US 20160369568A1

(19) United States

(12) Patent Application Publication

Cook III

(10) Pub. No.: US 2016/0369568 A1

(43) Pub. Date: Dec. 22, 2016

(54) **TWO-PHASE MANUFACTURE OF METAL MATRIX COMPOSITES**

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(21) Appl. No.: **14/908,071**

(22) PCT Filed: **Feb. 19, 2015**

(86) PCT No.: **PCT/US2015/016476**

§ 371 (c)(1),
(2) Date: **Jan. 27, 2016**

Publication Classification

(51) **Int. Cl.**

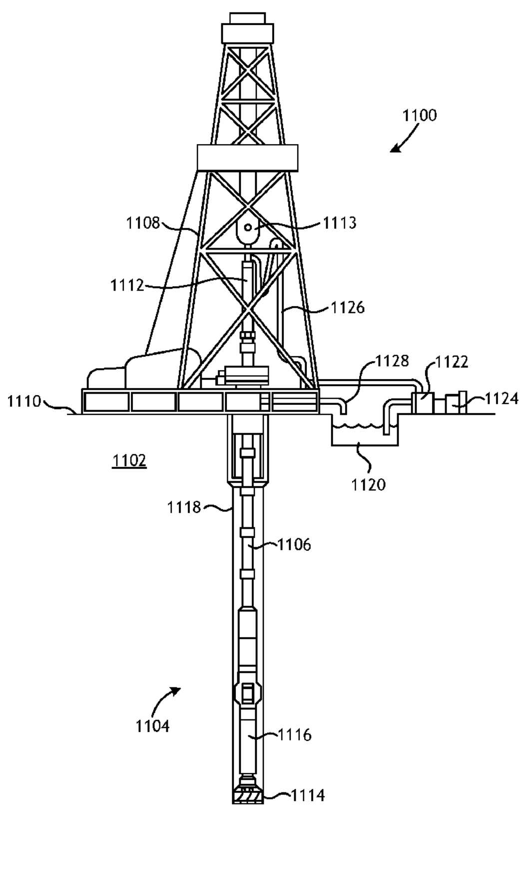
E21B 10/573	(2006.01)
B22D 25/02	(2006.01)
E21B 10/08	(2006.01)
E21B 7/12	(2006.01)
E21B 49/06	(2006.01)
E21B 10/28	(2006.01)
E21B 10/32	(2006.01)
E21B 7/06	(2006.01)
E21B 47/12	(2006.01)
B22D 19/06	(2006.01)
E21B 17/10	(2006.01)

