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(54) **SYSTEM AND PROCESS FOR FORMATION OF EXTRUSION STRUCTURES**

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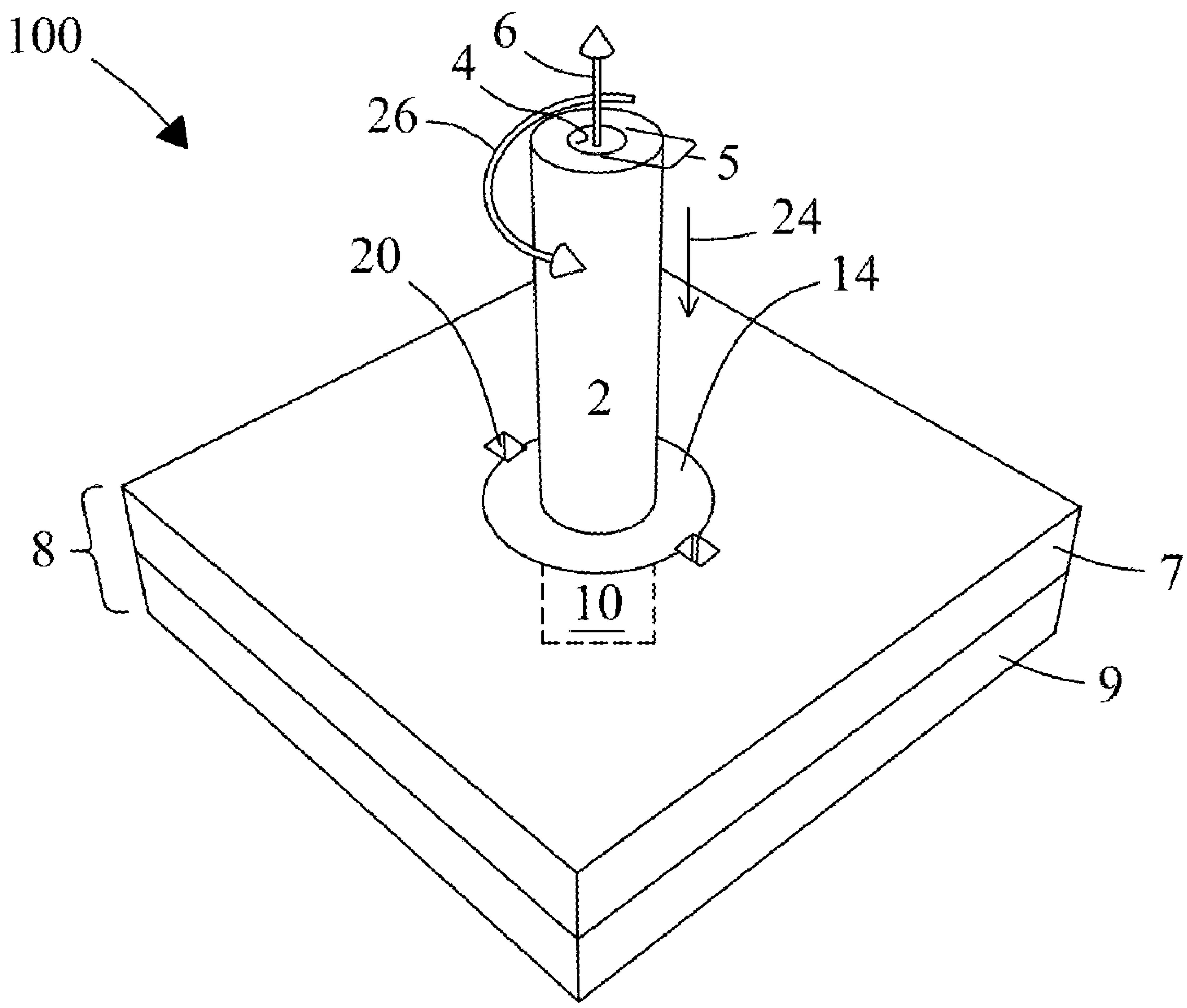
USPC **72/262**; 72/271; 72/269

(57) **ABSTRACT**

An extrusion apparatus and process are disclosed that produce high-performance extrusion structures. The extrusion apparatus includes a shear tool that applies a rotational shear force and an axial extrusion force to the face of a billet material that plasticizes the billet material. Plasticized material is extruded through an extrusion die along the length of the inner bore of the shear tool which yields hollow and solid extrusion structures. The process refines the microstructures of the extrusion structures and extrusion materials.



