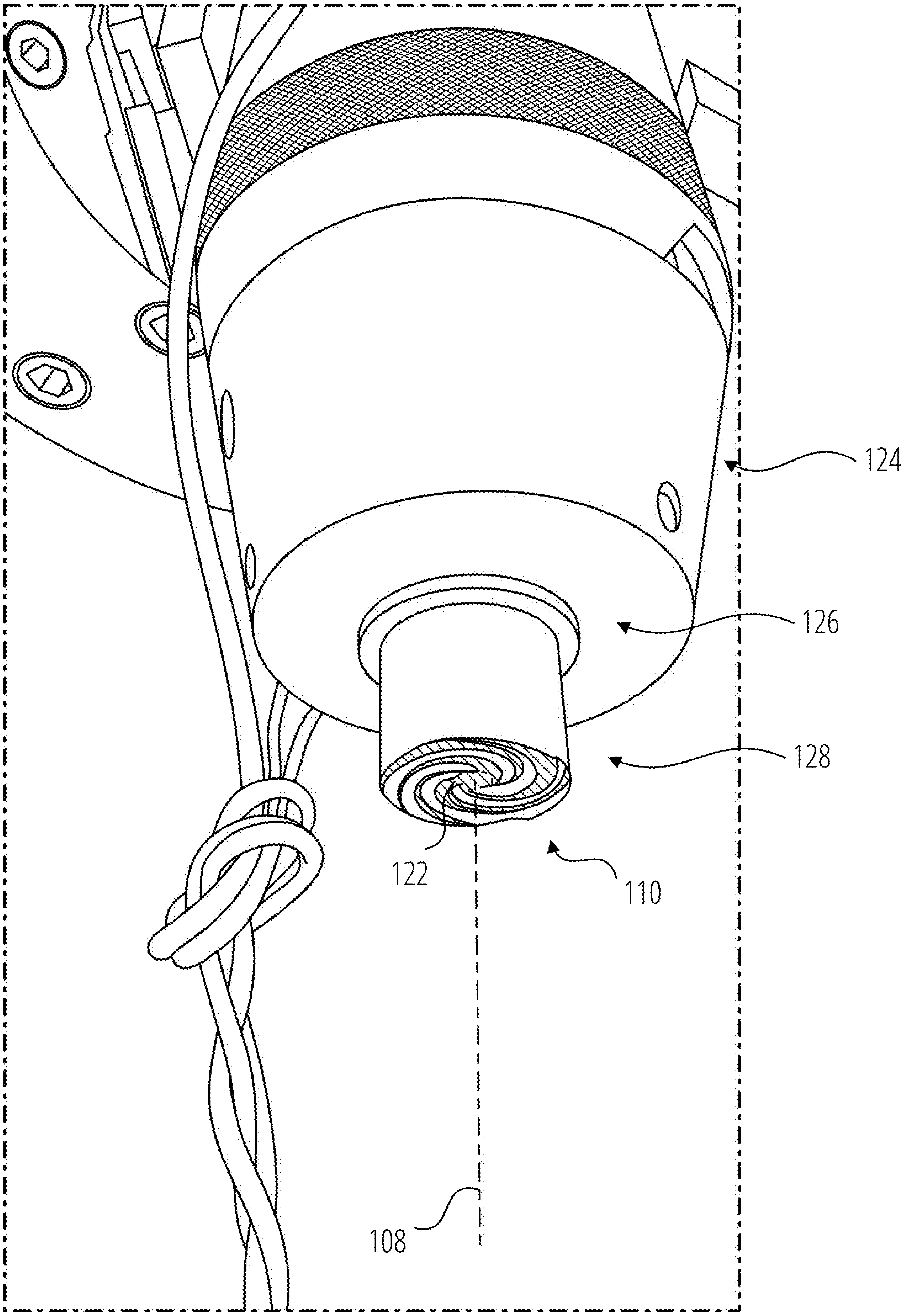


FIG. 1B

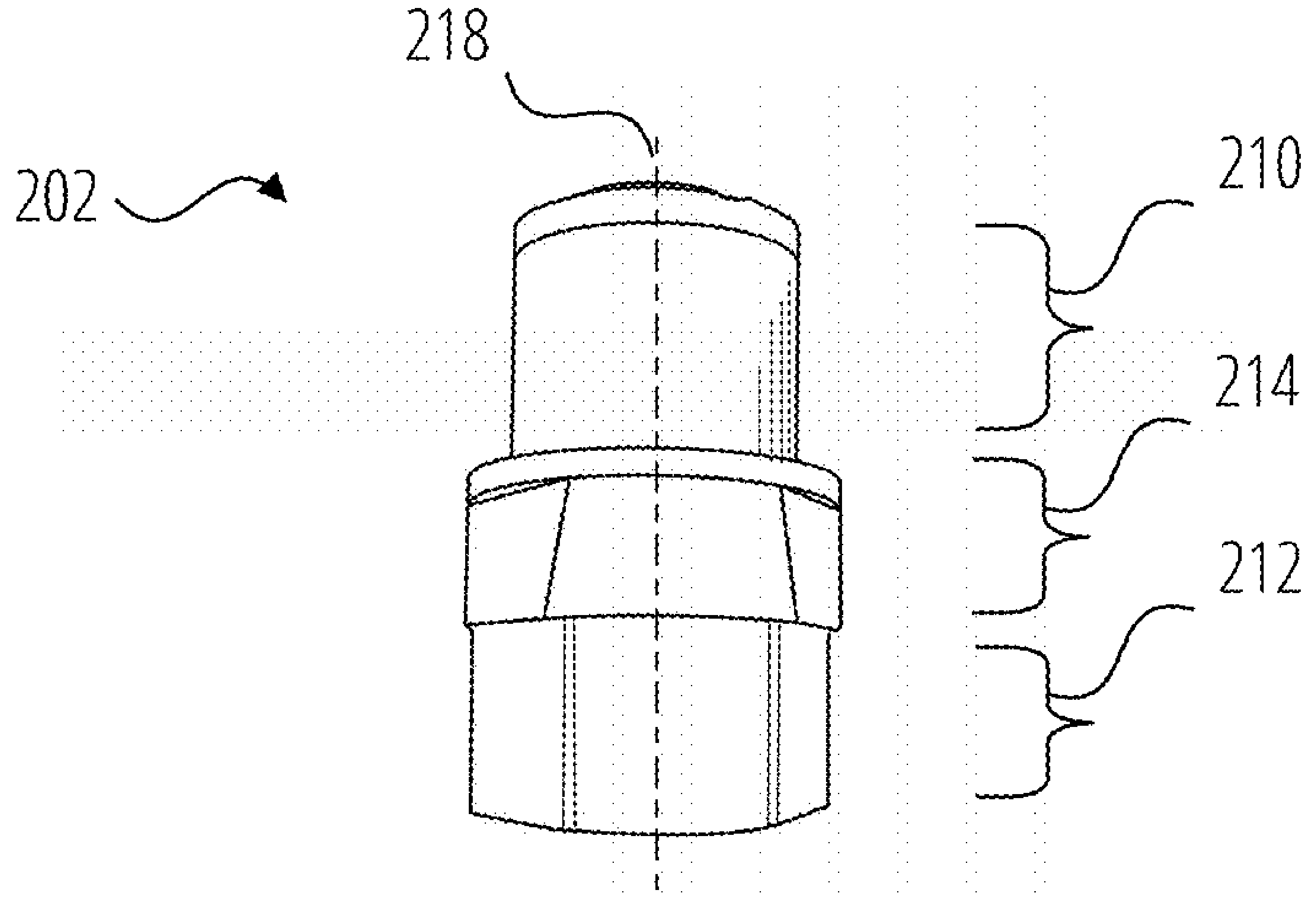


FIG. 2A

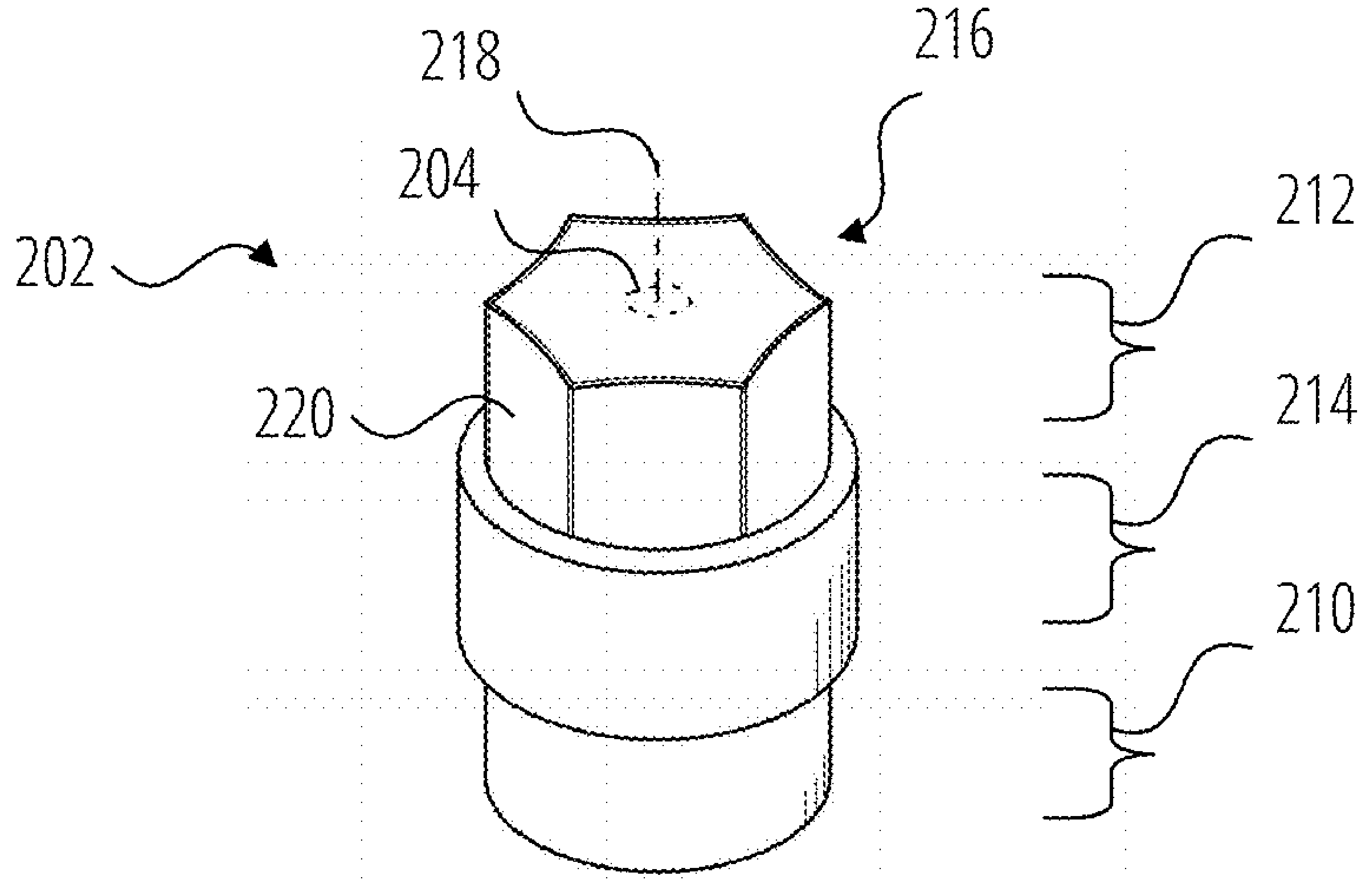


FIG. 2B

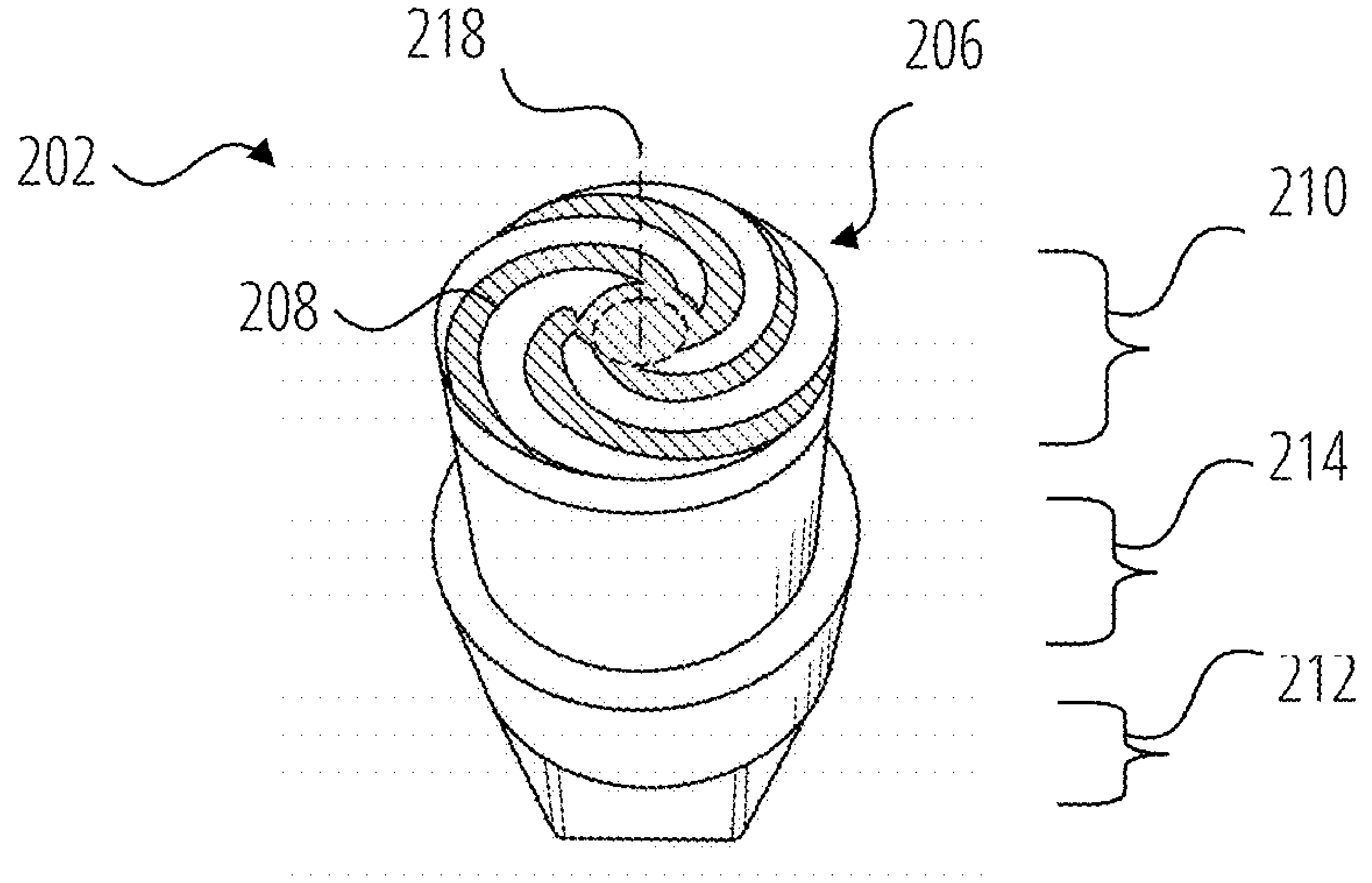


FIG. 2C

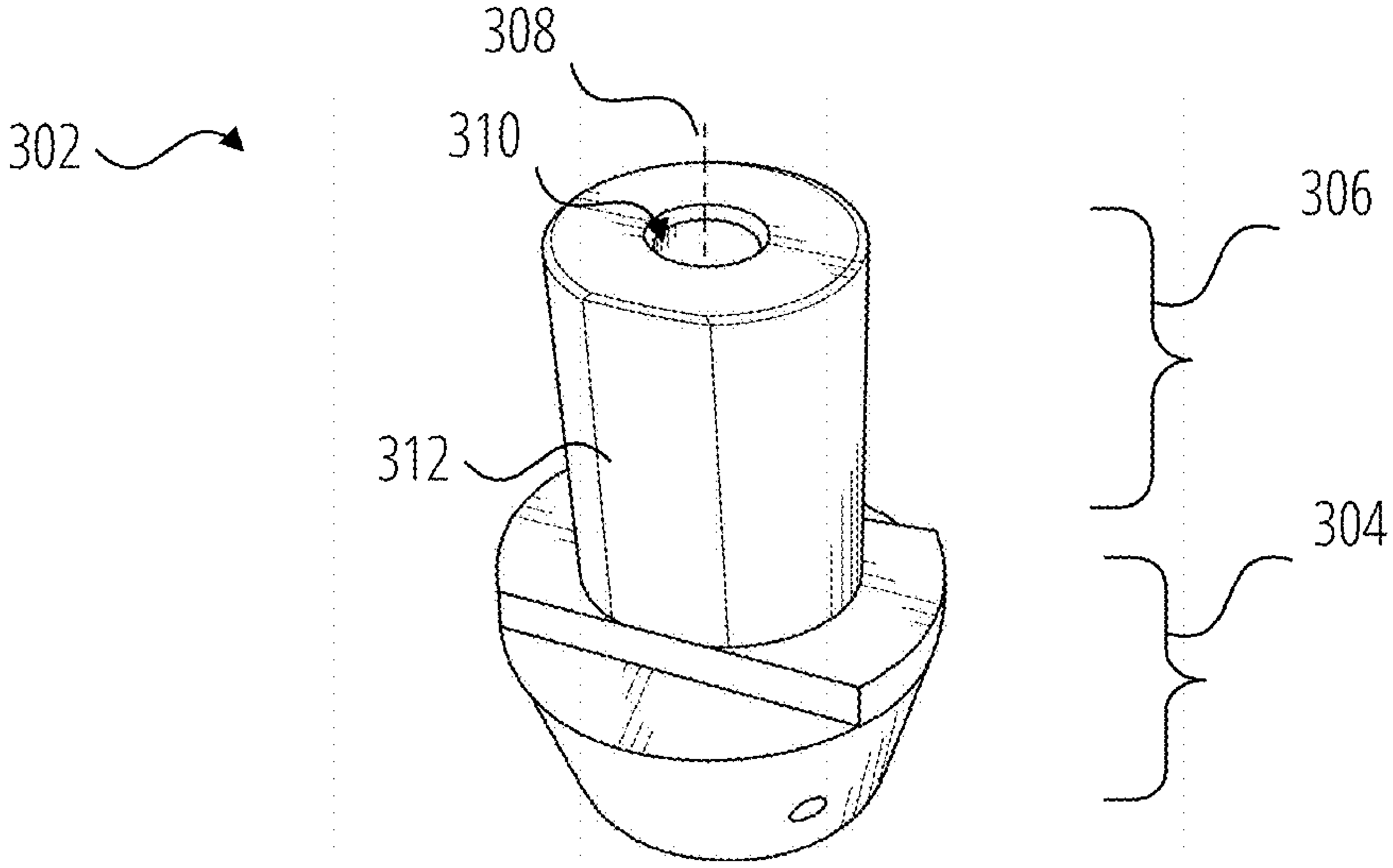


FIG. 3A

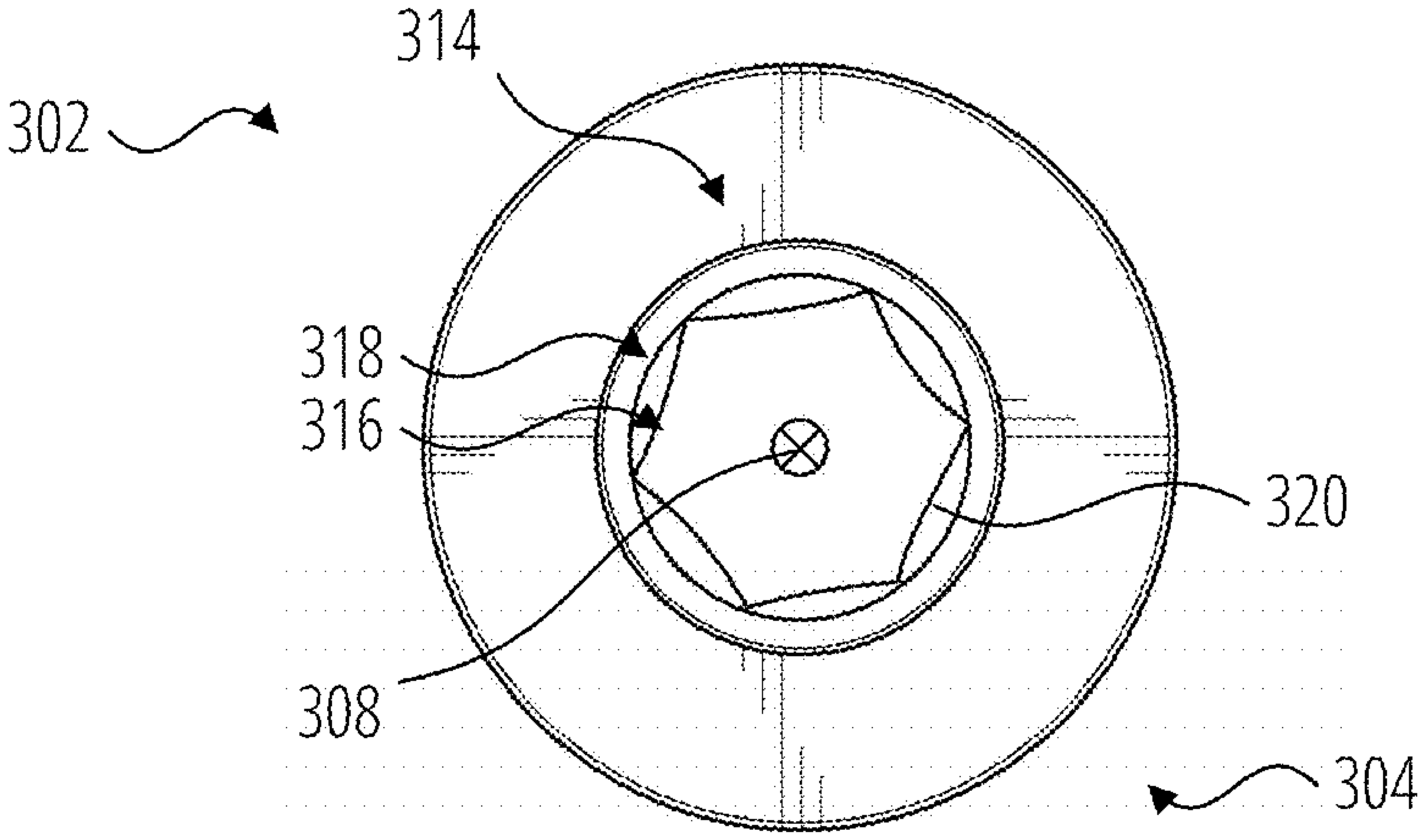