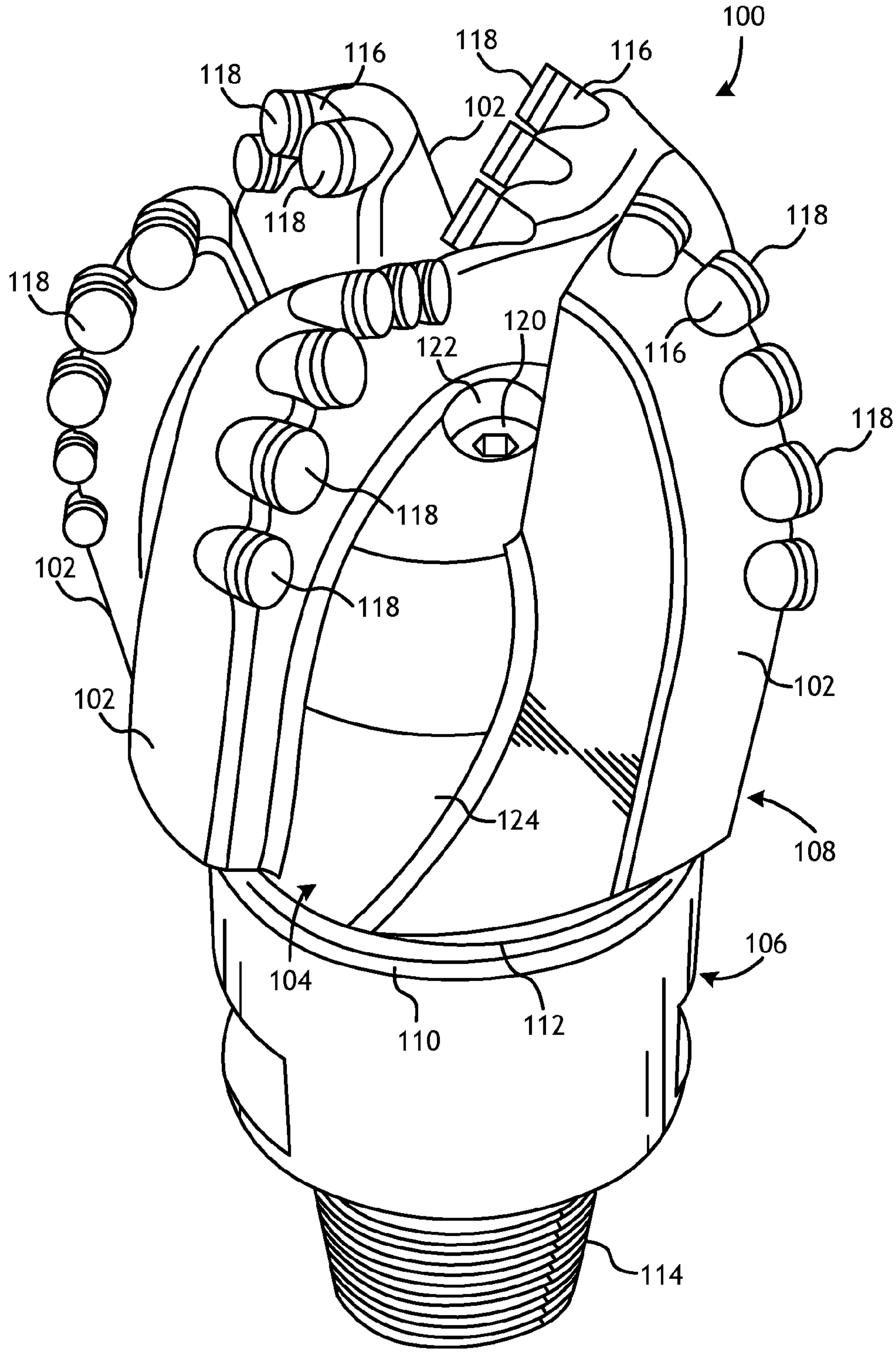
(52) **U.S. Cl.**

CPC ***E21B 10/573*** (2013.01); ***B22D 19/06*** (2013.01); ***B22D 25/02*** (2013.01); ***E21B 10/08*** (2013.01); ***E21B 7/12*** (2013.01); ***E21B 17/1078*** (2013.01); ***E21B 10/28*** (2013.01); ***E21B 10/32*** (2013.01); ***E21B 7/06*** (2013.01); ***E21B 47/12*** (2013.01); ***E21B 49/06*** (2013.01)

(57) **ABSTRACT**

A method for fabricating a metal-matrix composite tool includes positioning an inner mold within an outer mold and thereby defining a gap between the inner and outer molds. A first reinforcement material is then loaded into the gap, and the first reinforcement material is infiltrated at a first temperature with a first binder material and thereby forming an outer shell. The inner mold is then removed and a second reinforcement material is loaded at least partially into the outer shell and infiltrated at a second temperature with a second binder material and thereby forming a reinforced composite material. The second temperature is lower than the first temperature and the second binder material is different than the first binder material. The outer shell is attached to exterior portions of the reinforced composite material.

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102
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114