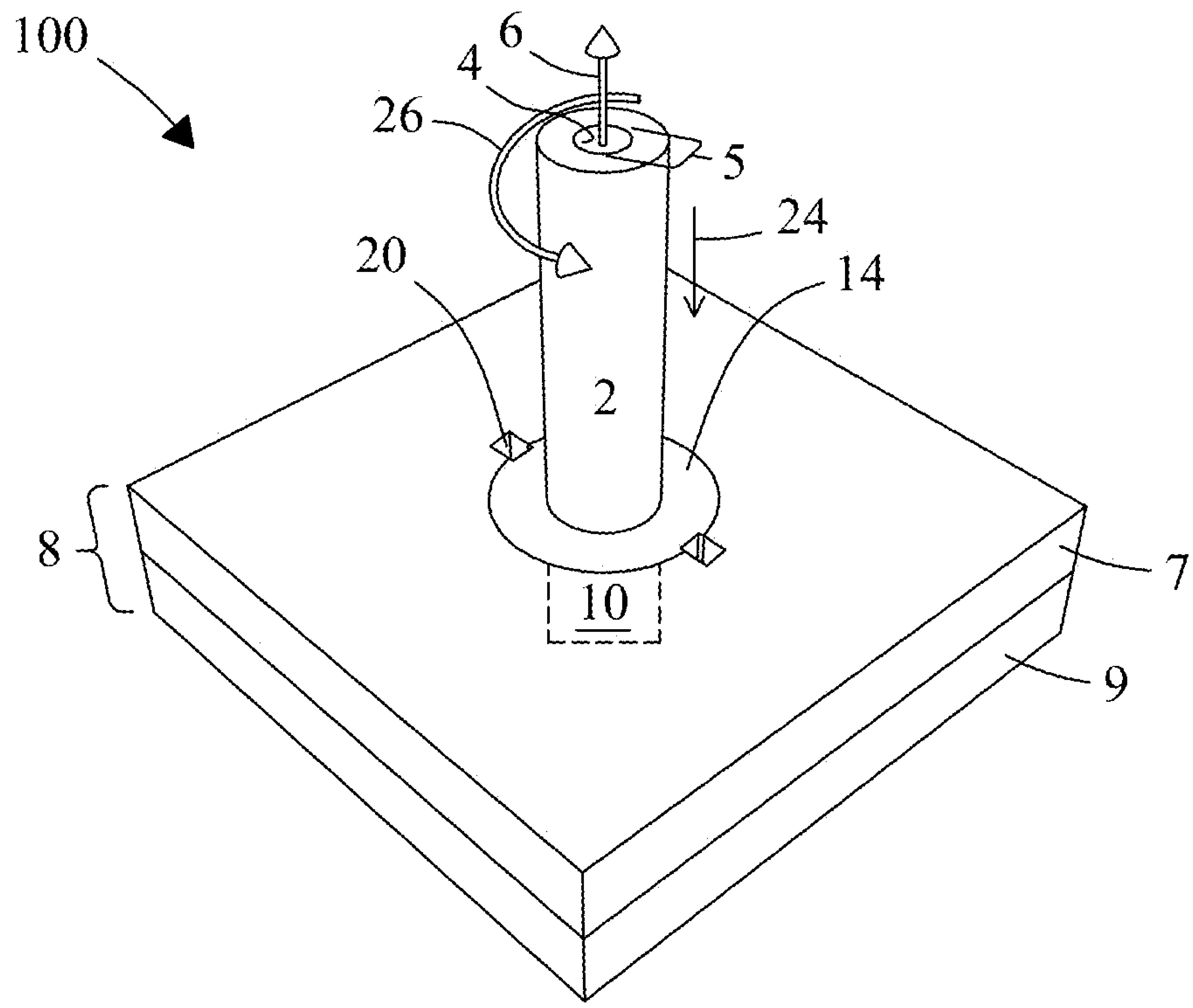


FIG. 1

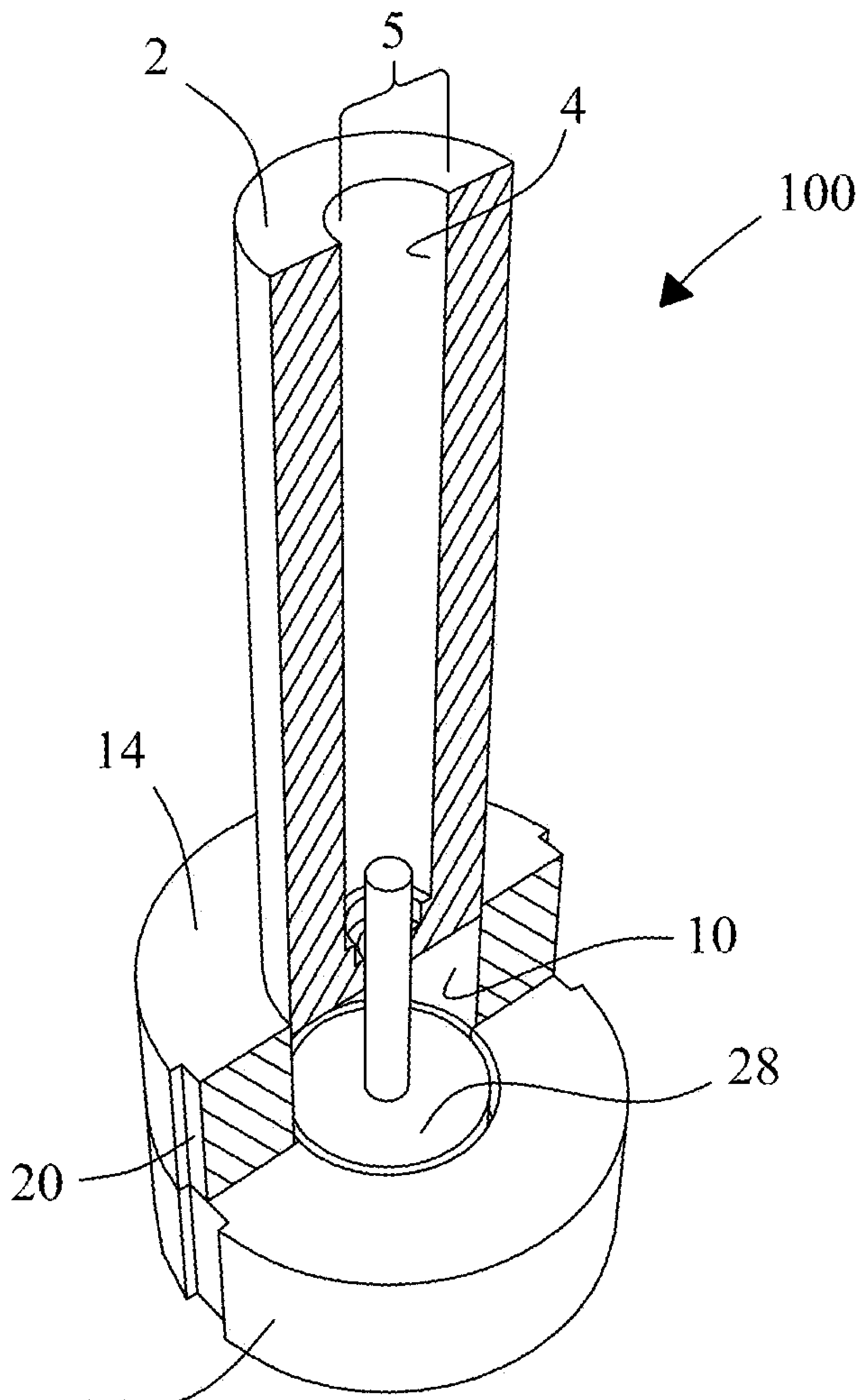


FIG. 2

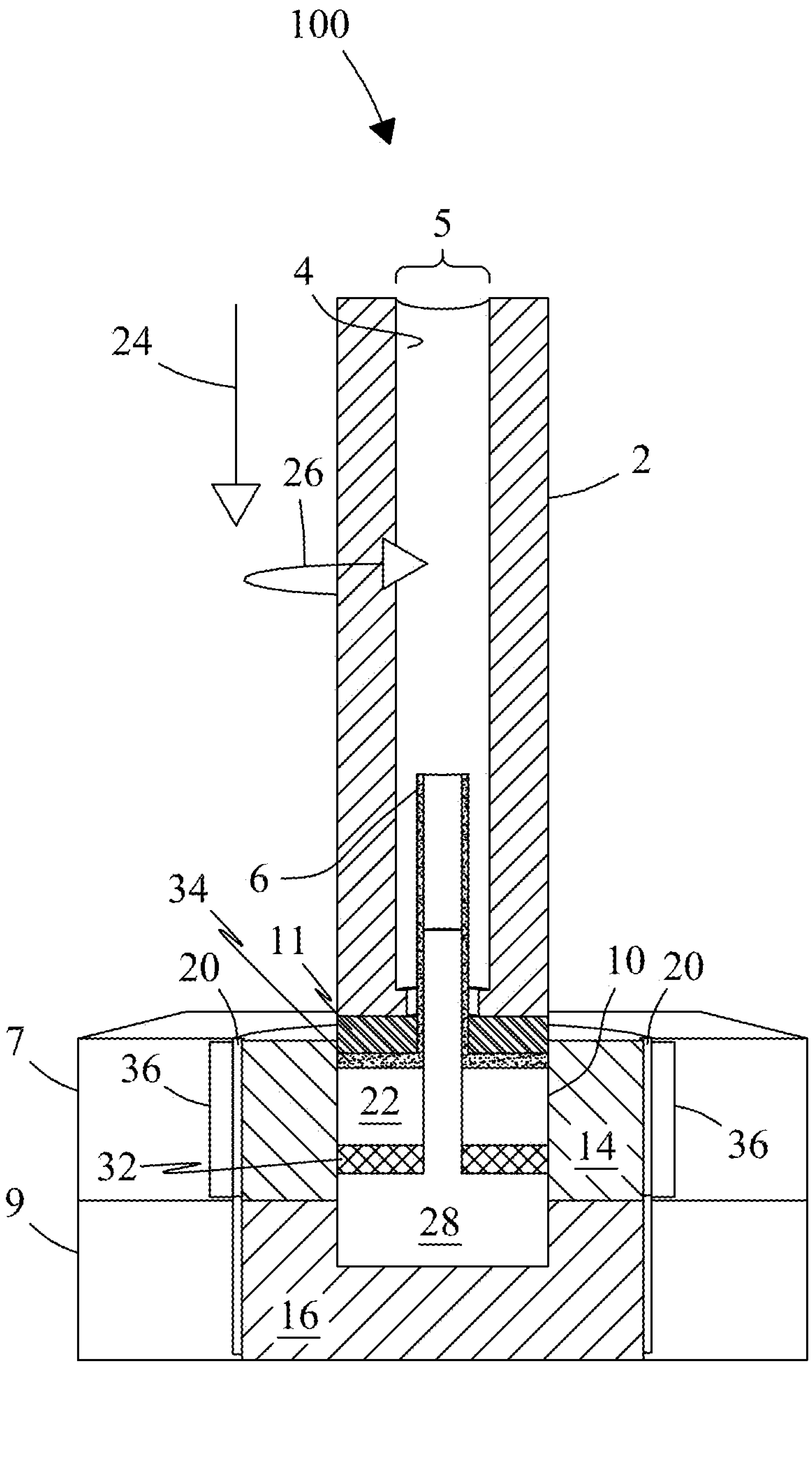


FIG. 3A

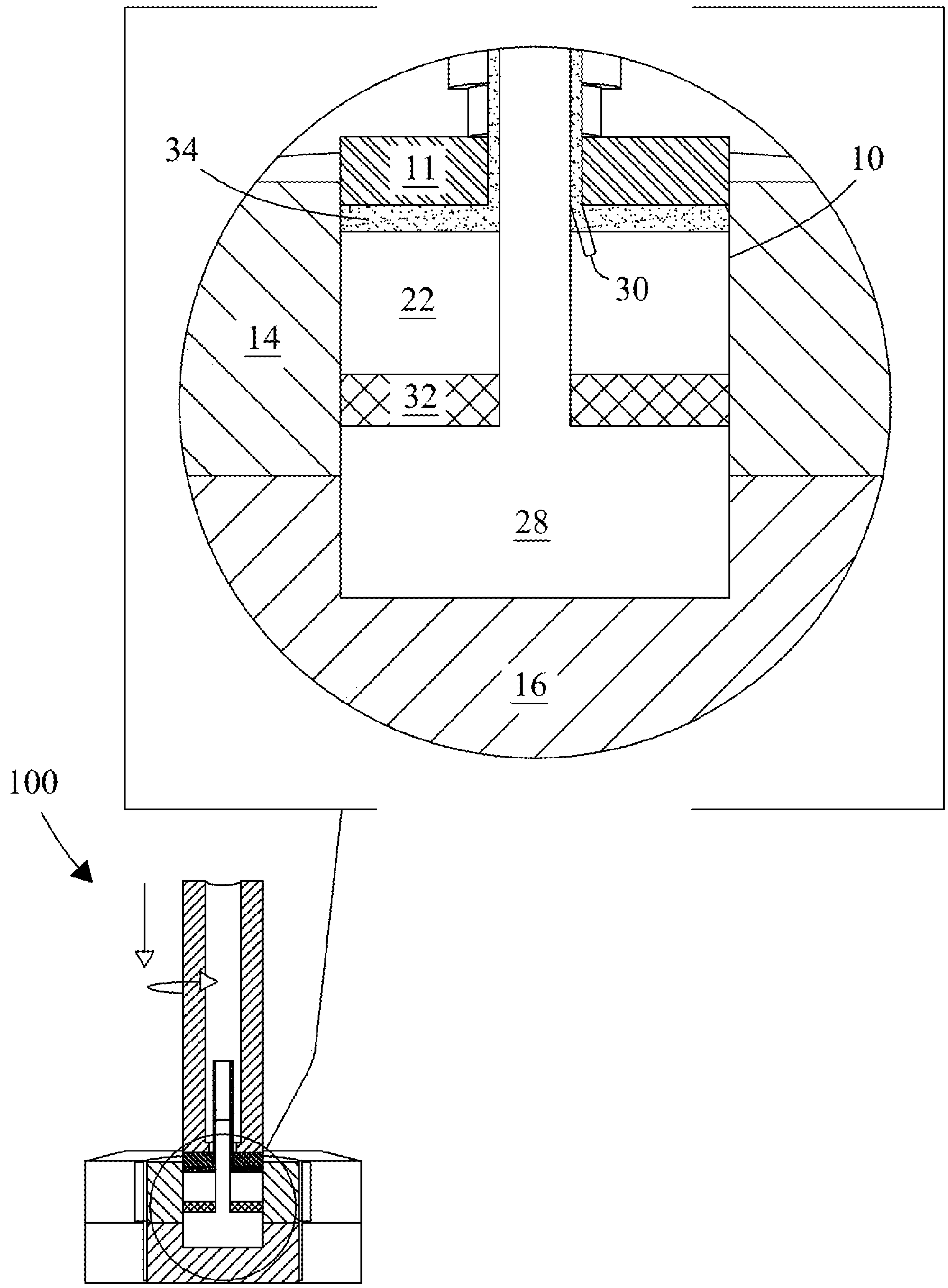


FIG. 3B

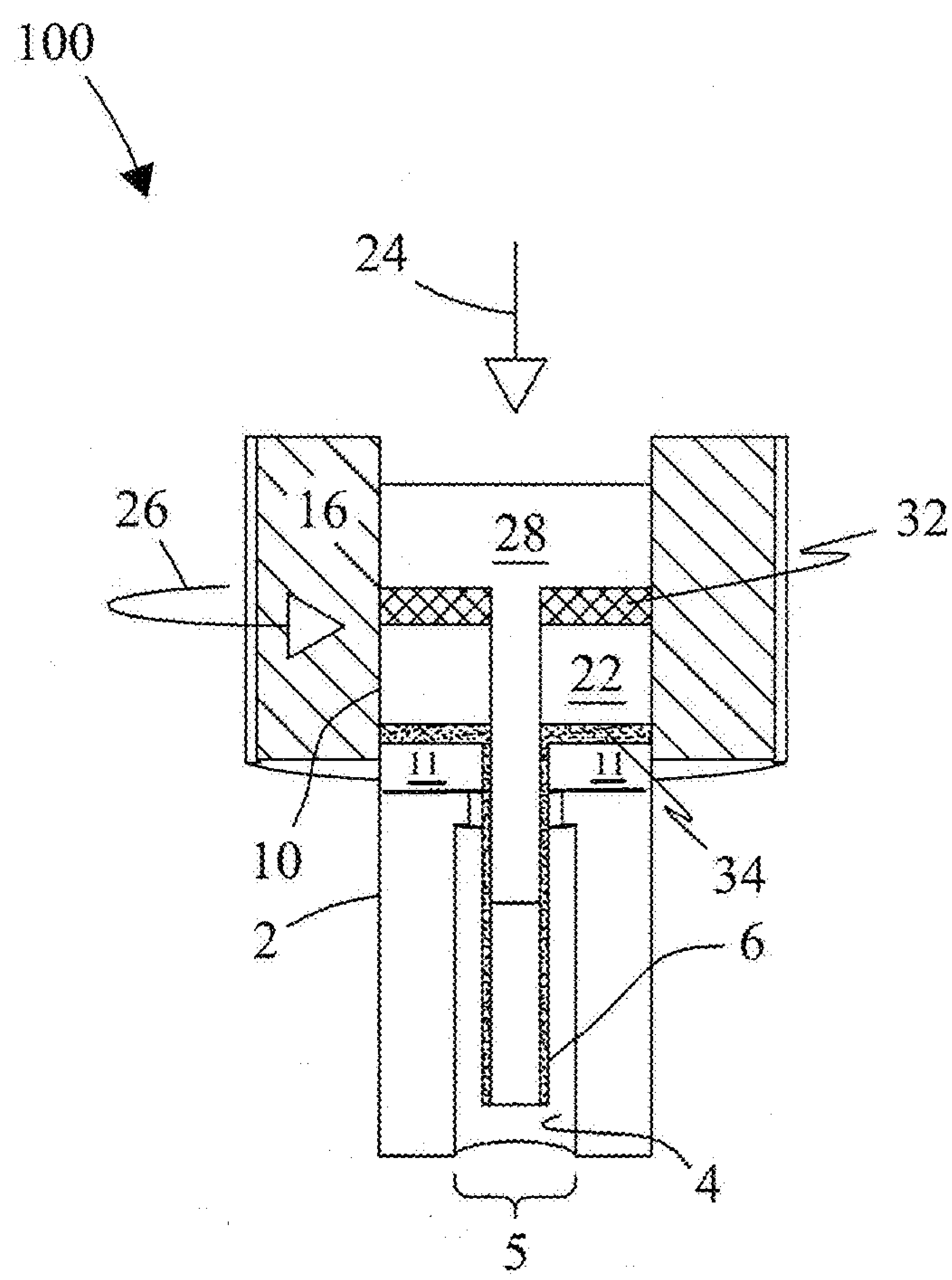