FIG. 3B

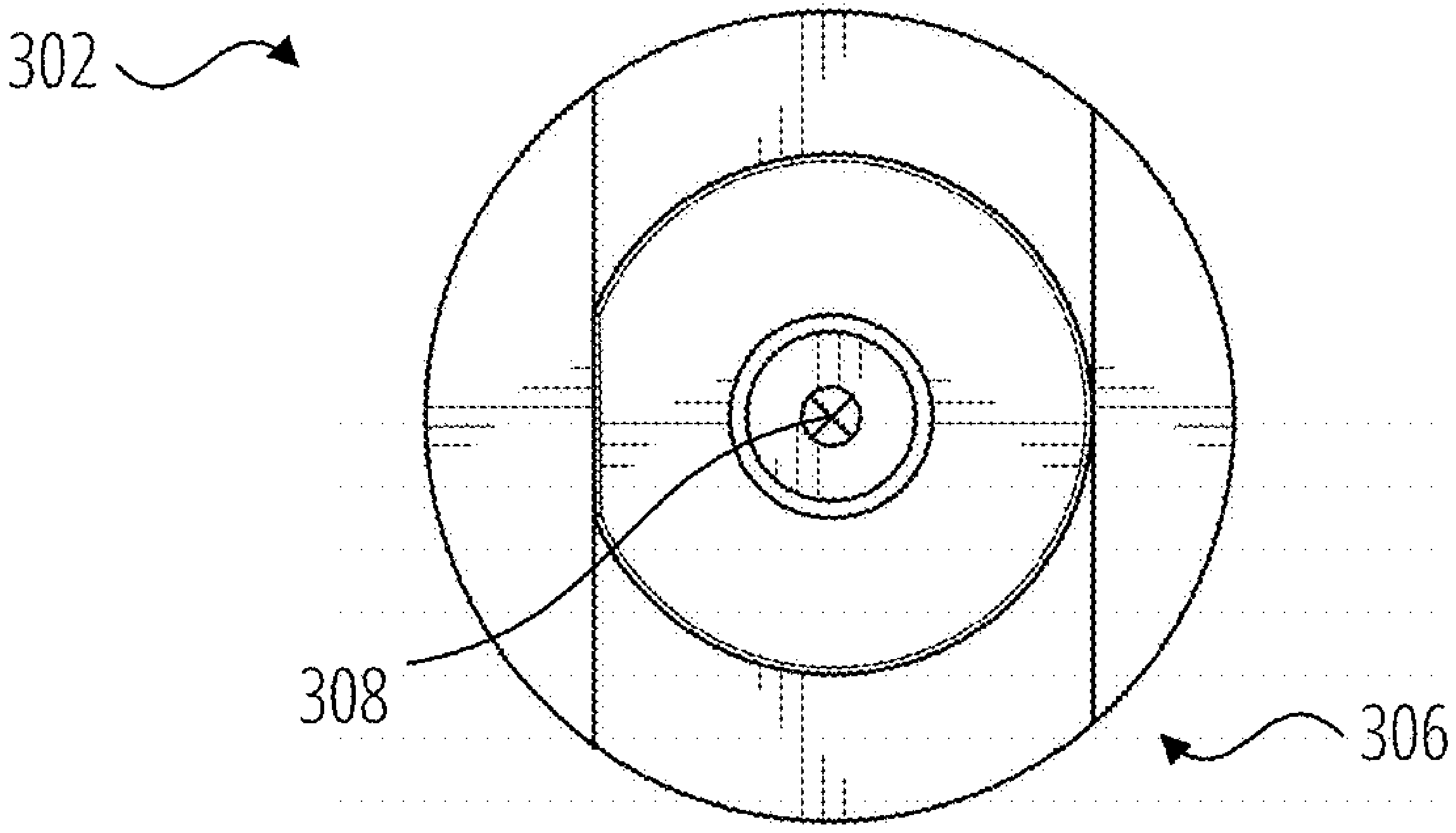


FIG. 3C

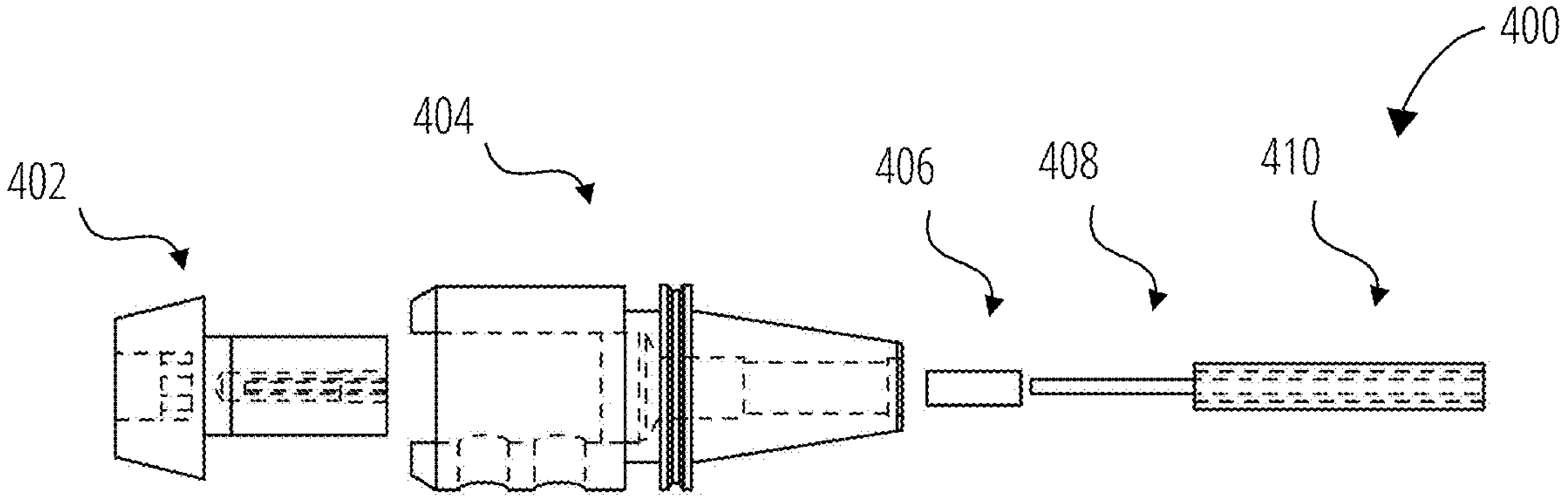


FIG. 4A

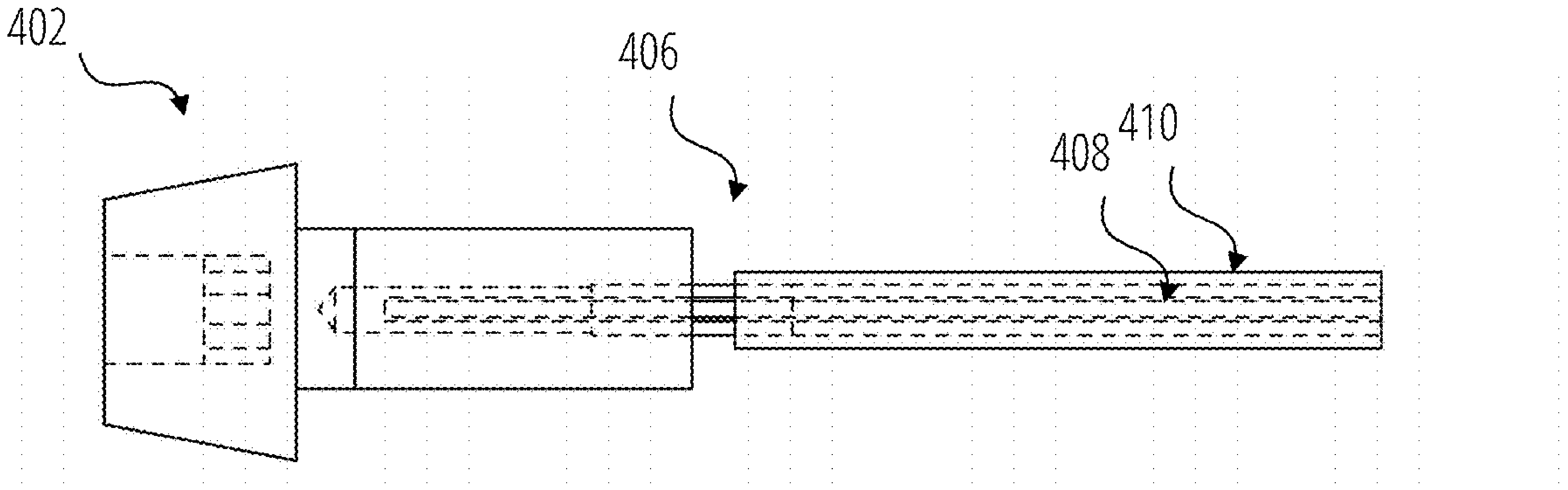


FIG. 4B

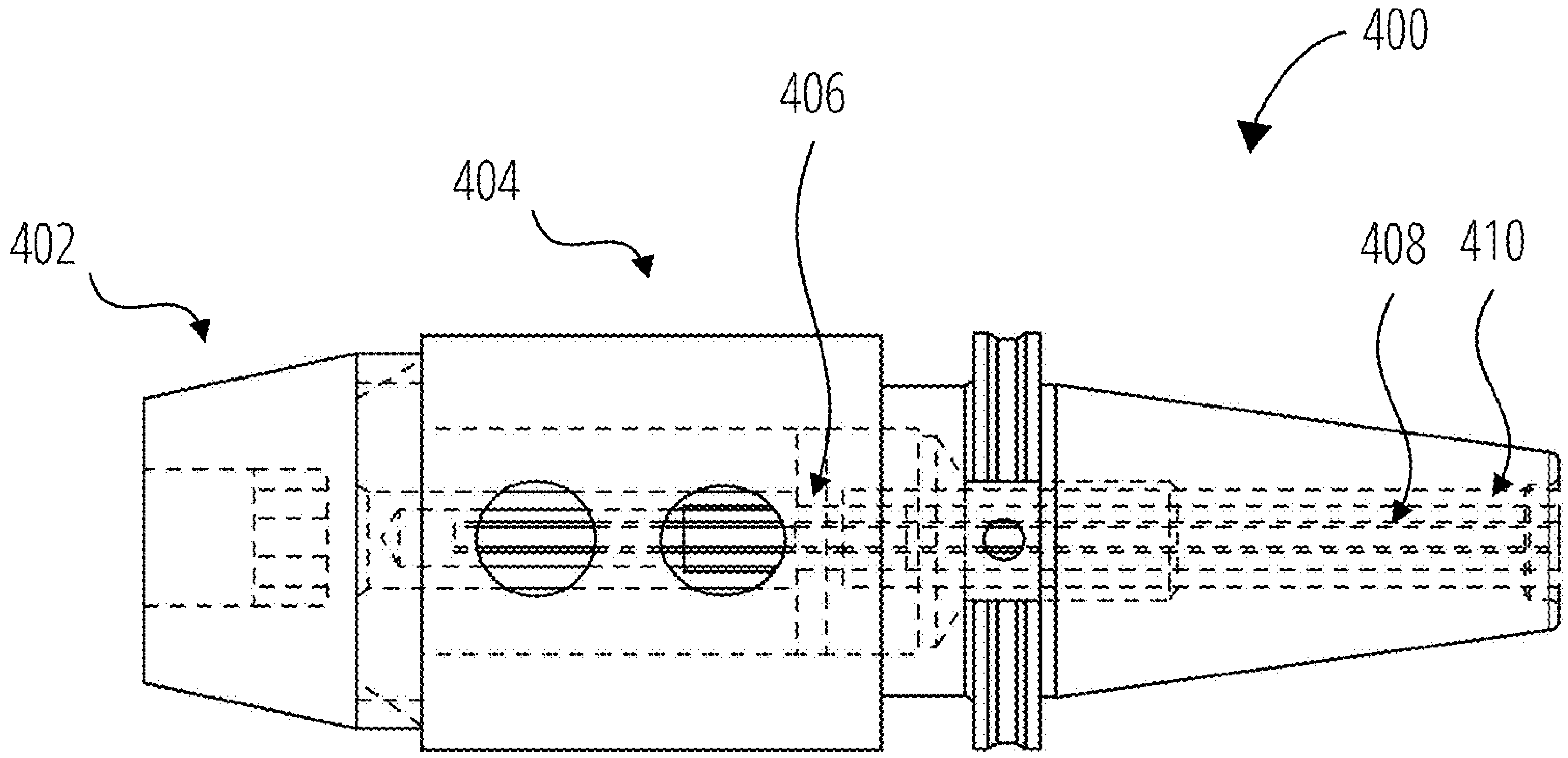


FIG. 4C

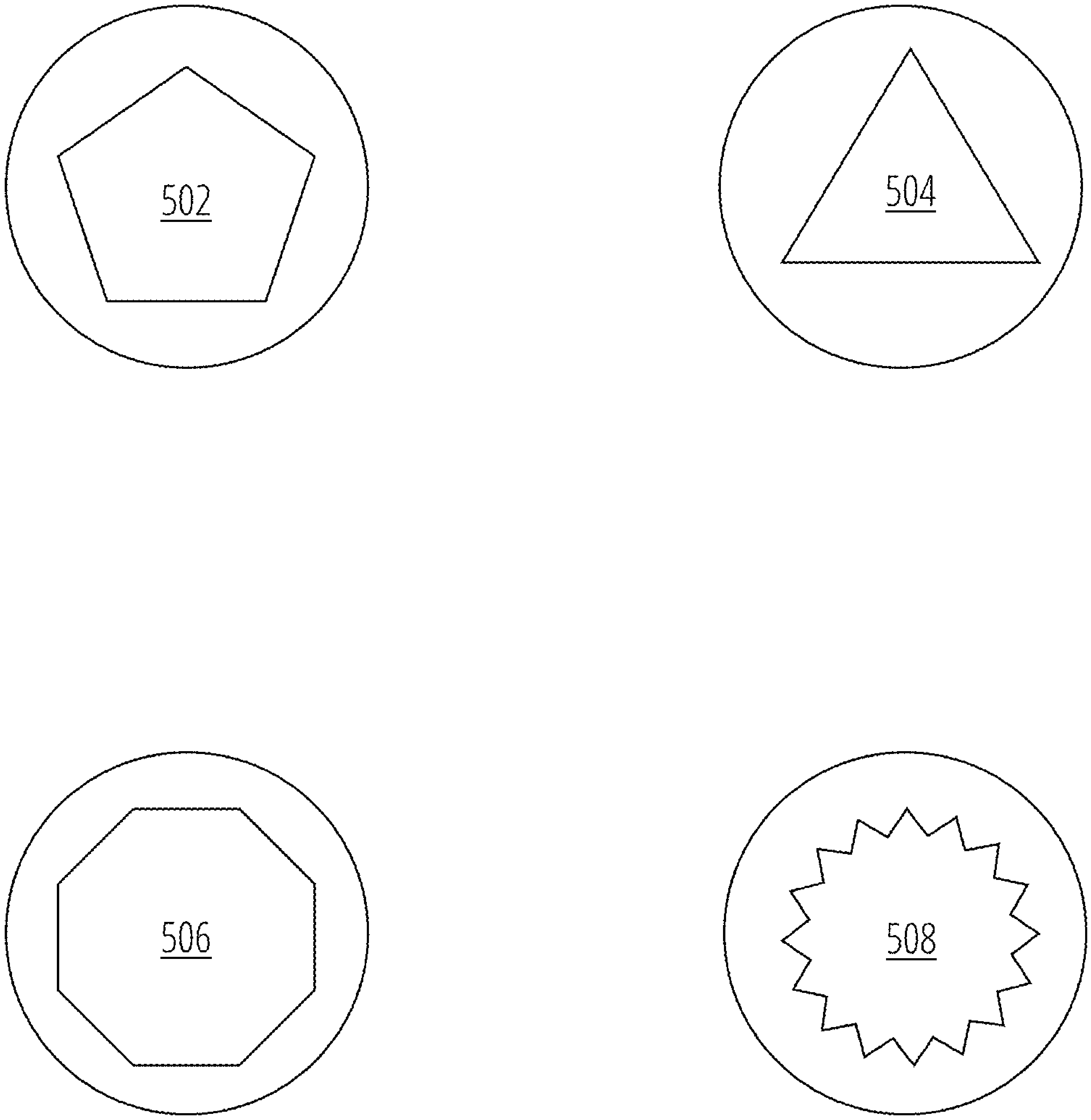


FIG. 5