FIG. 1

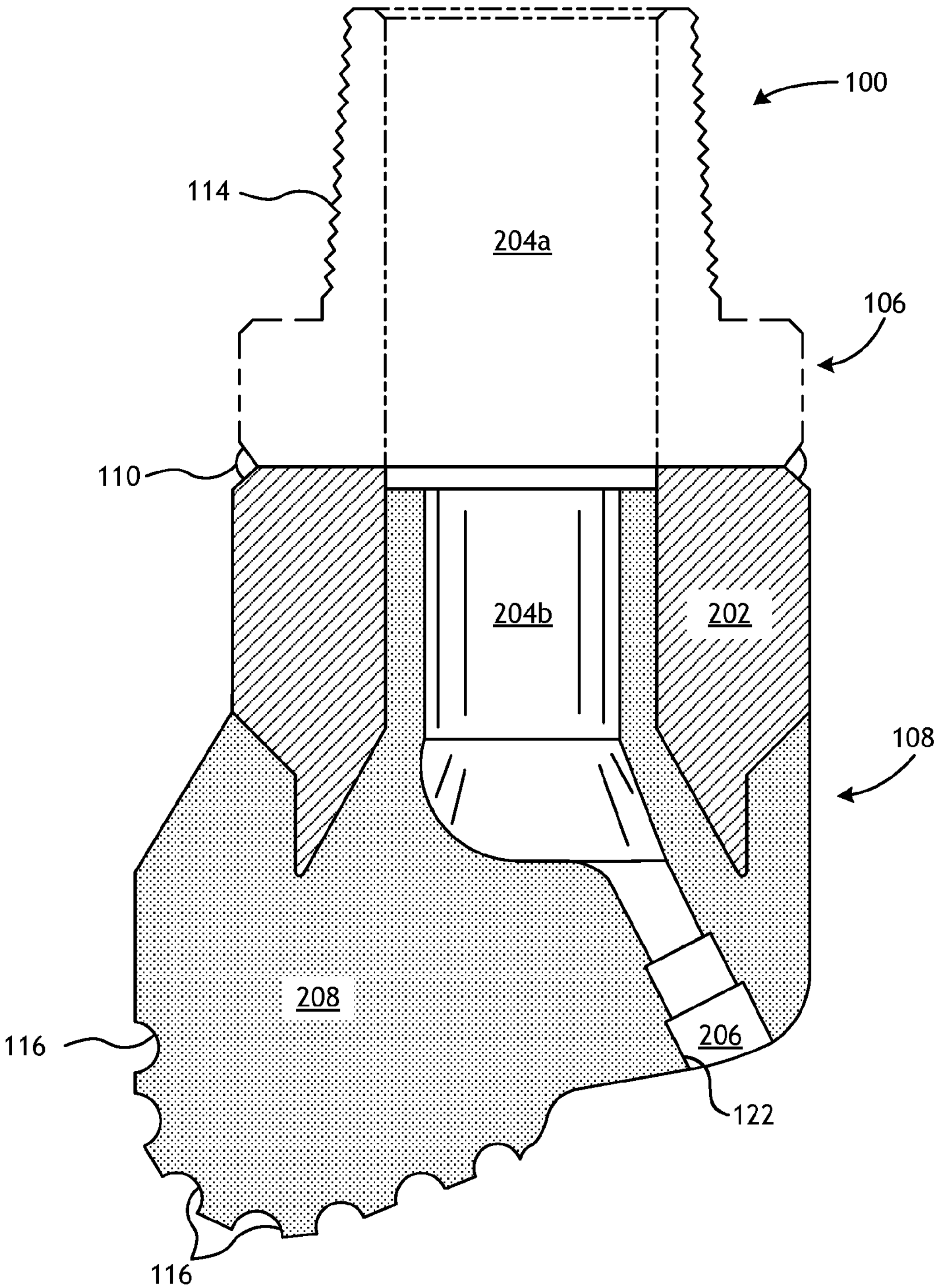
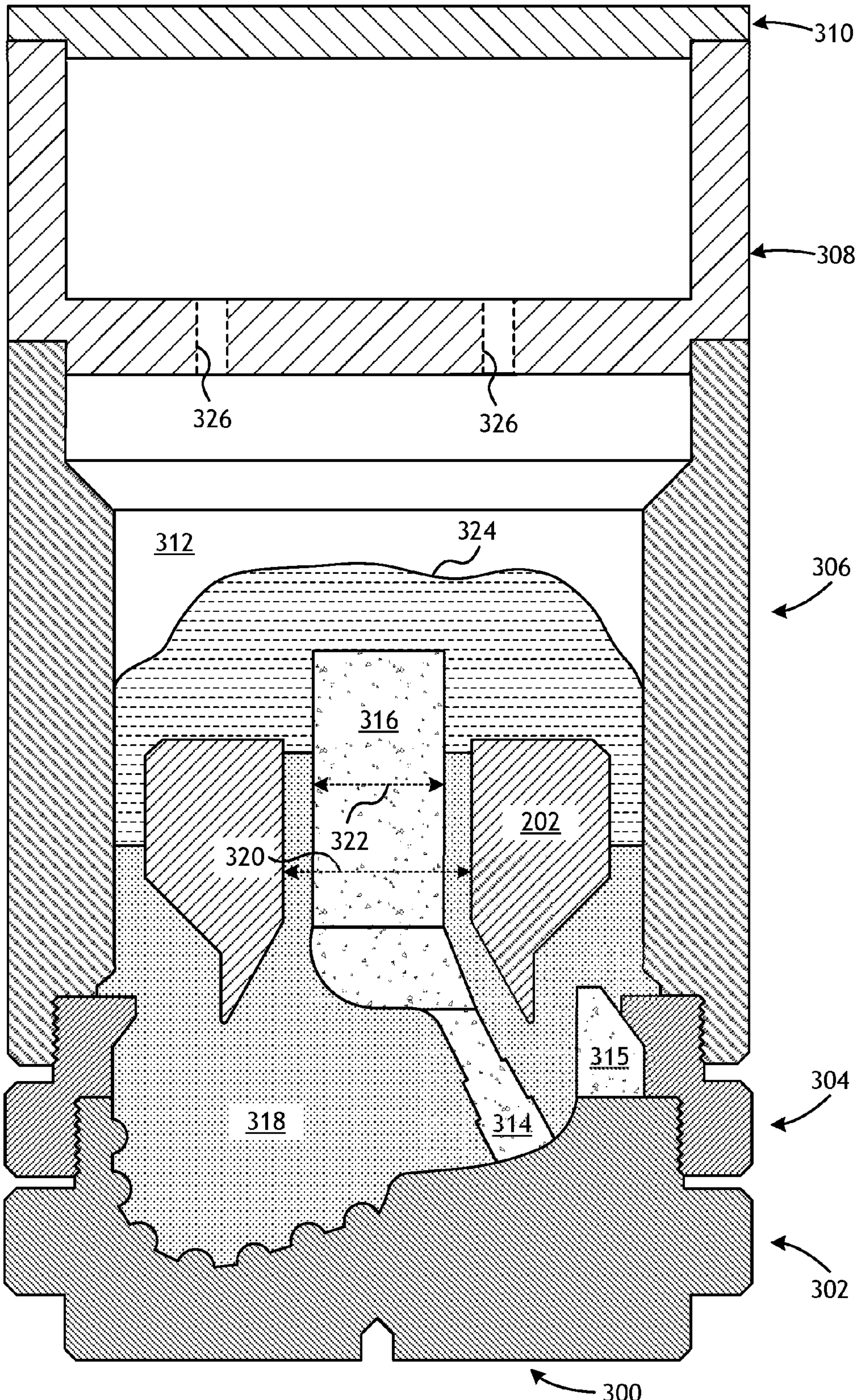