FIG. 3C

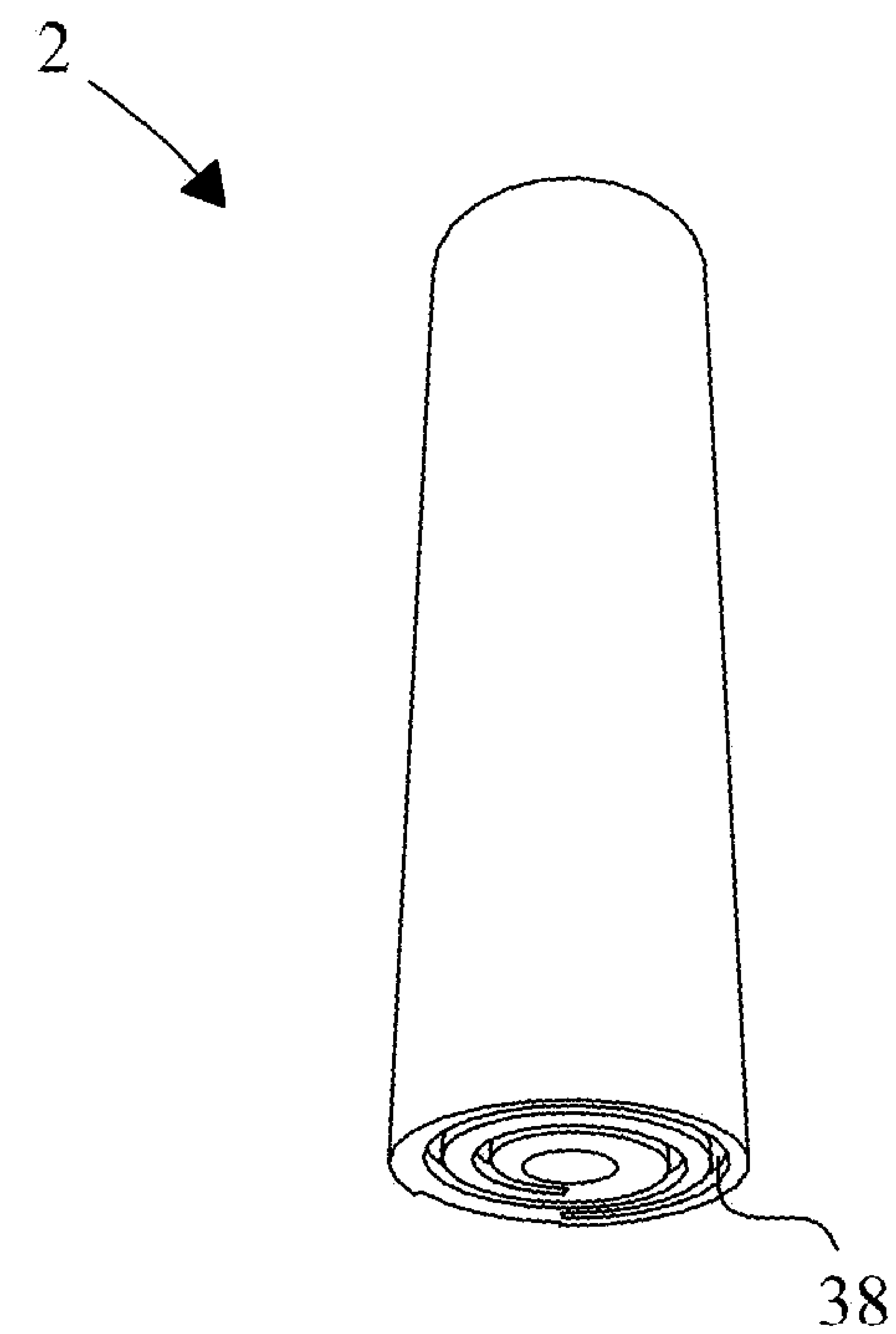

2
38

FIG. 4

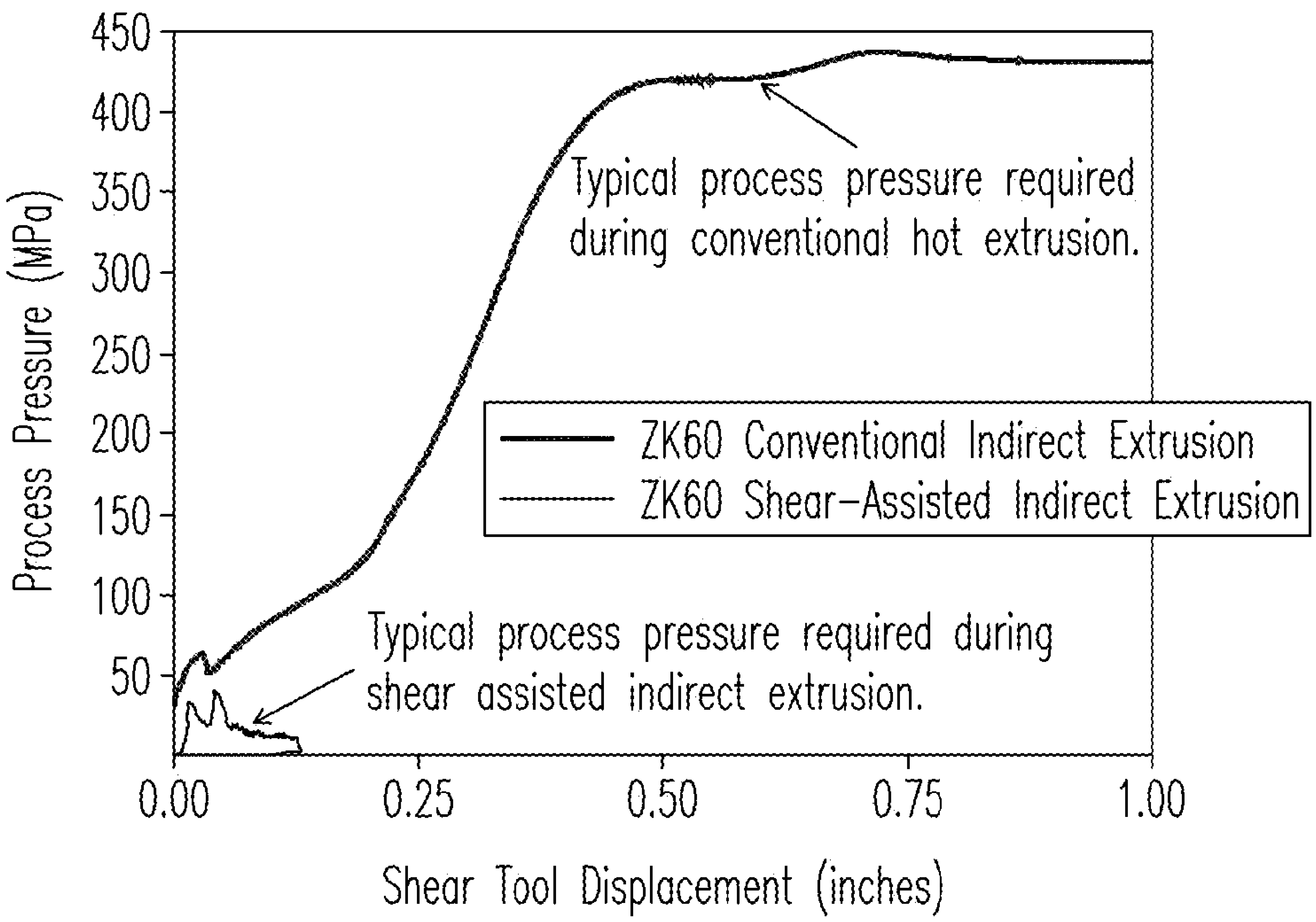
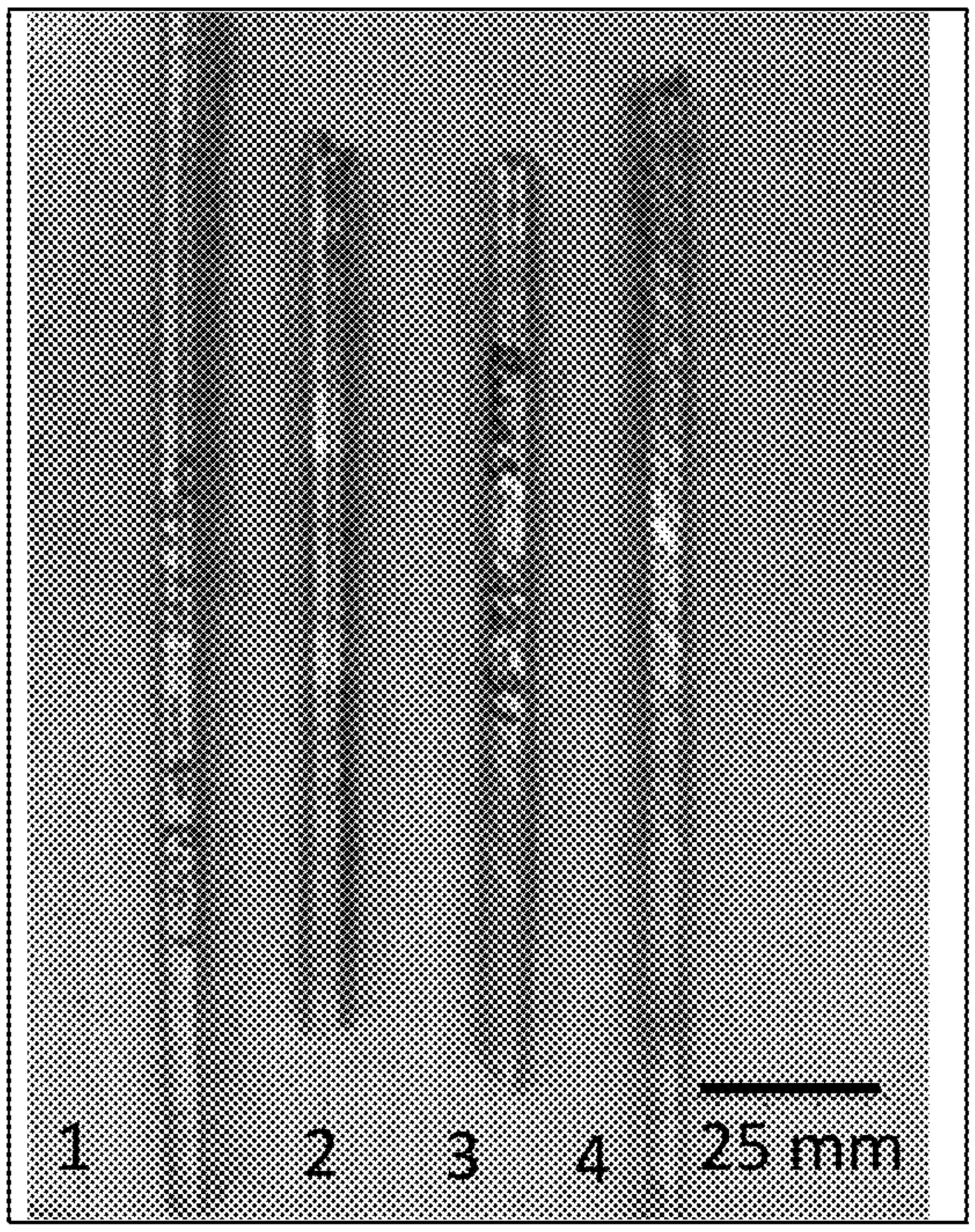

450
400
350
300
250
200
150
100
50
Process Pressure (MPa)
0.00
0.25
0.50
0.75
1.00
Shear Tool Displacement (inches)
Typical process pressure required during conventional hot extrusion.
Typical process pressure required during shear assisted indirect extrusion.
ZK60 Conventional Indirect Extrusion
ZK60 Shear-Assisted Indirect Extrusion