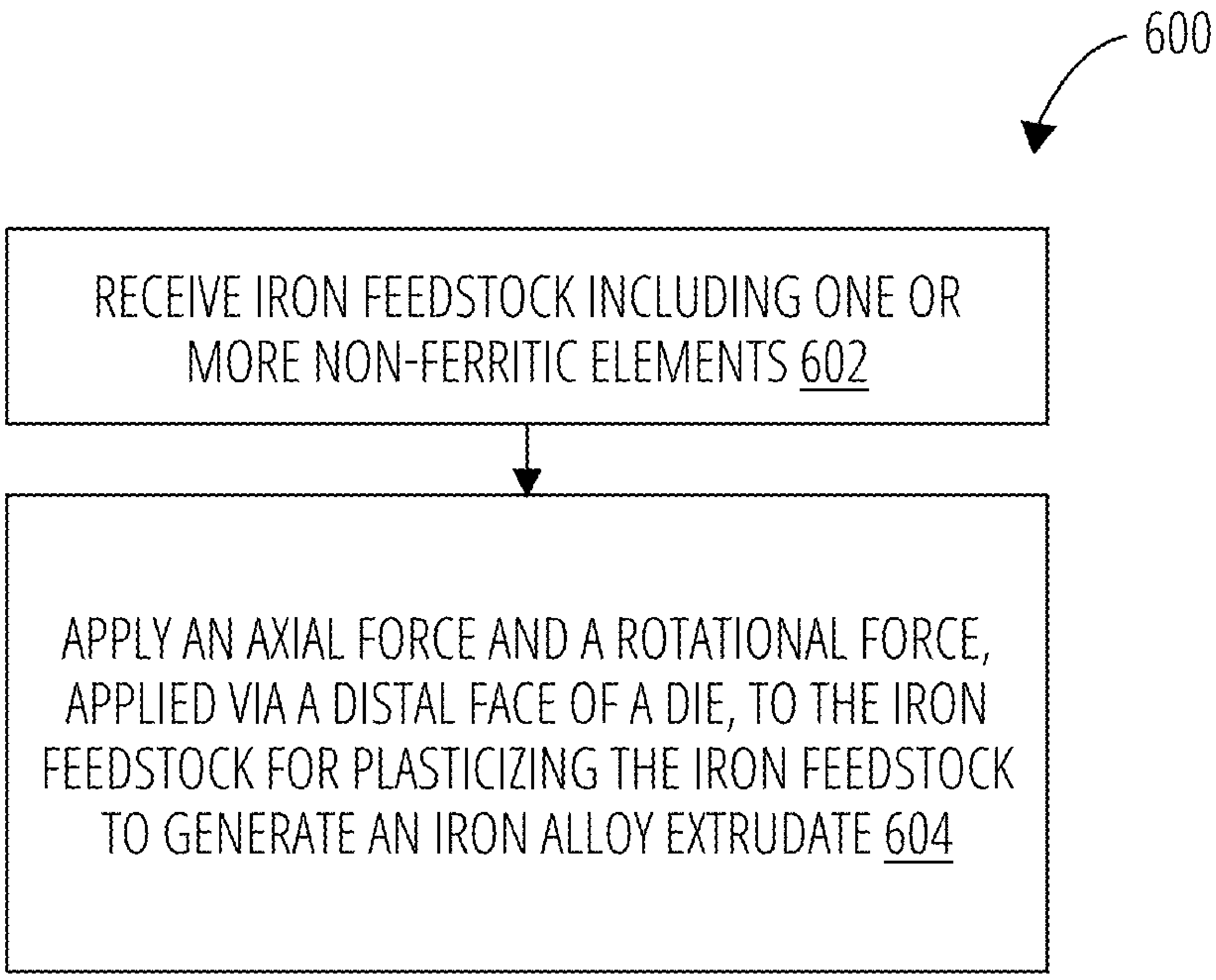

600
RECEIVE IRON FEEDSTOCK INCLUDING ONE OR MORE NON-FERRITIC ELEMENTS 602
APPLY AN AXIAL FORCE AND A ROTATIONAL FORCE, APPLIED VIA A DISTAL FACE OF A DIE, TO THE IRON FEEDSTOCK FOR PLASTICIZING THE IRON FEEDSTOCK TO GENERATE AN IRON ALLOY EXTRUDATE 604