FIG. 2


310
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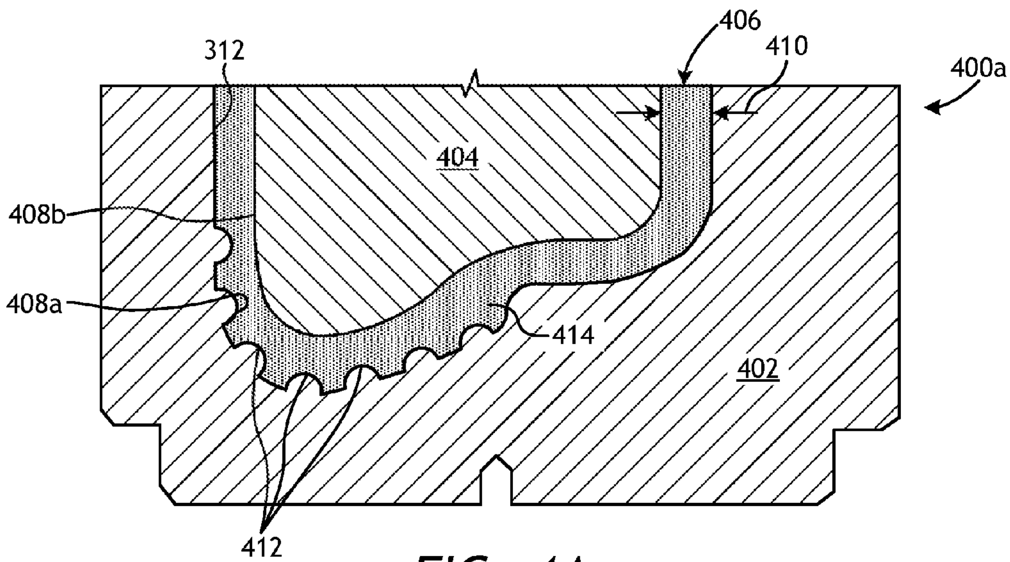
318
314
302
300

FIG. 3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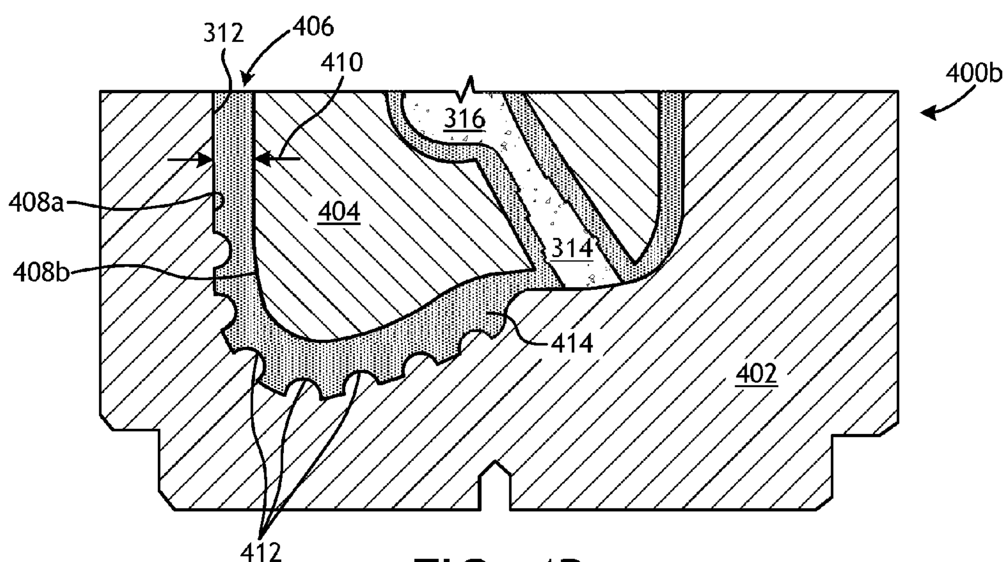
410
312
400a
404
408b
408a
414
402
412

FIG. 4A


312
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316
408a
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408b
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402
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FIG. 4B