FIG. 5

6



6

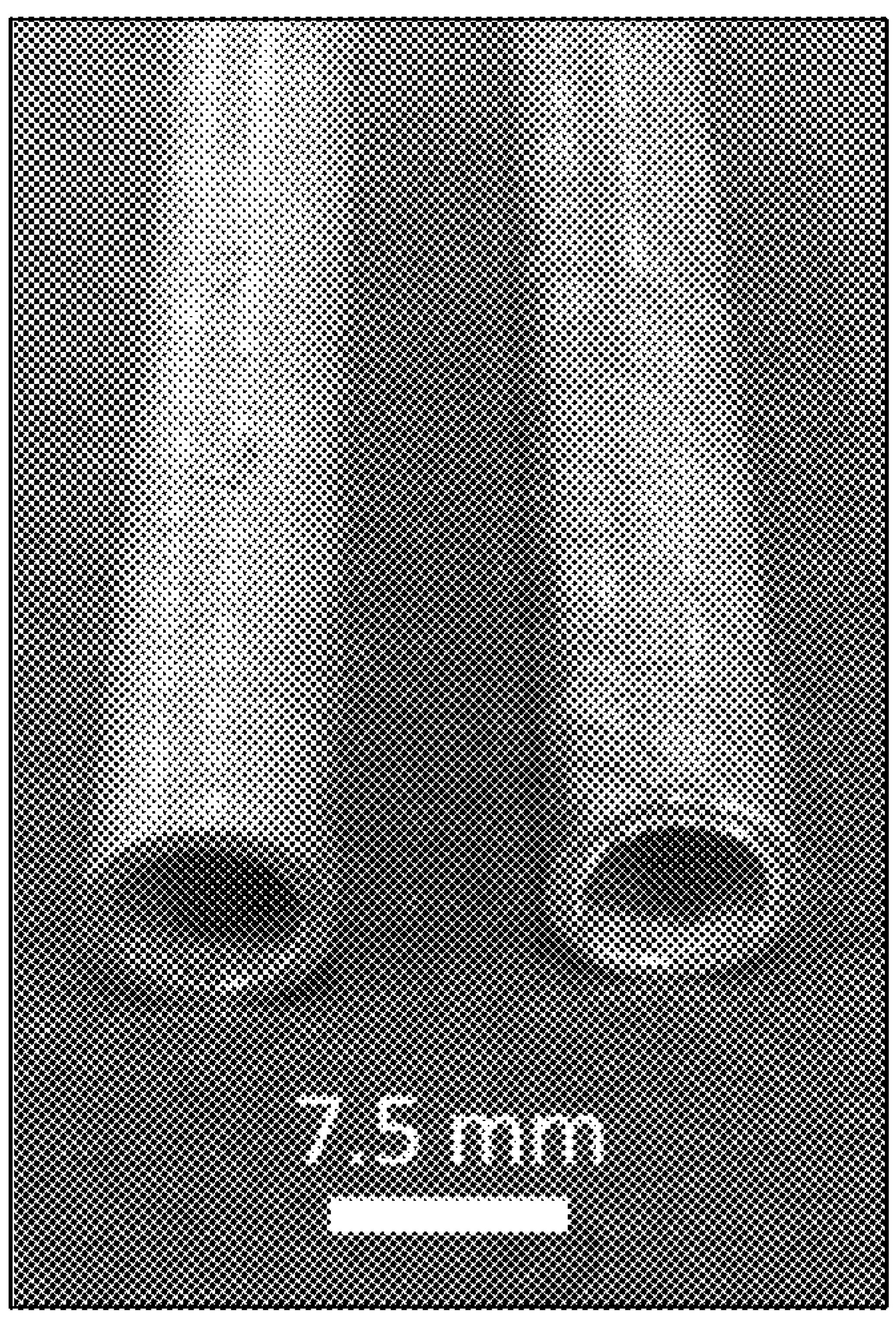


FIG. 6

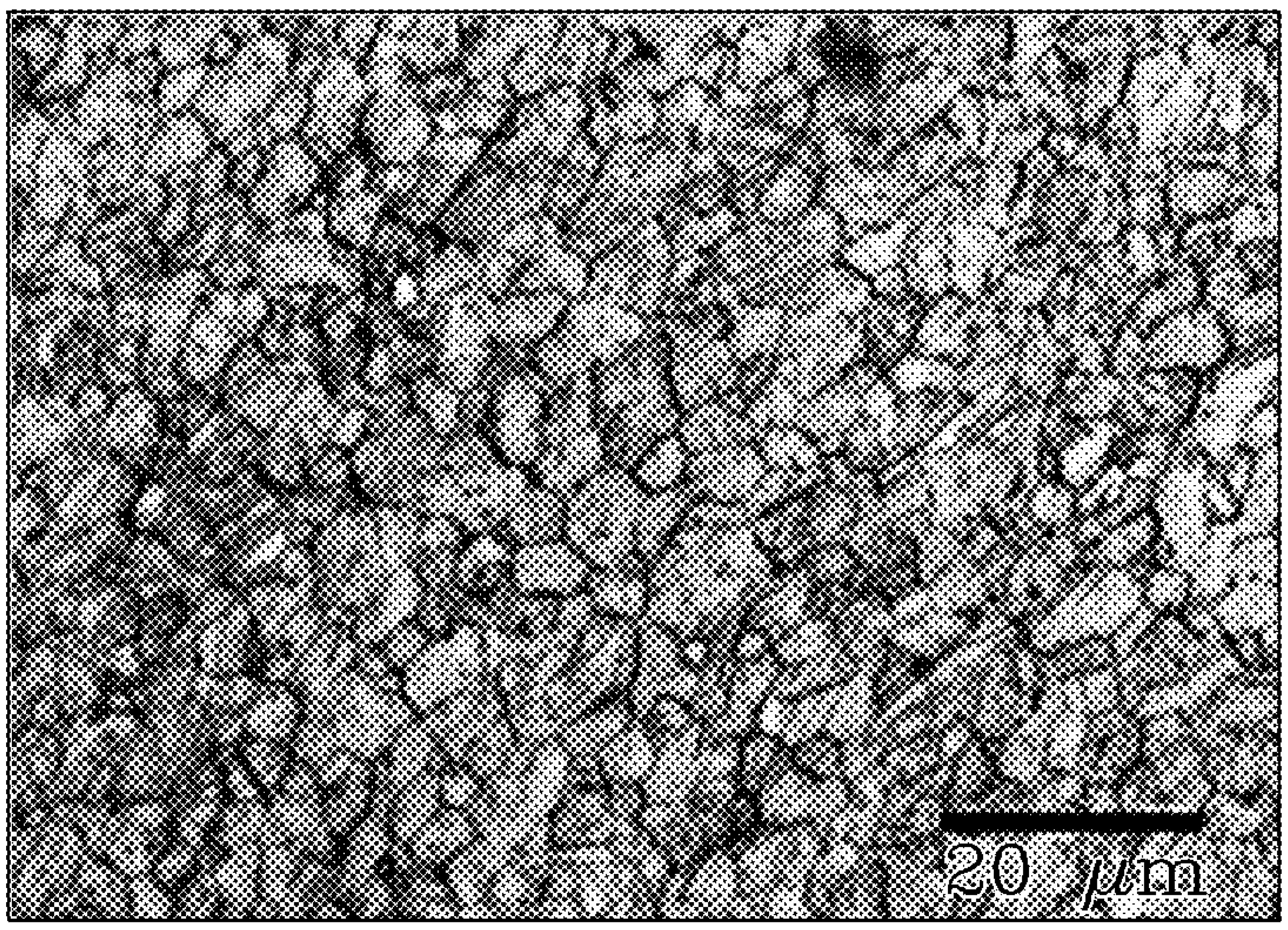


FIG. 7

SYSTEM AND PROCESS FOR FORMATION OF EXTRUSION STRUCTURES

CROSS REFERENCE TO RELATED APPLICATION

[0001] This is a Non-Provisional application that claims priority from U.S. Provisional Application No. 61/804,560 filed 22 Mar. 2013, which reference is incorporated herein in its entirety.

STATEMENT REGARDING RIGHTS TO INVENTION MADE UNDER FEDERALLY-SPONSORED RESEARCH AND DEVELOPMENT

[0002] This invention was made with Government support under Contract DE-AC05-76RLO-1830 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The present invention relates generally to extrusion processing and extrusion tools. More particularly, the invention relates to a shear-assisted extrusion system and process for production of extrusion structures including high-performance extrusion structures.

BACKGROUND OF THE INVENTION

[0004] Extrusion is a process in which a billet or block of material composed of metals, polymers, ceramics, or foodstuffs is forced through an extrusion die with a ram tool that transmits an extrusion force to the billet that plasticizes the material. The plasticized material is then extruded through the orifice of an extrusion die that forms an extrusion product (extrudate). The resulting extrusion product has a cross-sectional area or profile that is typically smaller than that of the original billet. In conventional extrusion, only the linear or axial motion of the ram plasticizes and extrudes the billet material. Extrusion processes fall under two general categories: (i) direct extrusion, and (ii) indirect extrusion. In direct extrusion, the extrusion die and a solid ram are positioned on opposite ends of the billet. In indirect extrusion, the extrusion die is attached to a hollow ram on the same side of the billet. A mandrel may be attached to the hollow ram during extrusion of the billet material to produce hollow extrudates. Problems with extrusion processing are well known in the art. Conventional extrusion requires high extrusion pressures on the order of 400 MPa or higher. In addition, non-uniform deformation of extrudates is common, which yields extrusion products with structural and physical property variations in both the longitudinal and transverse directions. Further, microstructure refinement is often inconsistent and typically insufficient so mechanical properties vary widely. And, while processes like mechanical alloying, rapid solidification, friction stir processing, equal channel angular extrusion, twist extrusion, waffle pattern rolling, non-axis symmetric rolling, and other processes have been used to make high performance materials, such processes are not presently cost-effective for commercial production. Accordingly, new extrusion processing tools and processes are needed that overcome conventional force requirements and other limitations of conventional extrusion processing. The present invention addresses these needs. The purpose of the foregoing abstract is to enable the United States Patent and Trademark Office and the public generally, especially scientists, engineers, and practitioners in the art who are not familiar with patent or legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The abstract is neither intended to define the invention of the application, which is measured by the claims, nor is it intended to be limiting as to the scope of the invention in any way.

SUMMARY OF THE INVENTION

[0005] The present invention includes an extrusion assembly and process for production of high-performance extrusion structures and extrusion products. The extrusion assembly may include a shear tool with an extrusion die of a selected shape. The shear tool is configured to apply a rotational shear (shearing) force and an axial extrusion pressure to the face of a billet material at the shear tool/billet interface positioned within the die chamber of the extrusion assembly that plastically deforms the billet material. The billet may include various selected materials including, but not limited to, e.g., metals, metal alloys, cast solids, powders, and non-solids. The extrusion die may be positioned at the billet end of the shear tool and may include an orifice with a selected shape and selected dimensions. The extrusion die may extrude the plasticized billet material along the length of the inner bore of the shear tool in response to the axial extrusion pressure applied to the face of the billet yielding extrusion structures and products with selected shapes including complex shapes with selected dimensions. The inner bore of the shear tool may include selected dimensions. The shear tool forms extrusion structures and products at an axial extrusion pressure significantly lower than required for extrusion structures without the shearing force applied. The extrusion die may extrude the plasticized billet material along the length of the inner bore of the shear tool in response to the axial extrusion pressure applied to the face of the billet material.

[0006] The present invention also includes a shear-assisted extrusion process that produces extrusion structures including high-performance extrusion structures. The process may include applying a rotational shearing force and an axial extrusion force to the face of the billet material at the shear tool/billet interface to plasticize the billet material. The shearing force may be applied at the shear tool/billet interface by rotation of the shear tool at a selected rotation speed relative to a stationary billet, or by rotation of the billet relative to a stationary shear tool, and/or by rotation of the shear tool at a rotation speed that is different relative to the rotation of the billet, or vice versa. The plasticized material may be extruded the through an orifice of an extrusion die positioned on the billet side of the shear tool. The orifice of the extrusion die may include various selected shape that yield extrusion structures with selected shapes. Rotational shear force values are not limited. Shear forces are selected that reduce the axial extrusion pressures needed to plasticize billet materials. The extrusion assembly extrudes the billet material at an axial extrusion force less than that required for extrusions performed without the rotational shearing force applied by the shear tool and/or the billet at the shear tool/billet interface.

[0007] In some applications, the billet may be a pierced cast billet, a pre-drilled cast billet, a solid cast billet, or loose powder billets.

[0008] Extrusion structures may be hollow or solid. The extrusion assembly may include a mandrel that inserts into the inner bore of the shear tool to a selected depth. In some applications, the mandrel may be introduced through the center of the billet and into the inner bore through an orifice of the extrusion die positioned at the billet end or other end of the shear tool. The mandrel may include a width dimension that is less than the dimension of the orifice of the extrusion die that forms a separation gap between the surface of the mandrel and the inner wall of the extrusion die when the mandrel is inserted. During extrusion, the separation gap allows plasticized materials to flow past the mandrel along the length of the inner wall of the extrusion die and into the inner bore of the shear tool that yields hollow extrusion structures with selected shapes. The extrusion die determines the wall thickness of hollow extrusion structures produced during extrusion.

[0009] Shapes are not limited. In various applications, extrusion structures may be hollow tubular structures with selected uniform or non-uniform inner dimensions and selected uniform or non-uniform wall thicknesses. In various applications, extrusion structures may be solid extrusion structures with selected uniform or non-uniform cross-sections. No limitations are intended.