FIG. 6

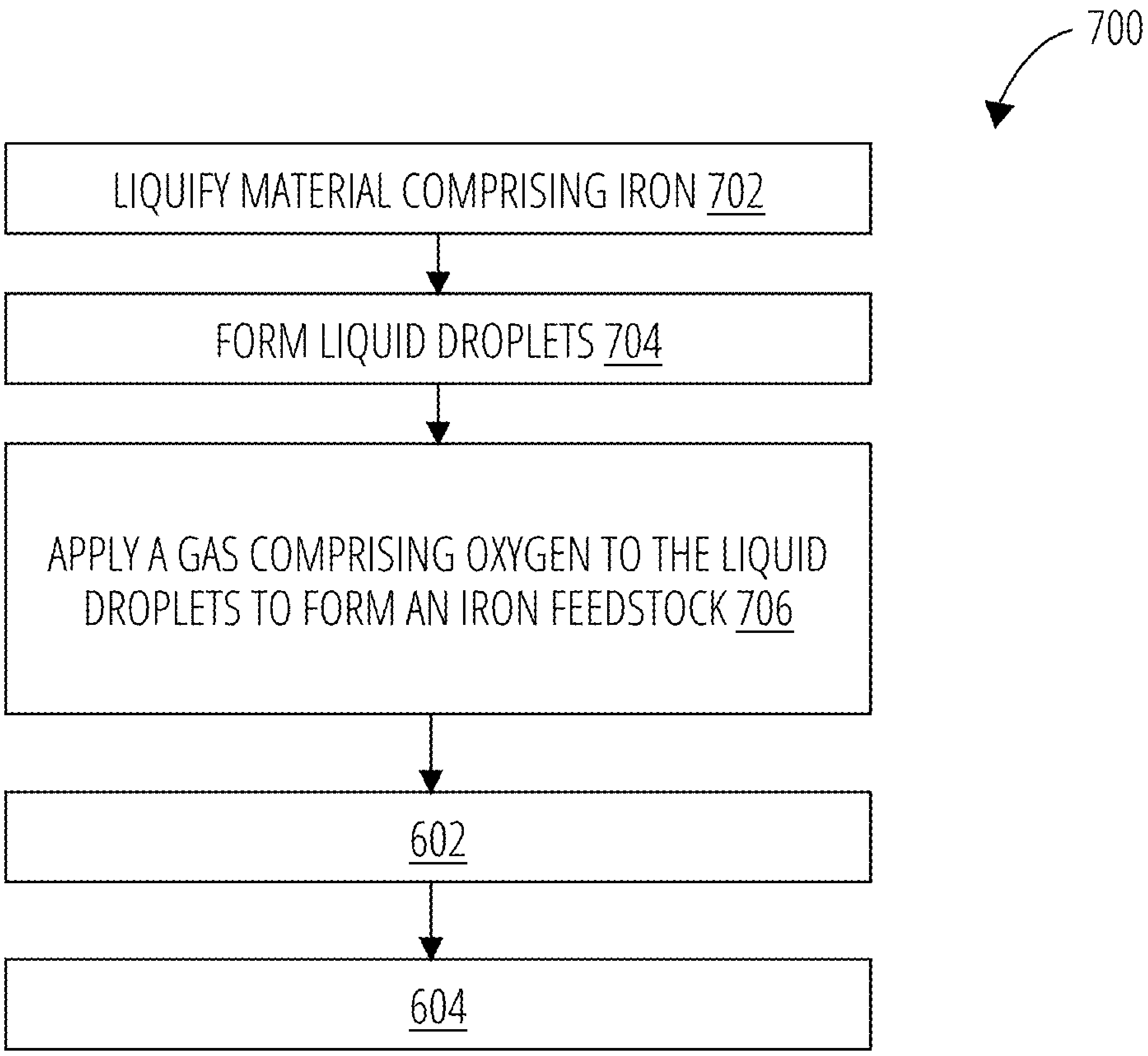

700
LIQUIFY MATERIAL COMPRISING IRON 702
FORM LIQUID DROPLETS 704
APPLY A GAS COMPRISING OXYGEN TO THE LIQUID DROPLETS TO FORM AN IRON FEEDSTOCK 706
602
604

FIG. 7

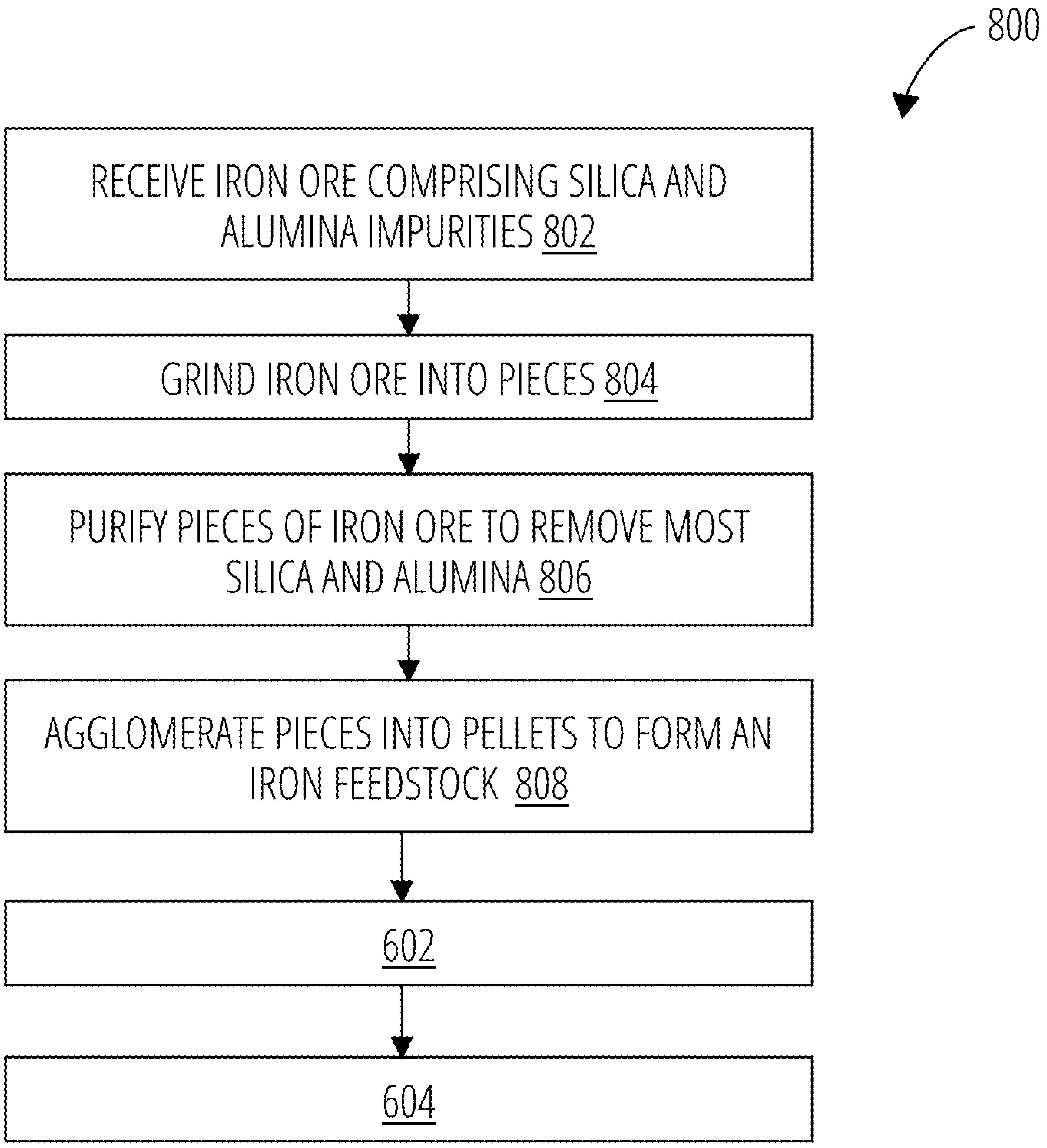

800
RECEIVE IRON ORE COMPRISING SILICA AND ALUMINA IMPURITIES 802
GRIND IRON ORE INTO PIECES 804
PURIFY PIECES OF IRON ORE TO REMOVE MOST SILICA AND ALUMINA 806
AGGLOMERATE PIECES INTO PELLETS TO FORM AN IRON FEEDSTOCK 808
602
604