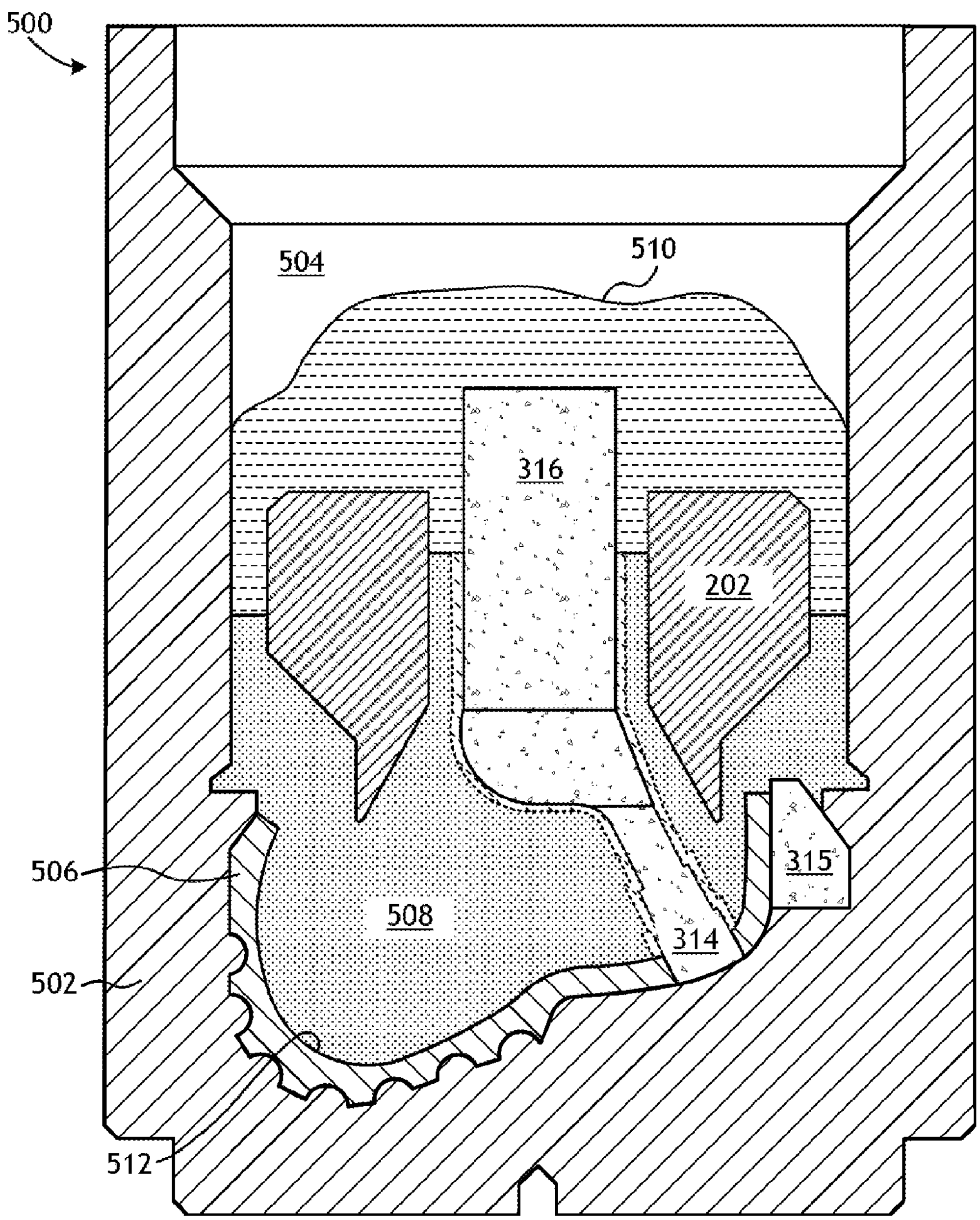


FIG. 5

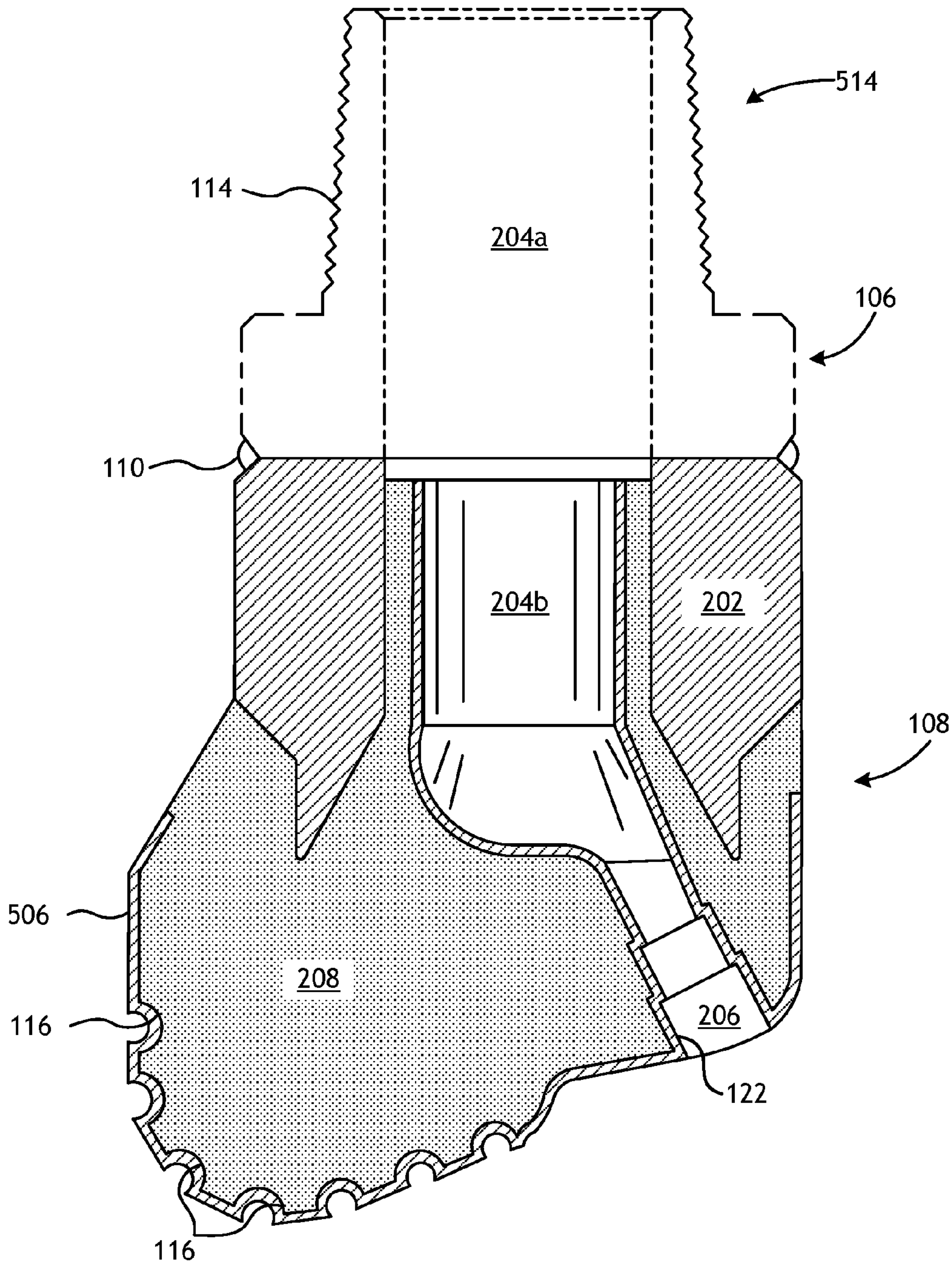


FIG. 5A

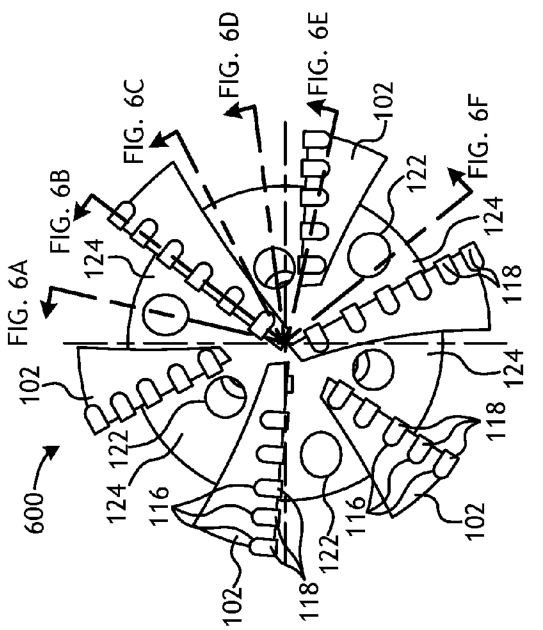


FIG. 6

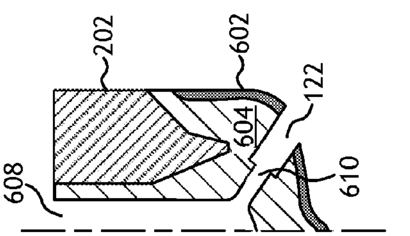


FIG. 6A

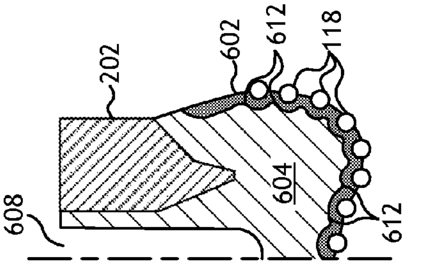


FIG. 6B