[0010] In some applications, the mandrel may be a fixed mandrel or a floating mandrel. In some applications, the extrusion die may be a bridge extrusion die. However, mandrels and extrusion dies are not limited thereto.

[0011] The shear tool may include one or more surface features positioned at the billet end of the shear tool that engage the face of the billet material to facilitate shear-assisted extrusion and flow of plasticized materials during operation. Features may include, but are not limited to, e.g., scrolls, flutes, vanes, or other features including combinations of these features.

[0012] In some applications, the extrusion assembly may include a heating device such as an external heating device or an embedded heating device and/or a cooling device positioned to heat or cool the billet material positioned within the die chamber, respectively. Billet materials may also be heated using the frictional heat generated from the plastically deformed billet materials.

[0013] Extrusion temperatures are not limited. In some applications, extrusion of the plasticized billet material may be performed at a temperature selected between about −196° C. and about 0° C. In some applications, extrusion of the plasticized billet material may be performed at a temperature selected between about 0° C. and about 1000° C., or greater.

[0014] Shearing forces applied by the present invention may be obtained by rotating the billet while keeping the shear tool stationary, by rotating the shear tool while keeping the billet material stationary, or by rotating the shear tool at a rotational speed different than the rotational speed of the billet material or vice versa.

[0015] In some applications, applying the rotational shear force and extruding the plasticized billet material may be performed simultaneously. In some applications, applying the rotational shear force and extruding the plasticized billet material may be performed independently from the other step.

[0016] In some applications, axial extrusion pressures required for extrusion may be reduced by at least a factor of about 16 times compared to extrusion operations performed without the rotational shearing force. In some applications, the axial extrusion pressure is at or below about 50 MPa. In some applications, the axial extrusion pressure is at or below about 25 MPa. However, axial pressures are not limited.

[0017] Feed rates for the billet are not limited. In some applications, feed rates may be between about 0.15 inches (0.38 cm) per minute and about 1.18 inches (3.0 cm) per minute.

[0018] Rotational speeds are not limited. In various applications, rotation may be performed at a rotation speed between about 500 revolutions-per-minute (rpm) and about 1000 rpm. In some applications, rotation may be performed at a rotation speed up to about 1000 rpm. In some applications, rotation speed may be between about 10 rpm and about 1000 rpm.

[0019] Shear-assisted extrusion processing of the present invention can refine the microstructure of billet materials including cast billet materials and powdered billet materials, or other processed materials. For example, billets containing coarse matrix grains and second-phase intermetallic particles with sizes up to a millimeter (1000 microns) may be refined in a single process step to yield smaller grains and particles. In some applications, the process refines the microstructure to yield fine matrix grains and second-phase intermetallic particles with a size less than or equal to about 10 microns. In some applications, the process yields very (ultra) fine matrix grains and second-phase intermetallic particles with a size less than or equal to about 1 micron or finer. In some applications, the process yields grains with a size less than about 100 nanometers or finer. However, no limitations are intended. In some applications, the present invention alters the morphology of second-phase particles in the starting billet material from an aspect ratio above about 2 to an aspect ratio below about 2 following the shear-assisted extrusion processing. In some applications, microstructure grains and particles of the original billet material are refined by at least a factor of 2 times to a size that is at least one-half that of the original billet material prior to extrusion processing or finer. Shear-assisted extrusion processing can also uniformly distribute grains and particles within the refined microstructure.

[0020] In some applications, extrusion structures are tubular extrusion structures that may be included as components of a compression device, a stent device, a bending-resistant device. Compression devices include, but are not limited to, e.g., compression bumpers or collapsible safety frames deployed in automobiles. In various applications, extrusion structures of the present invention may be incorporated as components of selected structures such as in support pillars or other structures deployed in vehicles to enhance mechanical properties, performance, or to resist bending. In some applications, extrusion structures may be included as components of a stent device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. **1** is an isometric external view of an extrusion assembly of an indirect extrusion type, according to one embodiment of the present invention.

[0022] FIG. **2** shows exemplary internal and external components of the extrusion assembly.

[0023] FIG. **3**A is a cross-sectional view of the extrusion assembly of FIG. **1**.

[0024] FIG. **3**B is an expanded view of the embodiment of FIG. **3**A.

[0025] FIG. **3**C shows a cross-sectional view of an extrusion assembly of a direct extrusion type, according to another embodiment of the present invention.

[0026] FIG. **4** is a perspective view of a shear tool that includes a scroll feature.

[0027] FIG. **5** compares extrusion pressure data for conventional indirect extrusion and shear-assisted extrusion of the present invention.

[0028] FIG. **6** shows exemplary tubular extrusion structures produced by the process of the present invention.

[0029] FIG. **7** is a photomicrograph showing grains and particles in the extrusion structure following extrusion processing.

DETAILED DESCRIPTION OF THE INVENTION

[0030] A new shear-assisted extrusion apparatus and process are disclosed for producing high-performance extrusion structures including, e.g., hollow and solid extrusion structures. In the following description, embodiments of the present invention are shown and described that include a best mode contemplated for carrying out the invention. It will be clear from the following description that the invention is susceptible of various modifications and alternative constructions. The present invention is intended to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention as defined in the claims. Therefore the description should be seen as illustrative and not limiting.

[0031] FIG. **1** shows an extrusion assembly **100** of an indirect extrusion type for production of high-performance extrusion structures. Extrusion assembly **100** may include a shear tool **2** that is configured to apply a rotational shear (shearing) force **26** and an axial extrusion force **24** to the face of a billet material (not shown) positioned within a die chamber **10** that assists plasticization of the billet material. Extrusion assembly **100** and shear tool **2** may be constructed of, e.g., steel alloys (e.g., H-13 tool steel), titanium alloys, nickel alloys, and combinations of these materials that resist physical and chemical wear at a wide range of temperatures, are mechanically strong, and effectively distribute heat through the billet during extrusion processing.

[0032] Extrusion assembly **100** may include a container **8** comprised of, e.g., an upper container plate **7** and a lower container plate **9**. Container **8** may also be a single component. No limitations are intended. In the instant embodiment, outer (top) die ring **14** and a lower die ring (described further in reference to FIG. **2**) couple together to form die chamber **10**. Die chamber **10** may also be a single machined component. Again, no limitations are intended. The billet (described hereafter in reference to FIG. **3**) may be positioned within die chamber **10** to provide aligned contact with shear tool **2** when shear tool **2** is introduced into die chamber **10** during operation.

[0033] Shear tool **2** may include an inner bore **4** of a selected inner dimension with orifices **5** positioned at respective ends of shear tool **2**. Outer (top) die ring **14** and lower die ring (not shown) secure shear tool **2** in die chamber **10**. Outer die ring **14** may be secured with locking keys (not shown) that insert into key slots **20** positioned on respective sides of shear tool **2**. Position and number of key slots **20** is not limited. During operation, plasticized billet materials extrude along the length of inner bore **4** and exit from an orifice **5** of shear tool **2** as extrusion structures (extrudates) **6**. Direction of release of extrudates is not limited, as detailed further herein.

[0034] FIG. **2** is a three-dimensional view of die assembly **100** showing selected internal components. In the figure, outer (top) die ring **14** is shown positioned atop bottom (base) die ring **16**. Keys (not shown) described previously in reference to FIG. **1** insert into key slots **20** positioned on opposite sides of outer die ring **14** that lock top die ring **14** and bottom die ring **16** together. A mandrel **28** is shown positioned at the base of die chamber **10**. Mandrels may include, e.g., fixed mandrels and floating mandrels. Mandrel **28** may insert into inner bore **4** of shear tool **2**, e.g., from the billet end of shear tool **2**. Mandrel **28** may direct flow of extruded billet materials along the length of inner bore **2**. Extruded materials may release through an orifice **5** positioned, e.g., at a top end of shear tool **2**. However, release is not limited thereto, as detailed further herein.

[0035] FIG. 3A is a cross-sectional view of extrusion assembly **100** of an indirect extrusion type described previously in reference to FIG. **1**. Extrusion assembly **100** is shown in assembled form with the flow of plasticized billet material illustrated during extrusion operation. In the figure, outer die ring **14** and lower die ring **16** couple together to form die chamber **10**. In some embodiments, die chamber **10** may also be a single machined component. Die chamber **10** may be assembled within the container between, e.g., upper container plate **7** and lower container plate **9**. In some embodiments, the container may also be a single component. In the figure, billet **22** is shown positioned within die chamber **10** to provide aligned contact with shear tool **2** when shear tool **2** is introduced into die chamber **10**. A mandrel **28** described previously in reference to FIG. **2** may be positioned in chamber **10**, which may insert to a selected depth in inner bore **4** of shear tool **2** during assembly through an optional spacer (e.g., a graphite spacer) **32** through billet **22** and through an orifice **5** of an extrusion die **11**. Extrusion die **11** may be positioned at the billet end of shear tool **2**. Extrusion dies are not limited. In some embodiments, a bridge die may be employed. Orifice **5** of extrusion die **11** may include selected shapes described further herein. The extrusion die determines at least in part the shape of extrusion structures produced during extrusion operation. Mandrel **28**, optional spacer **32**, and billet **22** may be secured in chamber **10** by introducing locking keys (described previously) into key slots **20** positioned on respective sides of outer die ring **14** as described previously herein.

[0036] In operation, shear tool **2** when introduced into chamber **10** applies a rotational shear (shearing) force **26** and an axial extrusion force **24** to the face of billet material **22** at the shear tool/billet interface within die chamber **10**. Rotational shear (shearing) force **26** assists or promotes plasticization of billet material **22**. In some embodiments, rotational shear (shearing) force **26** may be applied by rotating the shear tool **2** at a selected rotation speed while keeping billet **22** stationary. In some embodiments, rotational shear (shearing) force **26** may be applied by rotating the billet **22** while keeping shear tool **2** stationary. In some embodiments, rotational shear (shearing) force **26** is applied by rotating shear tool **2** and billet **22** at different rotation speeds relative to the other component or material.