FIG. 8

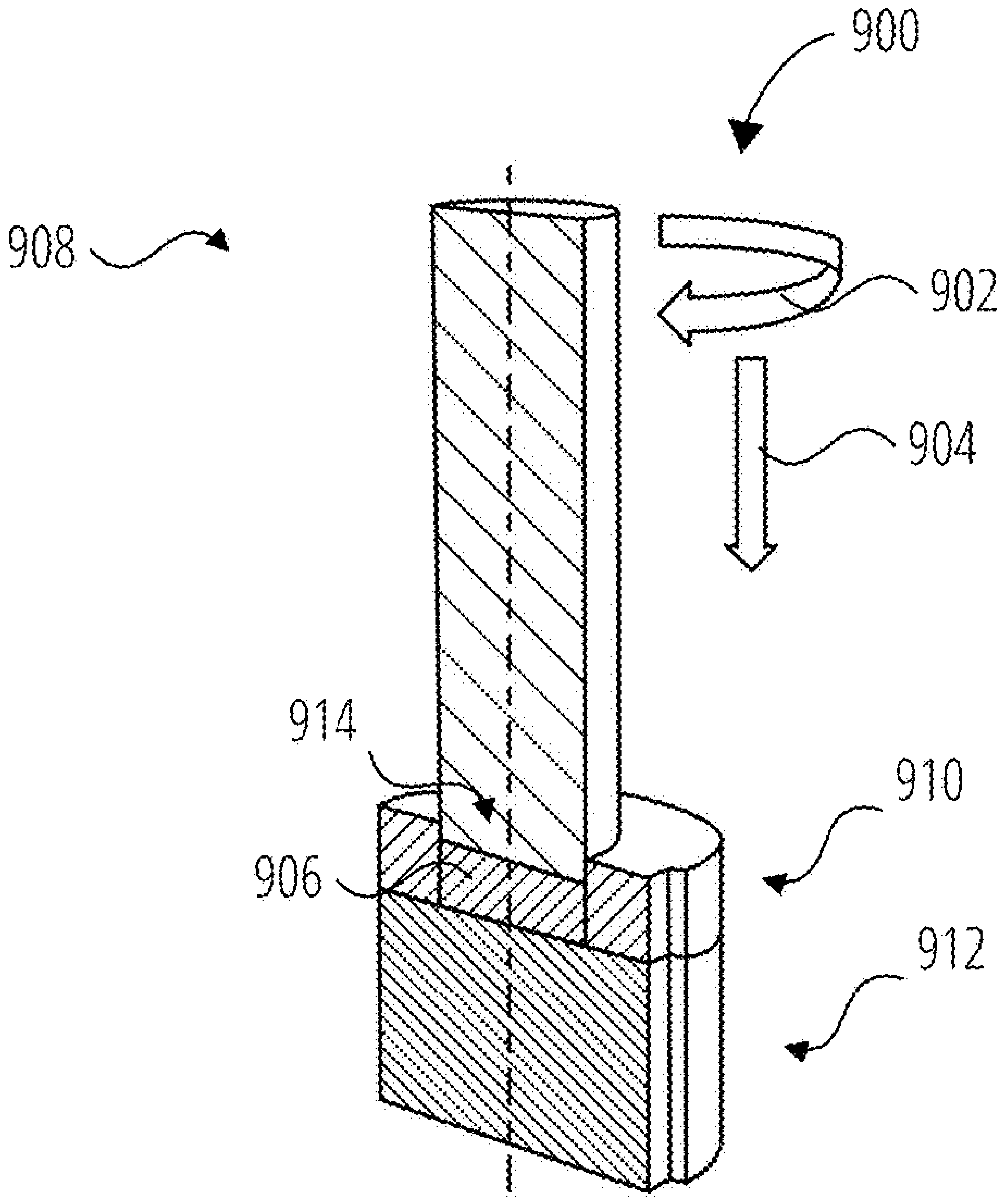


FIG. 9A

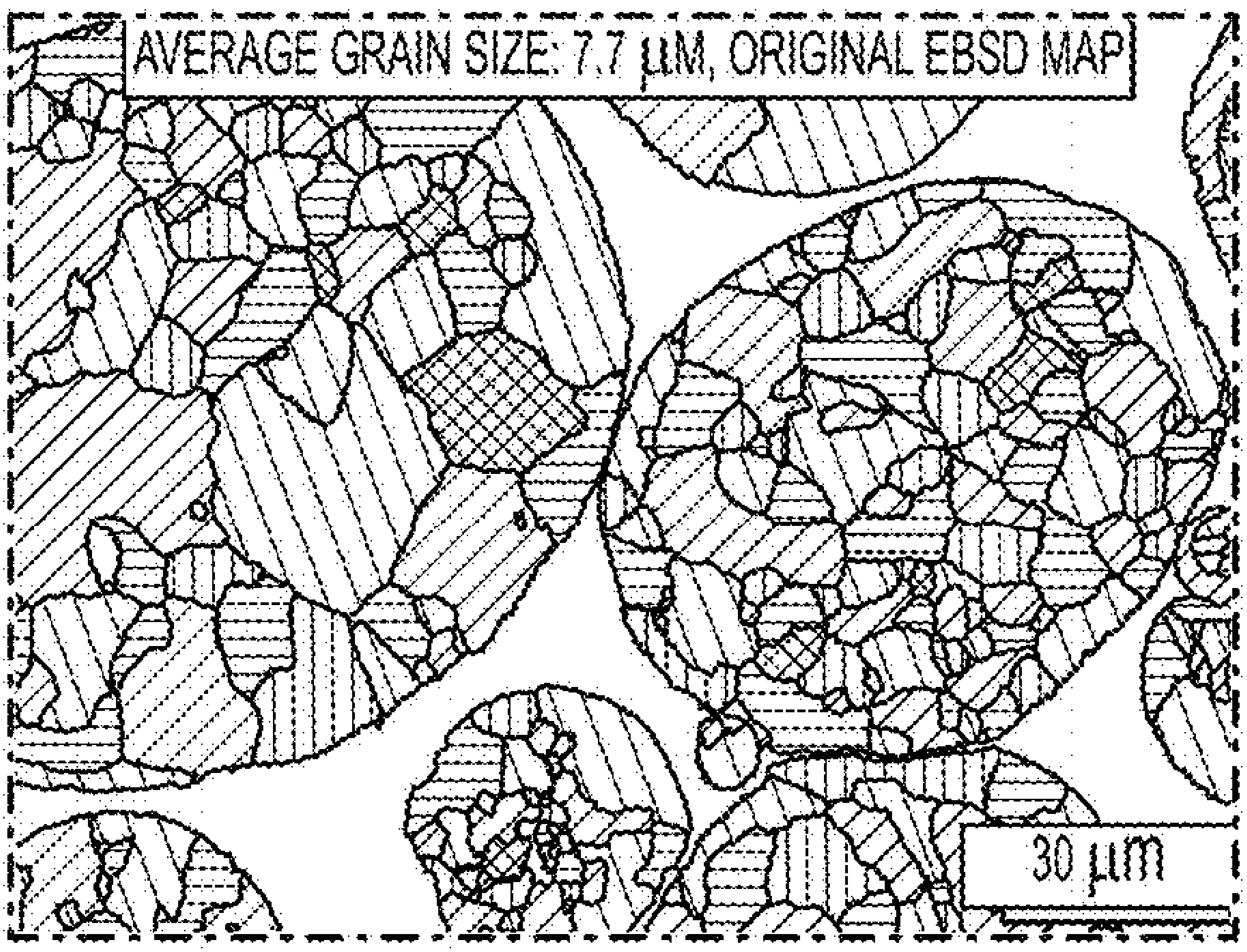


FIG. 9B

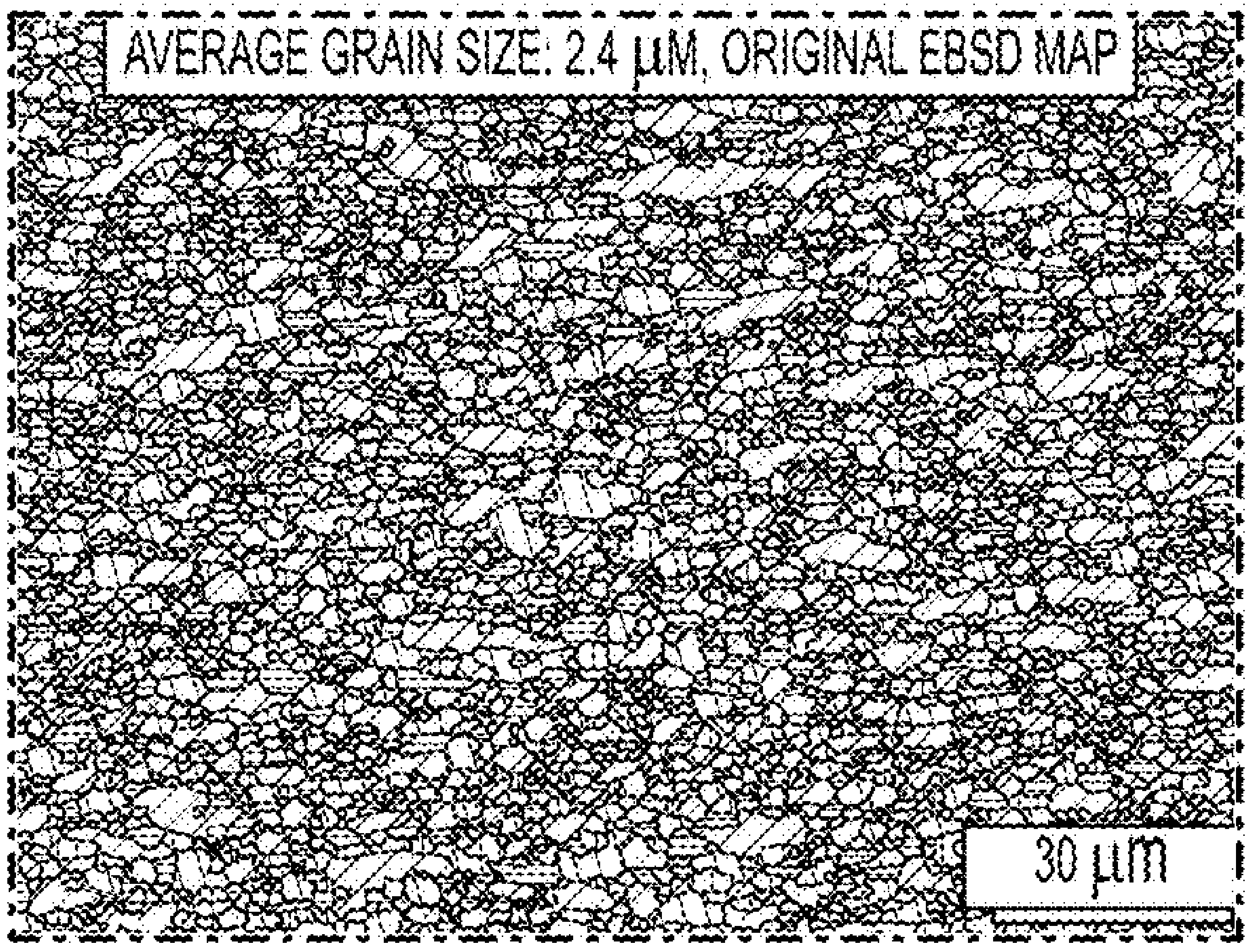


FIG. 9C

1002

	Empirical Fracture Toughness ($MPa\sqrt{m}$)	Test Temperature ($°C$)
ODS alloy extrudates	~250–500	~25

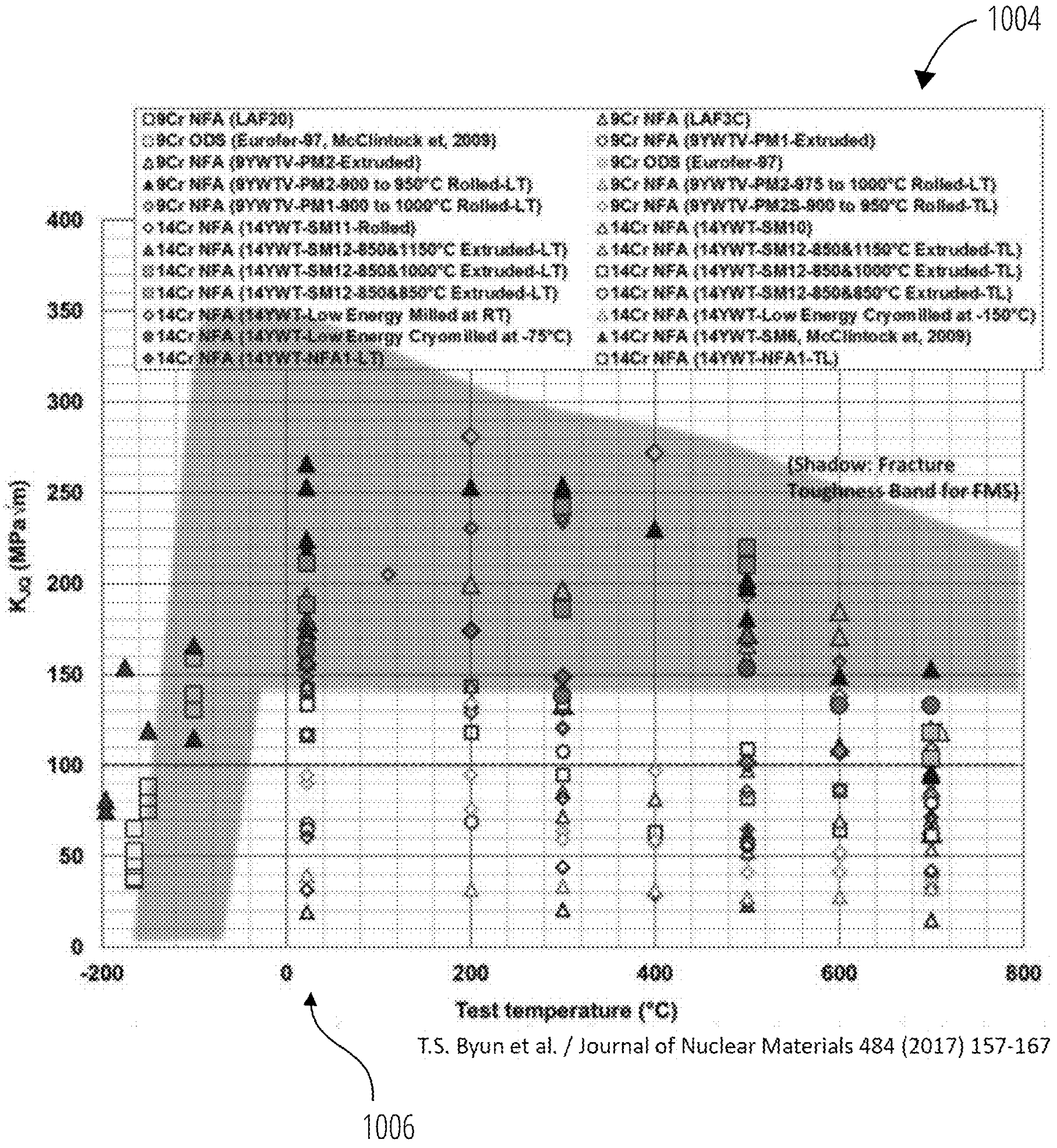


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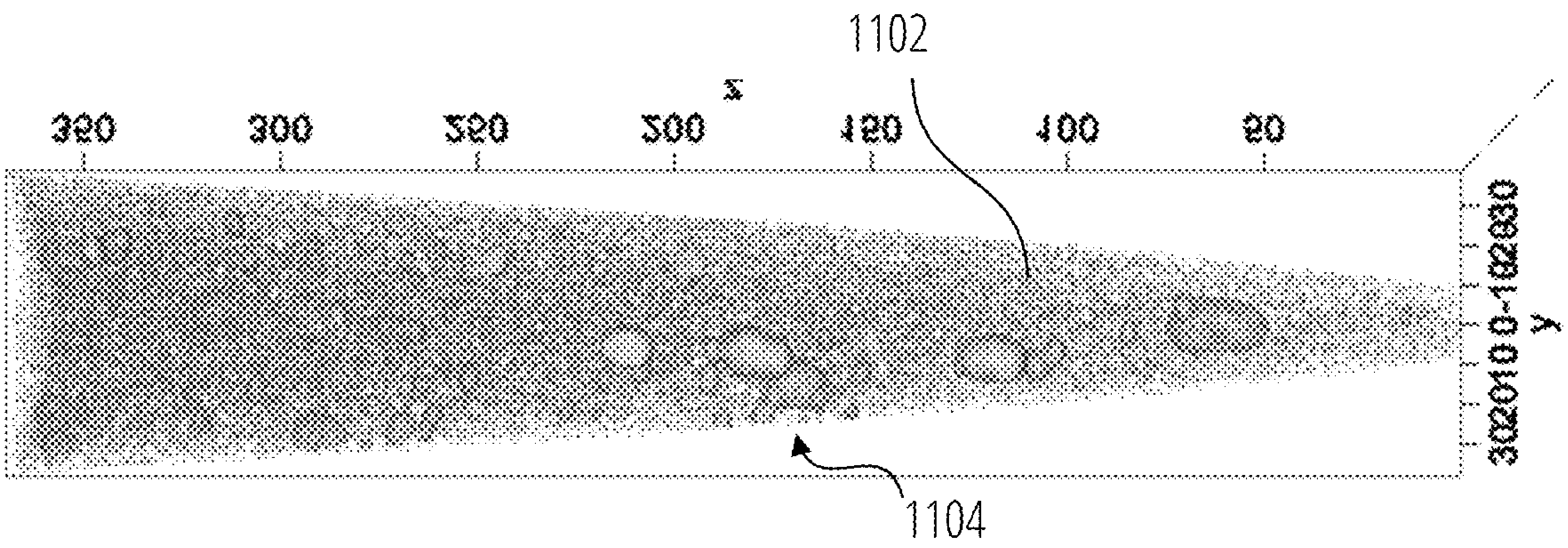
FIG. 10



1106

Bulk composition

Element	at. %	error at. %
Fe	83.89	0.025
Cr	14.36	0.008
W	0.911	0.002
Ti	0.397	0.001
O	0.221	0.001
Al	0.068	0.001
Y	0.155	0.001
C	0.002	0.000

1108

Small precipitates

Element	at. %	error at. %
Fe	79.65	0.0259
Cr	14.43	0.088
W	0.909	0.021
Ti	0.642	0.017
O	0.1649	0.028
Al	0.185	0.009
Y	2.532	0.035
C	0.000	0.000

FIG. 11

METHODS AND TOOLS FOR FRICTION EXTRUSION OF COMPOSITE EXTRUDATES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Application No. 63/410,556 filed on Sep. 27, 2022, the contents of which are herein incorporated by reference.

STATEMENT REGARDING RIGHTS TO INVENTION ADE UNDER FEDERALLY SPONSORED RESEARCH AND 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.

FIELD OF THE INVENTION

[0003] The present document relates generally to extrusion processing, extrusion tools, and resultant extrudates. More particularly, the present subject matter relates to a shear-assisted extrusion system and process for production of extrudates including high-performance composite extrudates.

BACKGROUND

[0004] Solid phase processing techniques such as friction consolidation and extrusion (FCE) and shear assisted processing and extrusion (ShAPE) of high melting point alloys use tooling made from materials that are very strong at high temperatures, such as tungsten rhenium hafnium carbide ("W-Re-HfC" herein), or another tungsten alloy tolerant of high temperatures (e.g., 2000K). A rod of W-Re-HfC is machined to form the desired tool (which can be referred to as a "die" herein) and held by a tool holder during use. These tooling materials are generally quite expensive. As an illustration, a representative cost of 1.25-inch diameter W-Re-HfC is approximately $2,000/inch for the material at the time of filing of this document, before machining costs. For example, raw materials for a 4-inch tool would cost approximately $8,000.

[0005] Certain tool holders use a set screw arrangement to hold the tool in place during solid phase processing, enabling transfer of the torque of a moving spindle to the tool and the material being processed. A relatively large portion of the tool, such as a shank, is inserted into the tool holder (or chuck), allowing engagement of the shank of the tool by screws through the holder to secure the tool to the holder. For example, a 4-inch tool would have approximately 2 inches inserted into the tool holder, contributing substantially to the raw material costs of the tool. Further, the set screw arrangement causes stress concentration during solid phase processing. Cracking and failure of the tool and tool holder can occur during use.

SUMMARY

ODS Alloys

[0006] Oxide dispersion strengthened (ODS) alloys exhibit high heat resistance, ductility, and strength, making these materials useful in various applications where high heat is a factor. For example, nuclear and fusion energy applications seek materials that maintain their performance under high temperature and stress in addition to radiation.

[0007] Certain approaches to processes of forming ODS steel through mechanical alloying are not viable for forming ODS alloys for nuclear and fusion energy applications. For example, ball milling an ODS precursor powder generates a resultant ODS alloy that is non-uniform and likely contaminated. Further, ball milling is too expensive and time consuming to be scaled for commercial applications.

Sponge Iron

[0008] Sponge iron is a relatively inexpensive form of iron that can be formed as an intermediate product from direct reduction ironmaking (DRI) processes. DRI processes can have lower carbon emissions as compared to blast furnace ironmaking. The intermediary sponge iron may not be useful on its own and is used as an iron feedstock. For example, in certain steel manufacturing processes, sponge iron can be melted down in an electric arc furnace (EAF) and purified for commercial use. Alloying elements can be added to the melted and purified sponge iron, including carbon to make steels.