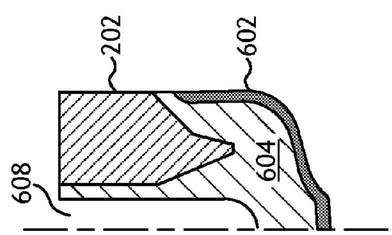


FIG. 6C

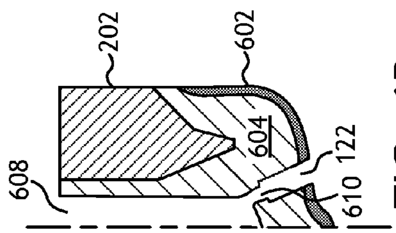


FIG. 6D

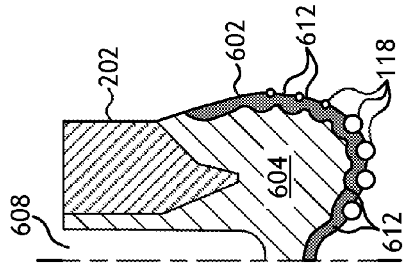


FIG. 6E

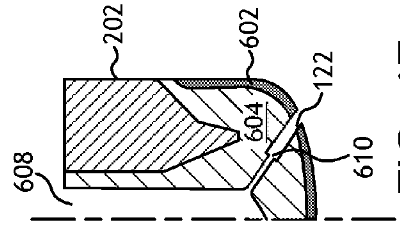


FIG. 6F

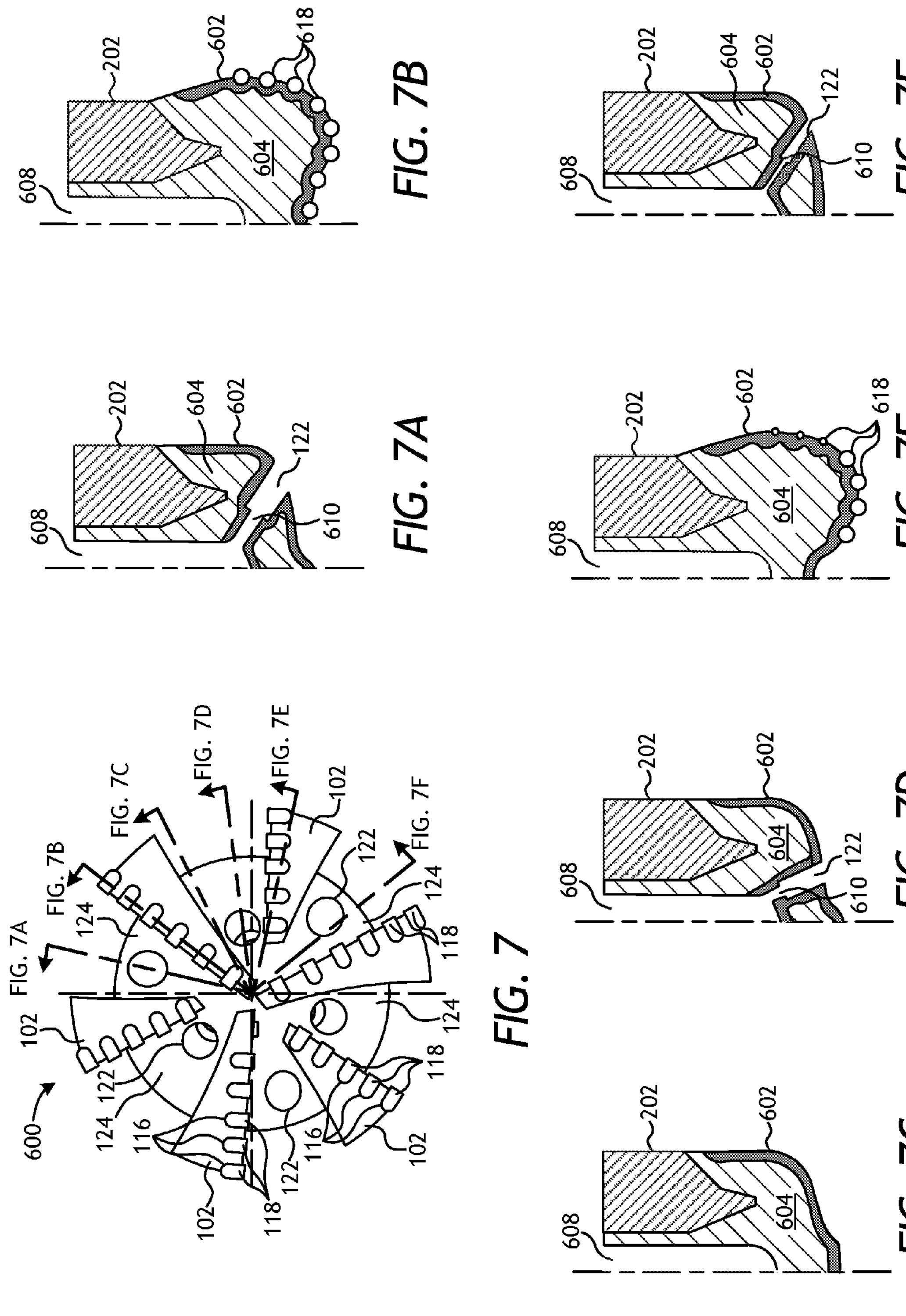


FIG. 7