[0037] Die assembly **100** may further include an optional heater/cooler **36** that couples externally to, or is embedded within, outer die ring **14** to heat or cool billet material **22** positioned within chamber **10**. Heating and cooling of billet material **22** can be used to assist deformation of billet material **22**, e.g., by softening the billet material in cases where the billet material shows limited initial plasticity. Heating may also be used, e.g., to lower frictional forces that assist extrusion of the plasticized billet material. All heating and cooling devices as will be selected by those of ordinary skill in the art in view of this disclosure are within the scope of the present invention. No limitations are intended.

[0038] Application of axial extrusion force **24**, rotational shear force **26**, and/or heat or cooling to billet material **22** plasticizes the billet material, which forms a region of plastic deformation (SPD) **34** positioned at the shear tool/billet interface. SPD region **34** is typically narrow (e.g., <300 microns) to reduce extrusion force **24** needed to extrude the plasticized billet materials.

[0039] Plasticized billet materials may enter into inner bore **4** through an orifice (not shown) positioned, e.g., at the billet end of shear tool **2**. In the instant embodiment, plasticized material extrudes past mandrel **28** and flows upward to yield extrusion structures (extrudates) **6** that are hollow extrusion structures (e.g., tubes). In some embodiments, extrusion structures may include uniform inner dimensions and wall thicknesses. In some embodiments, extrusion structures may include non-uniform inner dimensions and wall thicknesses. When mandrel **28** is not employed, extrusion structures are solid structures. Solid extrusion structures may include uniform dimensions or non-uniform dimensions. In the instant embodiment, extrusion structures (extrudates) **6** may be released through another orifice **5** positioned at the top end of shear tool **2**.

[0040] FIG. **3**B shows an expanded view of the die assembly **100** of FIG. **3**A. As shown in the figure, plasticized billet materials may flow from deformation region **34** through a gap **30** formed between the surface of mandrel **28** and the inner wall of extrusion die **11**. Other components of extrusion assembly **100** including billet **22** positioned in chamber **10**, optional spacer **32**, upper die ring **14**, and lower die ring **16** have been described previously herein.

[0041] FIG. **3**C is a cross-sectional view of another embodiment of extrusion assembly **100** of a direct extrusion type. Die assembly **100** is shown in assembled form and also shows flow of plasticized billet material during extrusion operation. In the figure, die assembly **100** includes a billet rotation tool or device, e.g., die ring **16**, configured to apply rotational shear force **26** to the billet material **22** positioned within die chamber **10**. Billet material **22** may be in aligned contact with tool **2** or a die support. A mandrel **28** described previously in reference to FIG. **3**A may be positioned in chamber **10**, which may insert to a selected depth in inner bore **4** of shear tool **2** during assembly through an optional spacer (e.g., a graphite spacer) **32** through billet **22** and through an orifice (not shown) of extrusion die **11** positioned at the billet end of shear tool **2**. Extrusion dies are not limited. In some embodiments, a bridge die may be employed. In operation, billet rotation tool **16** applies a rotational shear (shearing) force **26** and an axial extrusion force **24** to the face of billet material **22** at the shear tool/billet interface within die chamber **10**. Extrusion assembly **100** may further include an optional heater/cooler (not shown) described previously in reference to FIG. **3**A. Application of axial extrusion force **24**, rotational shear force **26**, and/or heat or cooling to billet material **22** plasticizes the billet material, which forms a region of plastic deformation (SPD) **34** positioned at the shear tool/billet interface. SPD region **34** is preferably narrow (e.g., <300 microns) to reduce the extrusion force **24** needed to extrude plasticized billet materials. Plasticized billet materials may flow downward from deformation region **34** and extrude through an orifice **5** of extrusion die **11** that is positioned at the billet end of tool **2** into inner bore **4**. Plasticized billet materials may then flow through gap (FIG. **3**B) formed between the external surface of mandrel **28** and the inner wall (not shown) of extrusion die **11**. In the instant embodiment, plasticized material extrudes past mandrel **28** and flows downward to yield extrusion structures (extrudates) **6** that are hollow extrusion structures (e.g., tubes). In some embodiments, extrusion structures may include uniform inner dimensions and wall thicknesses. In some embodiments, extrusion structures may include non-uniform inner dimensions and wall thicknesses. When mandrel **28** is not employed, extrusion structures are solid structures. Solid extrusion structures may include uniform dimensions or non-uniform dimensions. In the instant embodiment, extrusion structures (extrudates) **6** may be released through another orifice **5** positioned at the bottom end of tool **2**.

[0042] FIG. **4** is a perspective view showing an exemplary configuration for shear tool **2**. In the instant embodiment, shear tool **2** includes a scroll feature **38** positioned at an end (face) of shear tool **2** that engages the face of the billet (FIG. **3**) to facilitate shear-assisted extrusion and flow of plasticized materials. Features include, but are not limited to, e.g., scrolls, flutes, vanes, and like features. Number of features and types of features are not intended to be limited.

Billets

[0043] Billets may be in the form of solids, cast solids, blocks, semi-solids, non-solids, and/or powders. Cast billets may be cast using casting techniques known in the casting arts. Billets may be composed of, or include, any material that can be plastically deformed (plasticized) at selected temperatures. Billet materials are preferred that deliver desirable mechanical properties such as ductility, compression strength, bendability, or selected microstructural refinement, or other suitable properties to the extrusion structures or products produced. However, no limitations are intended. In various embodiments, billets may include or be constructed of various materials including selected alloys and high-performance alloys. In some embodiments, billets may employ magnesium alloys. Magnesium alloys include, but are not limited to, e.g., magnesium alloys (e.g., AZ31F); magnesium-aluminum (Mg—Al) alloys; magnesium-zinc (Mg—Zn) alloys; magnesium-zirconium (Mg—Zr) alloys; magnesium-silicon (Mg—Si) alloys (e.g., Mg-2Si; Mg-7Si); magnesium alloys that include rare-earth (RE) elements; magnesium alloys that include various non-rare-earth elements; magnesium-zinc-zirconium alloys (e.g., ZK60-T5), and combinations of these various alloys. While magnesium-based alloys are described herein due to their desirable ductility properties for compression applications, the present invention is not intended to be limited thereto. In some embodiments, billets used for extrusion may include a central bore or hollow cavity through which the mandrel may be introduced during extrusion. In some embodiments, billets may be solid billets that are pierced or predrilled prior to use.

Extrusion Shapes

[0044] The shear tool of the present invention may include an extrusion die that includes an inner bore with various selected shapes that delivers extrusion structures with selected shapes including complex shapes. Shapes include, but are not limited to, e.g., round, oval, circular, square, rectangular, triangular, pentagonal, hexagonal, octagonal, ellipsoidal, trapezoidal, rhombal, or combinations of these various shapes. Complex shapes include, but are not limited to, e.g., spherical, tetrahedral, pyramidal, pentagonal, pentagonal pyramidal, irregular, ortahedral, icosahedral, dedecahedral, stars, cones, boat-shape ovals, parallelograms, rounded rectangles, chevrons, round left, round right, bent arrows, arrows, double arcs, curved, obround, single-D, double-D, long-D, quad-D, letters, numerical, alpha-numerical, symmetrical shapes, non-symmetrical shapes, oblong shapes, rings, pictoral shapes, other non-standard shapes, including, e.g., embedded shapes such as, e.g., ovals within a square, squares within an oval, and like embedded shapes. All shapes as will be selected by those of ordinary skill in the art in view of the disclosure are within the scope of the present invention. No limitations are intended.

Process Parameters

[0045] TABLE 1 lists compositions of alloy billets and process parameters employed in selected extrusion tests.

TABLE 1

Test Matrix for selected extrusion structures of the present invention.

Test No.	Alloy	Ram Rotation (rpm)	Feed Rate (inches/min)
1	Mg—2Si	500	0.15
2	Mg—7Si	500	0.15
3	AZ31F	500	0.15
4	ZK60-T5	500	0.15

[0046] Billet feed rates are not limited. Feed rates may be selected that maximize extrusion throughput, plasticity, flow, uniformity of the extrudates, and other physical and mechanical properties. In some embodiments, feed rates for billet deformation may be greater than about 0.01 inches per minute. In some embodiments, feed rates for billet deformation may be between about 0.01 inches per minute and about 0.1 inches per minute. In some embodiments, feed rates for billet deformation may be between about 0.1 inches per minute and about 1.0 inches per minute. In some embodiments, feed rates for billet deformation may be between about 1.0 inches per minute and about 10 inches per minute.

Rotation

[0047] Rotation rates for the rotatable shear tool or the billet are not limited. In some embodiments, rotation may proceed at a rate up to about 1000 revolutions-per-minute (rpm). In some embodiments, rotation speed may be between about 50 rpm and about 500 rpm. In some embodiments, the process may include rotating the ram at a rate between about 500 rpm and about 1000 rpm.

Extrusion Temperatures

[0048] Extrusion temperatures are not limited. Temperatures may be selected that maximize shear on the face of the billet, plastic deformation of the selected billet materials, microstructure refinement, and other physical and mechanical properties. In some embodiments, extrusion may be performed at temperatures above about 100° C. In some embodiments, extrusion may be performed at temperatures between about 100° C. and about 500° C. In some embodiments, extrusion may be performed at temperatures between about 500° C. and about 1000° C. In some embodiments, extrusion may be performed at temperatures above about 1000° C. In some embodiments, extrusion may be performed at temperatures below about 100° C. In some embodiments, extrusion may be performed at temperatures between about 0° C. and about −100° C. In some embodiments, extrusion may be performed at temperatures between about −100° C. and about −196° C. (the temperature of liquid nitrogen). No limitations are intended. In other embodiments, temperatures may be selected that are identified from equilibrium phase diagrams of the selected alloys or the billet materials being processed. No limitations are intended.