[0009] That is, while the formation of the sponge iron is a solid phase process, certain uses of sponge iron to make alloys involve melting down the sponge iron. Melting metals is energy-intensive and contributes to carbon emissions. Further, adding greenhouse gas-emitting alloying elements, namely carbon, to the sponge iron further contributes to carbon emissions.

[0010] This document describes, among other things, examples of a tool assembly for friction extrusion that can comprise a friction extrusion die. The friction extrusion die can include a distal face and a proximal end. The distal face can define at least one topographical ridge or groove feature to induce plasticization of a material in response to an axial force and a rotational force applied by the distal face to the material. The friction extrusion die can define a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces. The proximal end can define a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder. The faceted cross-sectional profile can be sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

[0011] This Summary is intended to provide an overview of certain aspects of the present subject matter, which are further described in the below Detailed Description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0012] 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. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

[0013] FIG. **1**A illustrates a system for forming an extrudate, according to some examples.

[0014] FIG. 1B illustrates a tool for plasticizing material, according to some examples.

[0015] FIG. 2A illustrate an example of a tool in a side view.

[0016] FIG. 2B illustrates an example of a tool in a top-down view.

[0017] FIG. 2C illustrates an example of a tool in a bottom-up view.

[0018] FIG. 3A illustrates an example of a tool holder in a side view.

[0019] FIG. 3B illustrates an example of a tool holder in a bottom-up view.

[0020] FIG. 3C illustrates an example of a tool holder in a top-down view.

[0021] FIG. 4A illustrates an example of a tool assembly in an exploded view.

[0022] FIG. 4B illustrates an example of an interior tool assembly.

[0023] FIG. 4C illustrates an example of an exterior tool assembly.

[0024] FIG. **5** illustrates several an example of faceted cross-sectional profiles of a die.

[0025] FIG. **6** is a flowchart of an example of portions of a method of generating an extrudate.

[0026] FIG. **7** is a flowchart of an example of portions of a method of generating an extrudate.

[0027] FIG. **8** is a flowchart of an example of portions of a method of generating an extrudate.

[0028] FIG. **9**A illustrates a section view of an example of portions of a system for applying rotational force and axial force to a feedstock.

[0029] FIG. **9**B illustrates an example of grains of a feedstock.

[0030] FIG. **9**C illustrates an example of grains of an extrudate.

[0031] FIG. **10** is an example of a comparison of fracture toughness of an ODS alloy extrudate and certain comparison materials.

[0032] FIG. **11** includes an example of compositional data from APT needles of a bulk material and nanoparticle precipitates.

DETAILED DESCRIPTION

[0033] Methods and tool assemblies are described herein for solid phase processing in general and friction extrusion in particular. Friction extrusion plasticizes one or more input materials to form an extruded material, called an "extrudate" herein. The extrudate is generally an alloy of the one or more input materials.

[0034] FIG. 1A illustrates an example of portions of a system **100** for forming an extrudate **102**. The system **100** can include a tool **104** for applying force to a feedstock **106**. The system **100** can use shear assisted processing and extrusion (ShAPE) technology, such as involving applying an axial compressing force and a rotating shearing force to deform the feedstock **106**. The force(s) applied by the system **100** can cause plastic deformation of the feedstock **106** (e.g., "plasticize" the feedstock **106**), which can also be referred to as permanent or non-reversible deformation.

[0035] For example, an axial force can be applied along a direction of a longitudinal central axis **108** of the system **100** such as to provide compression. The longitudinal central axis **108** can define a central axis along which the extrudate **102** extends axially and about which the tool **104** can rotate. An axial compressive force can be applied by moving the tool **104** at a travel speed (e.g., mm/minute) along the longitudinal central axis **108**. The travel speed (and associated axial force) may vary during friction extrusion, for example, to maintain deformation of the feedstock **106**. The linear motion of the tool **104** to deform the feedstock **106** can be referred to as upset.

[0036] Concurrently, a rotating force can be applied about the longitudinal central axis **108**, such as to provide shearing. A rotating force can be applied by moving the tool **104** at a rotational speed (e.g., rotations/minute, "RPM") about the longitudinal central axis **108**. The rotation speed (and associated rotational force) may vary during friction extrusion. For example, the rotation speed can vary from 0 to approximately 2000 RPM. The rotating force can be continuous in a single direction. Additionally, or alternatively, the rotating force can oscillate in direction, for example, cyclically oscillating in direction.

[0037] The tool **104** can include a friction extrusion die. The tool **104** can include a distal face **110** that can define at least one topographical ridge or groove feature **112**. The groove feature **112** can include one or more spirals that can direct plasticized material inward towards a central passageway **114** of the tool **104**. The distal face **110** can include other surface morphologies or can be flat. The tool **104** can be formed of a metal, such as W-Re-HfC.

[0038] The feedstock **106** can include one or more materials to be plasticized. For example, the feedstock **106** can include one or more powdered materials. For example, the feedstock **106** can include or consist of ODS powder. The feedstock **106** can include one or more of beads, pellets, and/or flakes of material. For example, the feedstock **106** can include or consist of pellets formed from iron ore. The feedstock **106** can include a billet of material; the billet can consist of solid material, powdered material, or a combination thereof. The feedstock **106** can include material of any format to be plasticized, such as one or more of one or more billets, wires, rods, bars, tubes, or the like. The feedstock **106** may include one or more non-ferritic elements. The one or more non-ferritic elements can include impurities, such as those naturally found in raw forms of iron. In some examples, the one or more non-ferritic elements can be oxides, alloys, ceramics, or other compounds.

[0039] The feedstock **106** can be held, such as by a container **118**. The container **118** can include a cylindrical cannister that can be open on one end and closed on a second end. The cross-sectional shape of the canister may vary. The container **118** can include an optional mandrel **120** that can be located about the center of the container **118**.

[0040] The distal face **110** can be thrust against the feedstock **106** in the container **118** (or vice versa). An axial force and a rotating force can be applied to the tool **104** to plunge the distal face **110** into the feedstock **106**. For example, the axial force and the rotational force can be applied to a proximal end of the tool **104** (or associated tool assembly) and a distal end of the tool **104** imparts these forces to the feedstock **106**. Additionally, or alternatively, an axial force and a rotating force can be applied to the container **118** to provide a combination of shear and compressive forces to plasticize material.

[0041] In response to applying the axial force and the rotating force, the at least one topographical ridge or groove feature **112** induces plasticization of material at an interface **116** of the feedstock **106** with the distal face **110**. The extrudate **102** is formed of the plasticized material extruded from the system **100**. The central passageway **114** of the tool **104** can carry the extrudate **102** in a desired direction. For example, the central passageway **114** can carry the extrudate **102** along the longitudinal central axis **108** in a direction opposing the direction of the compressive axial force.

[0042] The extrudate **102** is formed of the solid phase processed feedstock **106**. The extrudate **102** can be formed without melting the feedstock **106**. The extrudate **102** can include a metal, an alloy, or a composite material. The extrudate **102** can have superior strength and hardness properties compared to the feedstock **106** or materials used to form the feedstock **106**. The system **100** can harden and strengthen the materials in forming the extrudate **102**.

[0043] FIG. 1B illustrates an example of portions of the tool **104** for plasticizing material. The tool **104** can include an optional extrusion aperture **122**. The extrusion aperture **122** can include an opening to the central passageway **114** for carrying away the extrudate **102**. For example, the extrusion aperture **122** can be located at or near the center of the distal face **110** that includes at least one topographical ridge or groove feature **112**.

[0044] The extrudate **102** can be formed to take on the shape of the extrusion aperture **122** and the central passageway **114**. As plasticized material is extruded by the tool **104** assembly, it can be confined by and can form to the shape of the central passageway **114**. For example, a central passageway **114** and extrusion aperture **122** having a circular cross-section can form a rod-shaped extrudate **102** with the circular cross-section. An extrudate **102** with a desired cross-sectional shape can be formed by forming the central passageway **114** and extrusion aperture **122** to have the desired cross-sectional shape, e.g., rectangular, square, triangle, oblong, or more complex shapes, such as T-slot cross-sections.

[0045] The size and shape of the extrudate **102** can be further formed by the optional mandrel **120**. When the container **118** is accompanied by the mandrel **120**, the plasticized material can be extruded between the extrusion aperture **122** on the exterior and the mandrel **120** on the interior, forming an extrudate with a hollow cross-section. That is, the mandrel **120** can be used with the central passageway **114** to extrude a tube-shaped extrudate **102**.

[0046] The tool **104** can be held in place during use by a tool holder **124**. A proximal end of the tool **104** (not pictured in FIG. 1B) can be held by the tool holder **124**. As shown in FIG. 1B, protruding from the tool holder **124** are a distal end **128** and, optionally, at least part of a medial section **126** of the tool **104**.

[0047] FIG. 2A-FIG. 2C illustrate example of portions of the tool **202** in multiple views. The tool **202** can comprise an example of the tool **104**. For example, the tool **202** can include a distal face **206**, which can comprise an example of the distal face **110**, and an extrusion aperture **204**, which can comprise an example of the extrusion aperture **122**. Further the tool **202** can include a spiral groove feature **208**, which can comprise an example of the at least one topographic ridge or groove feature **112**.

[0048] The tool **202** can further include a distal end **210**, a proximal end **212** and a medial section **214**. The medial section **214** connects the distal end **210** and the proximal end **212**. The medial section **214** can have a larger diameter than either the distal end **210** or the proximal end **212**, such as to define a shoulder. The shoulder defined by the medial section **214** can limit a depth of insertion of the proximal end **212** into a tool holder (e.g., tool holder **124**). The shoulder can support in aligning the tool into the tool holder by keeping the tool **104** centered on the longitudinal central axis **218**.

[0049] The distal end **210** is the end of the tool **202** configured to induce plasticization. The distal end **210** includes the distal face **206**. The distal end **210** can be exterior to a tool holder when in use. For example, as depicted in FIG. 1B, the distal end **128** protrudes from the tool holder **124**.

[0050] The proximal end **212** is the end of the tool **202** that can be configured to mate with a tool holder. The proximal end **212** can define a non-circular cross-sectional profile, such as a faceted cross-sectional profile **216** that can be configured to mate with a corresponding receiving end of a tool holder. The faceted cross-sectional profile **216** can be defined by an outer surface of the proximal end **212** of the tool **202**. Further, the outer surface of the proximal end **212** of the tool **202** can define a protrusion with the faceted cross-sectional profile **216** (e.g., a male connector).

[0051] The faceted cross-sectional profile **216** can define a number of faces **220** on the proximal end **212** of the tool **202**, the number of faces **220** being greater than or equal to two. The faces **220** can be referred to as “facets” of the faceted cross-sectional profile **216**. Respective faces **220** are defined by vertices of the faceted cross-sectional profile **216**. The number of faces **220** can be equal to the number of vertices defined by the faceted cross-sectional profile **216**. When the proximal end **212** forms a protrusion, an angle between respective faces of the tool **202** can be >180°.

[0052] As depicted in FIG. 2B, the respective faces **220** defined by the faceted cross-sectional profile **216** can include portions that extend outward away from a longitudinal central axis **218**, such as to help enable engagement by a tool holder of the respective faces **220**. The longitudinal central axis **218** can comprise an example of the longitudinal central axis **108**. The faces **220** can be located on the outer surface of the proximal end **212**.

[0053] The faces **220** can be curved, such as to help provide engagement of a tool holder, such as is described further in relation to FIG. 3A-FIG. 3C. Each individual face **220** can be curved such that a longitudinal center of the face **220** is closest to the longitudinal central axis **218**. The longitudinal edges of each face **220** (e.g., where a face **220** meets another face **220** along a longitudinal vertex) can extend furthest from the longitudinal central axis **218**. Each face **220** can be concave.

[0054] Generally, the faceted cross-sectional profile **216** can be non-circular, such as polygonal or otherwise substantially polygonal. That is, while polygons have generally straight edges, a substantially polygonal shape can have modestly curved edges, and polygonal can refer to an arrangement of vertices of a cross-sectional shape that define a polygonal shape when connected to each other by lines. For example, as depicted in FIG. 2B, the faceted cross-sectional profile **216** is substantially hexagonal. In other words, the slightly curved face **220** defined by the faceted cross-sectional profile **216** can form an outline of the cross-sectional profile that can be substantially hexagonal. The faceted cross-sectional profile **216** in FIG. 2B can be recognized as hexagonal or substantially hexagonal. Other examples of polygonal faceted cross-sectional profiles are discussed in relation to FIG. **5**. In some examples, the faceted cross-sectional profile **216** can be hypocycloidic in shape, or otherwise curved, such as define by a spline.

[0055] FIG. **3**A-FIG. **3**B illustrate an example of portions of a tool holder **302** in multiple views. The tool holder **302** can be configured to hold a tool, such as a friction extrusion die. For example, the tool holder **302** can be configured to hold the tool **202** of FIG. **2**A-FIG. **2**C. The tool holder **302** can comprise an example of the tool holder **124**. The tool holder **302** can include a receiving end **304** and a stem **306**.

[0056] The stem **306** can extend along a longitudinal central axis **308**, parallel to a central passageway **310**. The central passageway **310** can comprise an example of a continuation of the central passageway **114** of the tool **104**. The central passageway **310** can carry extrudate away from the tool. The stem **306** can include a flat area **312** for screws to attach to, such as discussed in association with FIG. **4**A-FIG. **4**C. The central passageway **310** can be omitted in some examples; the central passageway **114** may terminate with the tool **104**. For example, the extrudate **102** forms in the tool **104** and a short distance behind it (e.g., 65 mm). Inclusion of the central passageway **310** through the tool holder **302** enables formation of longer extrudates.

[0057] The receiving end **304** can be configured to receive at least part of a tool. The receiving end **304** can be configured to mate with at least the proximal end **212** of the tool **202**. The receiving end **304** can define a socket **314** that can be configured to mate with the faceted cross-sectional profile **216** of the proximal end **212** of the tool **202**. The socket **314** can be defined by a surface of the tool holder **302** extending inwards towards the center of the tool holder **302**. The socket **314** can be defined about a longitudinal central axis **308**. The longitudinal central axis **308** can be the longitudinal central axis **108**.

[0058] The socket **314** can define an engagement section **316** and, optionally, a non-engagement section **318**. The engagement section **316** can be configured to provide engagement with faces **220** defined by the faceted cross-sectional profile **216** of the tool **202**. The non-engagement section **318** can refer to any remaining portion of the socket **314**. The non-engagement section **318** can be configured to receive the medial section **214** of the tool **202**. The engagement section **316** can be located deeper within the socket **314** than the non-engagement section **318**. For example, the socket **314** in FIG. **3**B depicts a non-engagement section **318** at the opening of the socket and an engagement section **316** at the base of the socket **314**, where the non-engagement section **318** can be defined by a smooth circular cross-section that is not configured to engage with faces **220** of the tool **202**.