FIG. 7A

FIG. 7B

FIG. 7C

FIG. 7D

FIG. 7E

FIG. 7F

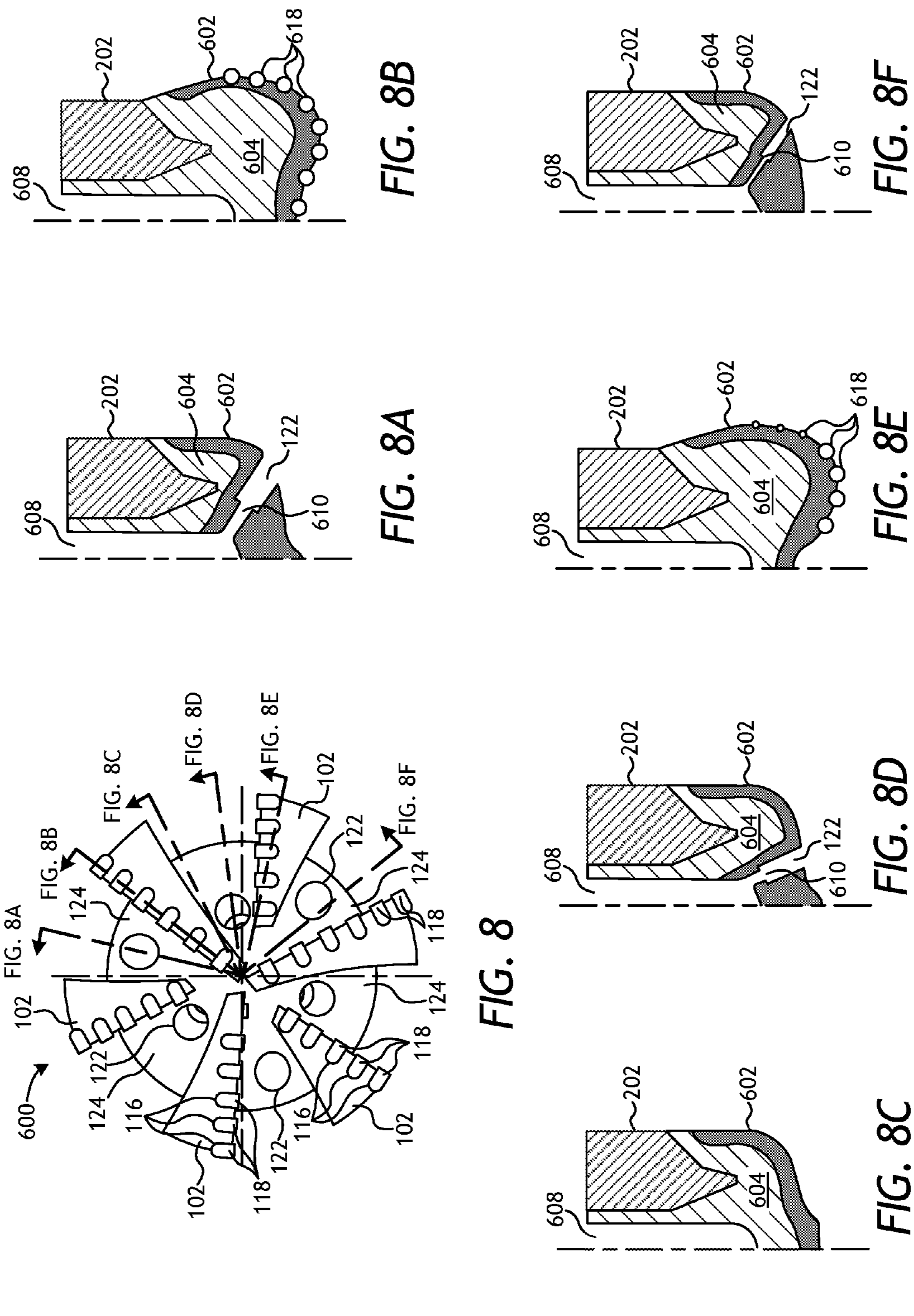


FIG. 8

FIG. 8A

FIG. 8B

FIG. 8C

FIG. 8D

FIG. 8E

FIG. 8F

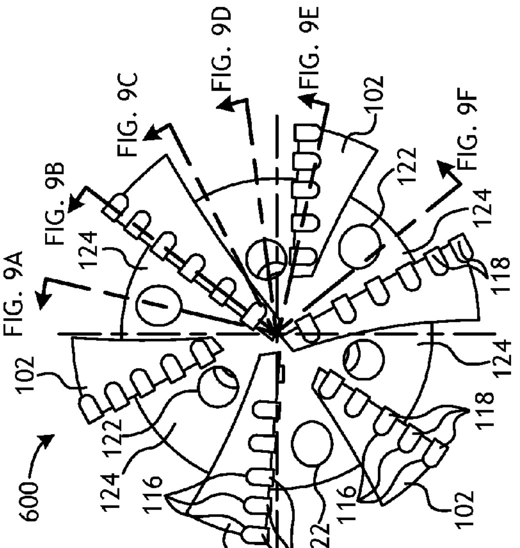


FIG. 9

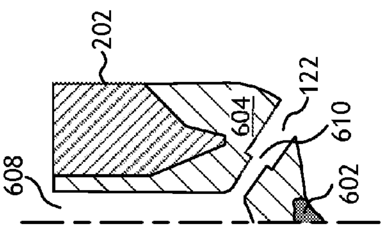