[0049] FIG. **5** plots extrusion pressure (axial load/billet cross sectional area) against the displacement (i.e., depth) of the shear tool. Data in the figure compare axial extrusion pressure (force) for shear-assisted extrusion processing of the present invention against conventional extrusion applied to the face of a 1.25" (3.18 cm) diameter magnesium alloy billet [e.g., a ZK60 grade magnesium-zinc-zirconium (Mg—Zn—Zr) alloy, Luoyang Kunyao Metal Material Co., Ltd., Luoyang, China]. As shown, significantly higher extrusion pressures are required for the extrusion performed absent the shear tool when compared to the shear-assisted extrusion. Maximum process pressure applied by the shear tool during shear-assisted extrusion is less than about 20 MPa at a shear tool displacement of 0.13 inches (0.32 cm). By comparison, conventional extrusion processing requires an extrusion pressure greater than about 400 MPa (e.g., 430 MPa) and a temperature of 350° C. (i.e., when billets are already soft), a factor of 16 times greater than shear-assisted extrusion processing of the present invention. In some embodiments, the present invention employs an extrusion pressure below about 50 MPa. In some embodiments, shear-assisted extrusion processing employs an extrusion pressure below about 25 MPa. Dimensions of hollow extrusion structures including the inner bore dimension and inner wall thickness are not limited. Extrusion structures may also be solid structures. Cross sectional dimensions, shapes, and length dimensions are not limited. TABLE 2 lists dimensions of exemplary hollow extrusion structures of the present invention obtained in selected extrusion tests from selected alloy billets. FIG. **6** shows photos of the tubes obtained.

[0050] TABLE 2 lists results obtained from extrusion of selected materials.

TEST #	ALLOY	O.D. Inches	O.D. mm	I.D. Inches	I.D. mm	Extrusion Ratio	Extrusion Rate
1	Mg—2Si	0.292	7.42	0.231	5.87	48.977	7.347
2	Mg—7Si	0.291	7.39	0.233	5.92	51.412	7.712
3	AZ31F	0.291	7.39	0.232	5.89	50.637	7.596
4	ZK60-TS	0.293	7.44	0.23	5.84	47.422	7.113
AVERAGE		0.292	7.41	0.232	5.88	49.612	7.442
STD. DEV.		9.5E−4	2.4E−2	1.3E−3	0.033	1.779	0.267

[0051] Extrusion ratio (R) may be calculated from Equation [1], as follows:

$$R=A_0/A_f \quad [1]$$

[0052] Here, (A_0) is the initial cross sectional area of the billet, and (A_f) is the final cross-sectional area of the extrusion structures following extrusion.

[0053] In some embodiments, shear-assisted extrusion of the present invention may be performed continuously to produce extrusion structures of any selected and/or extended lengths. In some embodiments, shear-assisted extrusion may be performed semi-continuously or batch-wise to produce various and/or multiple extrusion structures.

Microstructure Refinement

[0054] Shear-assisted extrusion processing of the present invention refines the microstructure of cast billets. For example, billets containing coarse matrix grains and second-phase intermetallic particles with sizes up to a millimeter (1000 microns) may be refined in a single process step. In some embodiments, the process yields a microstructure containing fine matrix grains and second-phase intermetallic particles with a size less than or equal to about 10 microns. In some embodiments, the process yields a microstructure containing very (ultra) fine matrix grains and second-phase intermetallic particles with a size less than or equal to about 1 micron or finer. However, no limitations are intended. For example, in some embodiments, the present invention alters the morphology of second-phase particles in the starting billet material from an aspect ratio above about 2 to an aspect ratio below about 2 following shear-assisted extrusion processing. In some embodiments, microstructure grains and particles of the original billet material are refined by at least a factor of 2 times or finer. Grains and/or particles are formed that have a size at least one-half that of grains in the original billet material prior to extrusion processing. Shear-assisted extrusion processing can further distribute grains and particles uniformly within the refined microstructure.

[0055] FIG. 7 is a photomicrograph showing refined grains in an exemplary high-performance extrusion structure following shear-assisted extrusion. In the figure, grains include a size below about 10 microns, and more particularly below about 5 microns. In some embodiments, the resulting microstructure may be amorphous, meaning grain size is approximately zero. Thus, no limitations are intended.

Applications

[0056] Extrusion structures of the present invention find application as parts, pieces, or components in various devices. In some embodiments, tubular extrusion structures of the present invention may find application as crush tubes or compression structures in front and rear bumpers of automobiles or in other compression applications. In other embodiments, extrusion structures of the present invention may be in the form of lightweight alloy tubes that find application as dissolvable stents. For example, tubes may be inexpensively produced and subsequently machined into stents. In yet other embodiments, hollow extrusion structures of the present invention may find application as bendable components, e.g., in pillar applications for use in automobiles. All applications as will be envisioned by those of ordinary skill in the art in view of the disclosure are within the scope of the present invention. No limitations are intended.

[0057] While preferred embodiments of the present invention have been shown and described, it will be apparent to those of ordinary skill in the art that many changes and modifications may be made without departing from the invention in its true scope and broader aspects. The appended claims are therefore intended to cover all such changes and modifications as fall within the spirit and scope of the invention.

What is claimed is:

1. A shear-assisted extrusion system for production of an extrusion structure, the system comprises:

a shear tool configured to simultaneously apply a rotational shearing force and an axial extrusion force to the face of a billet material at the shear tool/billet interface that plastically deforms the billet material, the shear tool includes an extrusion die with an orifice having a selected shape that extrudes the plasticized billet material that forms the extrusion structure with a selected shape at an axial extrusion force less than that required for extrusions performed absent the rotational shearing force.

2. The system of claim **1**, wherein the extrusion die is configured to extrude the plasticized billet material along the length of an inner bore of the shear tool in response to the axial extrusion pressure applied to the face of the billet material.

3. The system of claim **1**, further includes a mandrel configured to insert a selected depth into the inner bore of the shear tool during extrusion that allows plasticized material to flow past the mandrel along the length of the inner bore that yields a hollow extrusion structure.

4. The system of claim **3**, wherein the mandrel is a fixed mandrel or a floating mandrel, or the extrusion die is a bridge die.

5. The system of claim **1**, wherein the shear tool includes at least one surface feature disposed at an end thereof configured to engage the face of the billet during extrusion operation.

6. The system of claim **1**, further includes a heating or a cooling device disposed to heat or cool the billet material.

7. The system of claim **1**, wherein the system is configured to apply the shearing force at the shear tool/billet interface by rotation of the shear tool relative to a stationary billet, by rotation of the billet relative to a stationary shear tool, and/or by rotation of the shear tool at a rotation speed that is different relative to the rotation of the billet or vice versa.

8. A shear-assisted extrusion process for production of an extrusion structure or product, the process comprising the steps of:

applying a rotational shearing force and an axial extrusion force to the face of the billet material with a shear tool at the shear tool/billet interface at a selected rotation speed to plastically deform the billet material; and

extruding the plasticized material through an orifice of an extrusion die of the shear tool that includes a selected shape to form the extrusion structure or product with a selected shape at an axial extrusion force less than that required for extrusions performed absent the rotational shearing force.

9. The process of claim **8**, wherein the plasticized billet material extrudes along the length of the inner bore of the shear tool in response to the axial extrusion pressure applied to the face of the billet material.

10. The process of claim **8**, further including introducing a mandrel into the inner bore of the ram tool to a selected depth such that the plasticized material extrudes through the orifice of the extrusion die past the mandrel along the length of the inner bore of the shear tool producing a hollow extrusion structure with a selected shape.

11. The process of claim **10**, wherein the extrusion is performed with a fixed mandrel or a floating mandrel, or the extrusion is performed with a stationary bridge die.

12. The process of claim **8**, wherein applying the rotational shear force includes engaging the billet material with the shear tool that includes a feature disposed at the end thereof.

13. The process of claim **8**, wherein the extrusion structure includes a uniform inner wall thickness, a uniform inner dimension, and a selected shape; or a non-uniform inner wall thickness, a non-uniform inner dimension, and a selected shape.

14. The process of claim **8**, wherein the process includes heating or cooling the billet material with a selected heating device and/or cooling device.

15. The process of claim **8**, wherein the process includes heating the plasticized billet material with frictional heat generated during deformation of the billet material.

16. The process of claim **8**, wherein extrusion of the plasticized billet material is performed at a temperature selected between about −196° C. and about 0° C.; or between about 0° C. and about 1000° C.; or greater.

17. The process of claim **8**, wherein the rotational shear force is applied by rotating the billet at a selected rotational speed while keeping the shear tool stationary, by rotating the shear tool at a selected rotational speed while keeping the billet material stationary, or by rotating the shear tool at a selected rotational speed different than the rotational speed of the billet material or vice versa.

18. The process of claim **17**, wherein the selected rotational speed is up to about 1000 revolutions-per-minute.

19. The process of claim **8**, wherein the axial extrusion pressure is at or below about 50 MPa.

20. The process of claim **8**, wherein the process includes altering the morphology of second-phase particles in the billet material from an aspect ratio above about 2 prior to extrusion to an aspect ratio below about 2 following extrusion.

21. The process of claim **8**, wherein the process yields microstructure grains in the extrusion structure or product at least about one-half the size of the grains prior to extrusion.

22. The process of claim **8**, wherein the process yields microstructure grains with a size less than or equal to about 10 microns, less than or equal to about 5 microns, or finer.

23. The process of claim **8**, wherein the extrusion structure is a tubular extrusion structure included as a component of a compression device, a stent device, a bending resistant device, including combinations of these devices.

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