[0059] The engagement section **316** of the tool holder **302** can include a faceted cross-sectional profile complementary to or congruent with the faceted cross-sectional profile **216** of the tool **202** for mating. The faceted cross-sectional profile **216** of the tool **202** can fit snugly within the engagement section **316** of the tool holder **302**. The engagement section **316** can define faces **320** on an interior surface of the socket **314**.

[0060] The faces **320** of the tool holder **302** can be curved to reduce stress concentration. The faces **320** can extend inward towards the longitudinal central axis **308**, such as to help provide engagement by the tool holder **302** of respective faces **220** defined by the faceted cross-sectional profile **216** of the tool **202**. Each individual face **320** can be curved, for example, to align with respective curved faces **220** for mating. Each face **320** can be convex.

[0061] Additionally, or alternatively, the faces **220** of the tool **202** are flat and the faces **320** of the tool holder **302** are curved (e.g., convex). In such examples, the curved faces **320** of the tool holder **302** can spread out stress concentration. Additionally, or alternatively, the faces **220** of the tool **202** are curved (e.g., concave) and the faces **320** of the tool holder **302** are flat. In such examples, the curved faces **220** of the tool **202** can spread out stress concentration.

[0062] For example, a proximal end **212** of the tool **202** can be inserted into the receiving end **304** of the tool holder **302**. When inserted, each individual face **220** of the proximal end **212** of the tool **202** can abut a respective face **320** of the receiving end **304** of the tool holder **302**, such as to mate the tool **202** and the tool holder **302**. The mating enables the transfer of torque from the tool holder **302** to the tool **202** (and vice versa), such that when the axial force and the rotational force are applied, the abutted faces engage one another.

[0063] The curved faces **220** abutting the curved faces **320** shifts the stress concentration away from the vertices in the socket **314** and towards the center of the faces **220**, **320**. Because the stress is not concentrated at the vertices, the mating of the tool **202** and tool holder **302** can withstand greater stress before deforming the tool **202** (e.g., as compared to a non-curved face example). For example, a perfectly hexagonal faceted cross-sectional profile **216** would begin deforming such that the vertices of the facets are rounded off by the edges of the socket **314**, similar to stripping a screw head under too much torque.

[0064] Further, the tool **202** and tool holder **302** can mate without screws, unlike certain other tool holders. As a result, the tool **202** and tool holder **302** are less prone to cracking and failure during use than certain other screw-based tool holders. Further, the tool **202** can be made from a smaller length of W-Re-HfC if screws are not used, substantially reducing the raw material costs of forming a friction extrusion die.

[0065] The tool **202** has a socket **314** and the tool holder **302** can include a protruding proximal end **212**, if desired. In other words, the male connector of the tool **202** and female connector of the tool holder **302** can be inverted.

[0066] FIG. **4**A-FIG. **4**C illustrate an example of portions of a tool assembly **400** in multiple views. The tool assembly **400** can include a tool holder **402**, which can comprise an example of the tool holder **124** or the tool holder **302** previously discussed. The tool assembly **400** can further include a housing **404**, a fitting **406**, an inner cooling tube **408** and an outer cooling tube **410**. The tool assembly **400** can provide water cooling to the tool holder **302**.

[0067] The inner cooling tube **408** can provide water (e.g., chilled water) to a proximal end of the tool holder **402**. The inner cooling tube **408** can provide the ‘input’ water to cool the tool holder **402**. The chilled water cools the hot tool holder **402** such that the water absorbs heat and becomes heated water. The outer cooling tube **410** can carry away water (e.g., heated water) from the tool holder **402**. The outer cooling tube **410** can accommodate the ‘output’ water being flushed out. The outer cooling tube **410** can carry the heated water back to a chiller (e.g., a cooling chamber), where it is cooled and reused to cool the tool holder **402**.

[0068] The inner cooling tube **408** can fit within the outer cooling tube **410**, forming a cooling tube. The inner cooling tube **408** can be inserted within the tool holder **402** (e.g., through the stem **306**). The inner cooling tube **408** can be inserted into a cavity that is different from but substantially parallel to the central passageway **310**. The extrudate does not pass through the cooling tube. The fitting **406** can connect the outer cooling tube **410** to the tool holder **402**. The fitting **406** can provide a seal between the outer cooling tube **410** and the tool holder **402**. The fitting **406** can also provide a seal between the inner cooling tube **408** and the tool holder **402**.

[0069] The housing **404** can fit over the assembly comprising the inner cooling tube **408**, the outer cooling tube **410** and the fitting **406**. The housing **404** can fit over the stem **306** of the tool holder **402** and can attach via screws to a flat area **312** of the stem **306**. The housing **404** can leave the receiving end **304** of the tool holder **402** exposed for receiving a proximal end **212** of a tool **202**.

[0070] FIG. **5** illustrates several examples of faceted cross-sectional profiles of a tool, such as tool **202**, where "n" is a positive integer greater than two. For example, a tool can have a substantially pentagonal faceted cross-sectional profile **502**, a substantially triangular faceted cross-sectional profile **504**, a substantially octagonal faceted cross-sectional profile **506**, or, generally, a substantially "n"-sided faceted cross-sectional profile **508**.

[0071] Each example of a faceted cross-sectional profile can define a number of curved faces. For example, the n-sided faceted cross-sectional profile **508** has n curved faces. Each example of a faceted cross-sectional profile of a tool can be configured to mate with a tool holder having a congruent faceted cross-sectional profile. For example, a protruding proximal end having a pentagonal faceted cross-sectional profile **502** can be configured to mate with a socket having a pentagonal faceted cross-sectional profile.

[0072] FIG. **6** is an example of a flowchart of portions of a method **600** of generating an extrudate. The method **600** can be carried out using a system for friction extrusion, such as the system **100**. The method **600** can be carried out using a tool and tool holder configured to mate, such as tool **202** and tool holder **302**, or any various examples discussed in association with the figures herein. One or more features of these one or more examples may be combined to form other examples.

[0073] At block **602**, the method **600** can include receiving an iron feedstock including one or more non-ferritic elements. The iron feedstock can comprise an example of the feedstock **106**, such as powder, flakes, or billets. The one or more non-ferritic elements can include any impurity such as can be commonly found in an iron feedstock. According to some examples, the iron feedstock is an ODS powder, and the one or more non-ferritic elements can include yttrium, titanium, and oxygen, as discussed further in association with FIG. **7**. According to some examples, the iron feedstock is a sponge iron, and the one or more non-ferritic elements are impurities that can include silica and alumina, as discussed further in association with FIG. **8**.

[0074] At block **604**, the method **600** can include applying an axial force and a rotational force, applied via a distal face of a die, to the iron feedstock for plasticizing the iron feedstock to generate an iron alloy extrudate from the iron feedstock. The axial force and the rotational force can be applied by a friction extrusion system, such as the system **100**. The pressure generated by die imparting the axial force and the rotational force on the iron feedstock induce high stresses that cause the iron feedstock to undergo plastic deformation (e.g., "plasticize"). The plasticized material reforms (e.g., recrystallizes) as it is extruded from the die into the iron alloy extrudate having a different microstructure than the iron feedstock. That is, the iron alloy extrudate forms in situ from the plasticized material.

[0075] The microstructures of the iron alloy extrudates generated can have superior strength properties as a result of the method **600**, such as discussed further in association with FIG. **9**A-FIG. **9**C. This method **600** can produce iron alloys with better strength, ductility, and corrosion resistance at the macroscopic level together with increased and better performance. This method **600** can help reduce or eliminate the need for additional heating. That is, the heat generated from the friction of the die imparting the axial and rotational forces on the iron feedstock is sufficient to process the iron feedstock above its recrystallization temperature without requiring additional heating.

[0076] The die can include a friction extrusion die, such as tool **202** or any other example of the tools described herein. For example, the die can include a distal face defining at least one topographical ridge or groove feature to induce plasticization of a material in response to the axial force and the rotational force applied by the distal face to the material, the die defining a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces. Further, the die can include a proximal end defining a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder, the faceted cross-sectional profile sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

[0077] FIG. **7** is an example of a flowchart of portions of a method **700** of generating an extrudate. The method **700** can comprise an example of the method **600**. The method **700** can be used to generate an iron alloy extrudate that is an ODS steel extrudate. According to some examples, block **702** through block **706** comprise a process of gas atomization reaction synthesis (GARS) for forming ODS alloy precursor.

[0078] At block **702**, the method **700** can include liquifying material comprising iron. The liquified material can further comprise chromium, titanium, and yttrium. For example, the material can be an iron alloy comprising chromium, titanium, and yttrium. Additionally, or alternatively, the iron can be any iron, such as iron ore or other unprocessed forms of iron, which may include other non-ferritic elements. The material can be liquified by heating, if desired, for example, in a crucible. Additionally, or alternatively, high pressure may liquify the material. According to some examples, the material comprising iron can be superheated.

[0079] At block **704**, the method **700** can include forming liquid droplets. The forming of liquid droplets can be referred to as 'atomization.' The liquid iron can be forced through a nozzle such as to form a stream of droplets. The nozzle can include a predetermined pour tube geometry and one or more nozzle jets to produce a desired flow rate of liquid droplets.

[0080] At block **706**, the method **700** can include applying a gas (e.g., at a specified pressure) comprising oxygen to the liquid droplets for form an iron feedstock. The gas can be an inert gas, such as argon or another noble gas. The gas can be applied by one or more nozzles aimed to intercept the stream of droplets of liquid iron. The pressure of the gas being applied is specified to intercept the stream of droplets of liquid iron and reduce by a reduction reaction. For example, the specified pressure can generate a fast-moving stream of gas.

[0081] As the liquid iron is expelled from the nozzle, the gas comprising oxygen can cause an in situ oxidization reaction. The gas can rapidly cool the liquid iron droplets into a solid while forming an oxidized layer on the surface. The cooled oxidized droplets are an iron feedstock that can be termed an ODS alloy precursor powder.

[0082] At block **602** and block **604**, the method **700** can include using the ODS alloy precursor as an iron feedstock to generate an iron alloy extrudate that is an ODS alloy. The ODS alloy can include a bulk material and nanoparticle precipitates dispersed in the bulk material. In some examples, the nanoparticle precipitates can have a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material. The nanoparticle precipitates can have a relatively higher atomic percentages of non-ferritic elements, such as titanium, oxygen, and yttrium, such as in comparison with the bulk material. Conversely, the bulk material can have a relatively higher atomic percentage of iron than the nanoparticle precipitates. According to some examples, the ODS iron alloy can have a fracture toughness exceeding 250 $MPa \cdot m^{1/2}$ at room temperature.

[0083] The resultant ODS alloy extrudate can be potentially viable for nuclear and fusion energy applications. For example, unlike certain ODS alloys generated using ball milling, the present ODS alloy extrudate can have a uniform microstructure. The microstructure of the ODS alloy is discussed in greater detail in association with FIG. **11**. The method **700** can be less expensive and less time consuming than the conventional ball-milling processes. As a result, the method **700** can be more commercially viable than certain other processes.

[0084] FIG. **8** is a flowchart of an example of portions of a method **800** of generating an extrudate. The method **800** can comprise an example of the method **600**. The method **800** can be used to generate an iron alloy extrudate such as a sponge iron extrudate. For example, block **802** through block **808** can comprise a process of forming a sponge iron feedstock from iron ore.

[0085] At block **802**, the method **800** can include receiving iron ore comprising silica and alumina impurities. The iron ore comprises one or more non-ferritic elements in the silica and alumina impurities. The iron ore can be an unprocessed raw material. The iron ore can comprise any composition of silica and alumina impurities.

[0086] At block **804**, the method **800** can include grinding the iron ore into pieces of iron ore. The pieces of iron ore can be approximately gravel-sized or smaller, according to some examples.

[0087] At block **806**, the method **800** can include purifying the pieces of iron ore to remove most silica and alumina. The purification can include one or more processes for removing silica and/or alumina. For example, the purification can include reducing by reduction reaction (e.g., direct reduction processes). The purification process may leave some silica and alumina, such as on the order of 5-30 weight percent of oxides. According to some examples, the oxide concentration is closer to 8-10 weight percent.

[0088] At block **808**, the method **800** can include agglomerating the pieces into pellets to form an iron feedstock. According to some examples, the iron pellets can be at least 70 weight percent iron. The iron pellets can be a sponge iron feedstock.

[0089] At block **602** and block **604**, the method **800** can include using the iron pellets, such as an iron feedstock, such as to generate an iron alloy extrudate that is a sponge iron extrudate. The method **800** can make use of the silica and alumina remaining in the iron pellets. During the plasticization and extrusion, the non-ferritic silica and alumina can be broken down and re-dissolved in the metal matrix, forming a metal matrix composite. The non-ferritic silica and alumina can provide reinforcement that can strengthen and harden the resultant crystalline structure. According to some examples, the extrudate is a high strength sponge iron having a yield strength within a range of 40 to 50 kilopounds per square inch (ksi) at room temperature and having a hardness within a range of 300 to 400 Vickers Pyramid Number (HV).

[0090] The method **800** can directly make iron alloys using sponge iron without requiring adding a greenhouse gas emitting ingredient, namely carbon and its associated products. Moreover, the method **800** can help eliminate the energy-intensive melting step in steelmaking. In other words, the method **800** can help provide an alternative, lower-emission process of using sponge iron.

[0091] FIG. **9**A illustrates an example of a section view of portions of a system **900** for applying rotational force **902** and axial force **904** to a feedstock **906**. The system **900** can comprise an example of the system **100**. The system **900** can include a tool **908**, which can comprise an example of the tool **104** or tool **202**.

[0092] The feedstock **906** can be held in place, such as by a ring **910**, which can also be referred to as a container, on a backing block **912**. The ring **910** can be formed of a nickel-chromium-based superalloy such as Inconel® and the backing block **912** can be formed of a nickel alloy, or a refractory alloy.

[0093] The system **900** can include a thermocouple **914**, such as for monitoring temperature at or near an interface between the tool **908** and feedstock **906**. For example, the thermocouple **914** can be inserted in a slot in the tool **908** from the side. The slot can be, for example, located one millimeter above the interface. The thermocouple **914** can be used to monitor and adjust the temperature in order to change the microstructure of the extrudate. For example, responsive to determining the temperature is below a recrystallization temperature of an alloy being extruded, the system **900** can increase a travel speed and/or a rotating speed of the tool **908**.

[0094] When the rotational force **902** and the axial force **904** are applied to the tool **908**, the feedstock **906** is plasticized, changing its microstructure. FIG. **9**B shows an example of a microstructure of the feedstock **906** before plasticization. FIG. **9**C shows an example of a microstructure of a resultant extrudate.

[0095] FIG. **9**B illustrates an example of grains of the feedstock **906**. The illustration is generated from empirical electron backscatter diffraction (EBSD) of an ODS precursor at 30 micrometers (“microns”). At 30 microns, the empty space between each powder of ODS precursor can be resolved, in this example. The average grain size of the feedstock **906** is 7.7 microns.

[0096] FIG. **9**C illustrates an example of grains of an extrudate that can be generated by the system **900**. The illustration is generated from empirical EBSD of an ODS alloy extrudate generated by the method **700**. As a result of the extrusion, the average grain size can be reduced to 2.4 microns. The plasticization induced by the rotational force **902** and the axial force **904** has broken down the larger grains of FIG. **9**B, which recrystallized as the smaller grains of FIG. **9**C.

[0097] The comprehensive resizing of the grains during extrusion indicates the feedstock **906** is fully processed (e.g., plasticized) by the friction extrusion. This enables generating ODS alloy extrudates with uniform microstructures, such as desirable for commercial use. Other approaches, such as balled-milled ODS alloys that are conventionally extruded, can have non-uniform microstructures, which are prone to cracking and failure.

[0098] FIG. **10** is an example of a comparison of fracture toughness of an ODS alloy extrudate and certain comparison materials. An empirical data **1002** can be compared to a plot **1004** including comparison materials **1006**. Samples of ODS alloy extrudates can be formed by methods **700** were tested to measure the empirical data **1002**. The comparison materials **1006** include other ODS steels that have been formed in conventional ways including ball milling and normal forming processes such as extrusion, including steels that have been hot worked and cold worked.

[0099] As can be compared, the fracture toughness of the ODS alloy extrudates **1002** greatly exceed the comparison materials **1006** at room temperature. The ODS alloy extrudates **1002** have fracture toughness exceeding 250 $\mathrm{MPa{\cdot}m^{1/2}}$ at room temperature, according to some examples. The ODS alloy extrudates **1002** have fracture toughness exceeding 400 $\mathrm{MPa{\cdot}m^{1/2}}$ in some examples. The comparison materials **1006** have a maximum fracture toughness of approximately 270 $\mathrm{MPa{\cdot}m^{1/2}}$ at room temperature. In other words, the ODS alloys generated using method **700** outperform the comparison materials **1006**.

[0100] FIG. **11** includes an example of compositional data from APT needles of a bulk material **1102** and nanoparticle precipitates **1104**. The APT needles were taken from samples of ODS alloy extrudates generated by method **700**. The nanoparticle precipitates **1104** are dispersed in the bulk material **1102**. According to some examples, the nanoparticle precipitates **1104** have a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material. The nanoparticle precipitates **1104** may also be referred to as nano-oxides.

[0101] The bulk material **1102** is associated with empirical bulk composition data **1106** and the nanoparticle precipitates **1104** are associated with empirical precipitate composition data **1108**. The bulk material **1102** has a relatively higher atomic percentage of iron than the nanoparticle precipitates. The nanoparticle precipitates **1104** have a relatively higher atomic percentage of non-ferritic elements than the bulk material **1102**. The non-ferritic elements can include at least one of titanium, oxygen, yttrium, chromium, or other non-ferritic elements.

[0102] The ODS alloy extrudates generated by method **700** are dimensionally stable under stress at a temperature of 650° C. For example, ongoing creep testing at the time of this filing indicate the ODS alloy extrudates having creep properties that are superior to reduced activation ferritic martensitic (RAFM) steels and castable nanostructured alloys (CNAs). The ongoing creep testing indicates the ODS alloy extrudates have creep properties comparable to the ODS Eurofer® steel alloys, being able to withstand the load for approximately 100 hours at 650° C., having a creep rupture stress of approximately 150 MPa. The ongoing creep testing indicates these ODS alloy extrudates have a crystalline structure that is dimensionally stable and resistant to deformations induced by creep at temperatures greater than or equal to 650° C.

[0103] The ODS ally extrudates that are dimensionally stable at 650° C. are better suited for nuclear and fusion applications than comparison materials. For example, RAFM steels are limited to operating at or below 550° C. Further, the method **700** is expected to reduce costs by at least a factor of 2 when compared to comparison materials (e.g., RAFM).

[0104] To better illustrate the inductor structures and formation or fabrication techniques described herein, a non-limiting set of Example embodiments are set forth below as numerically identified Examples.

[0105] Example 1 is a tool assembly for friction extrusion, the tool assembly comprising a friction extrusion die comprising: a distal face defining at least one topographical ridge or groove feature to induce plasticization of a material in response to an axial force and a rotational force applied by the distal face to the material, the friction extrusion die defining a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces; and a proximal end defining a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder, the faceted cross-sectional profile sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

[0106] Example 2 is the tool assembly of example 1, wherein the faceted cross-sectional profile of the proximal end of the friction extrusion die is configured to mate with a receiving end of the tool holder.

[0107] Example 3 is the tool assembly of example 2, wherein the receiving end of the tool holder defines a socket configured to mate with the faceted cross-sectional profile of the proximal end of the friction extrusion die, wherein respective inward-facing faces of the socket extend inward toward a longitudinal central axis of the socket to provide the engagement by the tool holder of the respective faces of defined by the faceted cross-sectional profile.

[0108] Example 4 is the tool assembly of example 2, wherein vertices of the respective faces defined by the faceted cross-sectional profile extend outward away from a longitudinal central axis to enable the engagement by the tool holder of the respective faces.

[0109] Example 5 is the tool assembly of example 1, wherein the faceted cross-sectional profile is polygonal.

[0110] Example 6 is the tool assembly of example 1, wherein the faceted cross-sectional profile is defined by an outer surface of the proximal end of the friction extrusion die.

[0111] Example 7 is the tool assembly of example 6, wherein the outer surface of the proximal end of the friction extrusion die defines a protrusion with the faceted cross-sectional profile.

[0112] Example 8 is a method of friction extruding, the method comprising: receiving iron feedstock including one or more non-ferritic elements; and applying an axial force and a rotational force, applied via a distal face of a die, to the iron feedstock for plasticizing the iron feedstock to generate an iron alloy extrudate from the iron feedstock.

[0113] Example 9 is the method of example 8, wherein the applying the axial force and the rotational force incudes using a friction extrusion die comprising: the distal face defining at least one topographical ridge or groove feature to induce plasticization of a material in response to the axial force and the rotational force applied by the distal face to the material, the die defining a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces; and a proximal end defining a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder, the faceted cross-sectional profile sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

[0114] Example 10 is the method of example 8, wherein the received iron feedstock comprises an oxide dispersion strengthened (ODS) alloy precursor, the ODS alloy precursor produced at least in part using a gas atomization process, the gas atomization process including use of a gas mixture comprising oxygen.

[0115] Example 11 is the method of example 10, wherein the one or more non-ferritic elements comprise at least one of yttrium, titanium, or oxygen.

[0116] Example 12 is the method of example 10, wherein the iron alloy extrudate is an ODS iron alloy comprising: bulk material; and nanoparticle precipitates dispersed in the bulk material, the nanoparticle precipitates having relatively higher atomic percentages of non-ferritic elements comprising at least one of titanium, oxygen, or yttrium, in comparison with the bulk material, the nanoparticle precipitates having a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material, and wherein the bulk material has a relatively higher atomic percentage of iron than the nanoparticle precipitates.

[0117] Example 13 is the method of example 12, the ODS iron alloy having a fracture toughness exceeding 250 megapascals by square root meter ($MPa \cdot m^{1/2}$) at room temperature.

[0118] Example 14 is the method of example 8, wherein the received iron feedstock has been generated from iron ore, the iron feedstock comprising iron pellets, the iron pellets being at least 70 weight percent iron.

[0119] Example 15 is the method of example 14, wherein the one or more non-ferritic elements comprise at least one of silica or alumina.

[0120] Example 16 is the method of example 9, wherein the iron alloy extrudate is a high strength sponge iron, the high strength sponge iron having a yield strength within a range of 40 to 50 kilo-pounds per square inch (ksi) at room temperature.

[0121] Example 17 is the method of example 9, wherein the iron alloy extrudate is a high strength sponge iron, the high strength sponge iron having a hardness within a range of 300 to 400 Vickers Pyramid Number (HV).

[0122] Example 18 is a friction extrusion comprising: an oxide dispersion strengthened (ODS) iron alloy having a fracture toughness exceeding 250 megapascals by square root meter ($MPa \cdot m^{1/2}$) at room temperature, the ODS iron alloy comprising: bulk material; and nanoparticle precipitates dispersed in the bulk material, the nanoparticle precipitates having relatively higher atomic percentages of non-ferritic elements including at least one of titanium, oxygen, or yttrium, in comparison with the bulk material, and wherein the bulk material has a relatively higher atomic percentage of iron in comparison with the nanoparticle precipitates.

[0123] Example 19 is the friction extrusion of example 18, the nanoparticle precipitates having a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material.

[0124] Example 20 is the friction extrusion of example 18, wherein the friction extrusion is dimensionally stable under stress at a temperature of 650° C.

[0125] Example 21 is an apparatus comprising means to implement of any of Examples 1-20.

[0126] Example 22 is a system to implement of any of Examples 1-20.

[0127] Example 23 is a method to implement of any of Examples 1-11 or Example 20.

[0128] Each of these non-limiting examples can stand on its own or can be combined in various permutations or combinations with one or more of the other examples.

[0129] 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 herein as "examples." Such examples can include elements in addition to those shown or described. However, the present inventor also contemplates examples in which only those elements shown or described are provided. Moreover, the present inventor also contemplates 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.

[0130] 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" can include "A but not B," "B but not A," and "A and B," unless otherwise indicated. In the appended claims, 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, 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.

[0131] The method examples described herein may be machine or computer-implemented at least in part. Some examples may include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device or system to perform methods as described in the above examples. An implementation of such methods may include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code may include computer readable instructions for performing various methods. The code may form portions of computer program products. Further, the code may be tangibly stored on one or more volatile or non-volatile computer-readable media during execution or at other times.

[0132] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) can 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. 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 can 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 can lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description, 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.

What is claimed is:

1. A tool assembly for friction extrusion, the tool assembly comprising:

a friction extrusion die comprising:

a distal face defining at least one topographical ridge or groove feature to induce plasticization of a material in response to an axial force and a rotational force applied by the distal face to the material, the friction extrusion die defining a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces; and

a proximal end defining a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder, the faceted cross-sectional profile sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

2. The tool assembly of claim **1**, wherein the faceted cross-sectional profile of the proximal end of the friction extrusion die is configured to mate with a receiving end of the tool holder.

3. The tool assembly of claim **2**, wherein the receiving end of the tool holder defines a socket configured to mate with the faceted cross-sectional profile of the proximal end of the friction extrusion die, wherein respective inward-facing faces of the socket extend inward toward a longitudinal central axis of the socket to provide the engagement by the tool holder of the respective faces of defined by the faceted cross-sectional profile.

4. The tool assembly of claim **2**, wherein vertices of the respective faces defined by the faceted cross-sectional profile extend outward away from a longitudinal central axis to enable the engagement by the tool holder of the respective faces.

5. The tool assembly of claim **1**, wherein the faceted cross-sectional profile is polygonal.

6. The tool assembly of claim **1**, wherein the faceted cross-sectional profile is defined by an outer surface of the proximal end of the friction extrusion die.

7. The tool assembly of claim **6**, wherein the outer surface of the proximal end of the friction extrusion die defines a protrusion with the faceted cross-sectional profile.

8. A method of friction extruding, the method comprising:

receiving iron feedstock including one or more non-ferritic elements; and

applying an axial force and a rotational force, applied via a distal face of a die, to the iron feedstock for plasticizing the iron feedstock to generate an iron alloy extrudate from the iron feedstock.

9. The method of claim **8**, wherein the applying the axial force and the rotational force incudes using a friction extrusion die comprising:

the distal face defining at least one topographical ridge or groove feature to induce plasticization of a material in response to the axial force and the rotational force applied by the distal face to the material, the die defining a central passage to carry an extrudate of the material in a proximal direction in response to the applied axial and rotational forces; and

a proximal end defining a faceted cross-sectional profile to mate a with a corresponding receiving end of a tool holder, the faceted cross-sectional profile sized and shaped to receive the rotational force through engagement by the tool holder of respective faces defined by the faceted cross-sectional profile.

10. The method of claim **8**, wherein the received iron feedstock comprises an oxide dispersion strengthened (ODS) alloy precursor, the ODS alloy precursor produced at least in part using a gas atomization process, the gas atomization process including use of a gas mixture comprising oxygen.

11. The method of claim **10**, wherein the one or more non-ferritic elements comprise at least one of yttrium, titanium, or oxygen.

12. The method of claim **10**, wherein the iron alloy extrudate is an ODS iron alloy comprising:

bulk material; and

nanoparticle precipitates dispersed in the bulk material, the nanoparticle precipitates having relatively higher atomic percentages of non-ferritic elements comprising at least one of titanium, oxygen, or yttrium, in comparison with the bulk material, the nanoparticle precipitates having a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material, and wherein the bulk material has a relatively higher atomic percentage of iron than the nanoparticle precipitates.

13. The method of claim **12**, the ODS iron alloy having a fracture toughness exceeding 250 megapascals by square root meter ($MPa \cdot m^{1/2}$) at room temperature.

14. The method of claim **8**, wherein the received iron feedstock has been generated from iron ore, the iron feedstock comprising iron pellets, the iron pellets being at least 70 weight percent iron.

15. The method of claim **14**, wherein the one or more non-ferritic elements comprise at least one of silica or alumina.

16. The method of claim **9**, wherein the iron alloy extrudate is a high strength sponge iron, the high strength sponge iron having a yield strength within a range of 40 to 50 kilo-pounds per square inch (ksi) at room temperature.

17. The method of claim **9**, wherein the iron alloy extrudate is a high strength sponge iron, the high strength sponge iron having a hardness within a range of 300 to 400 Vickers Pyramid Number (HV).

18. A friction extrusion comprising:

an oxide dispersion strengthened (ODS) iron alloy having a fracture toughness exceeding 250 megapascals by square root meter (MPa·$m^{1/2}$) at room temperature, the ODS iron alloy comprising:

bulk material; and

nanoparticle precipitates dispersed in the bulk material, the nanoparticle precipitates having relatively higher atomic percentages of non-ferritic elements including at least one of titanium, oxygen, or yttrium, in comparison with the bulk material, and wherein the bulk material has a relatively higher atomic percentage of iron in comparison with the nanoparticle precipitates.

19. The friction extrusion of claim **18**, the nanoparticle precipitates having a density within a range of $10^{22}/m^3$ to $10^{23}/m^3$ dispersed in the bulk material.

20. The friction extrusion of claim **18**, wherein the friction extrusion is dimensionally stable under stress at a temperature of 650° C.

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