FIG. 9A

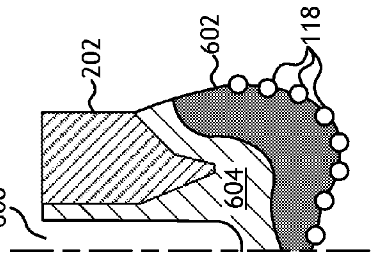


FIG. 9B

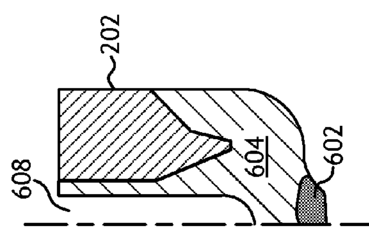


FIG. 9C

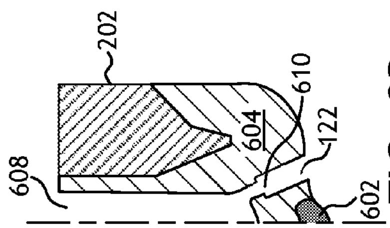


FIG. 9D

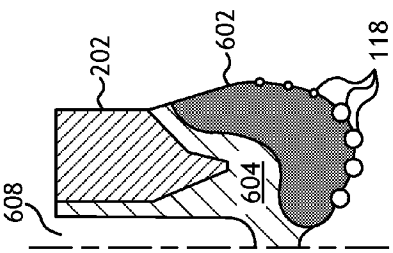


FIG. 9E

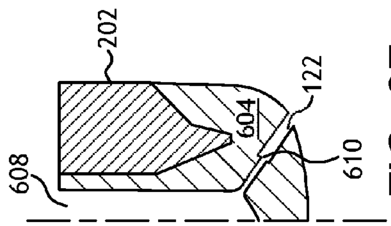
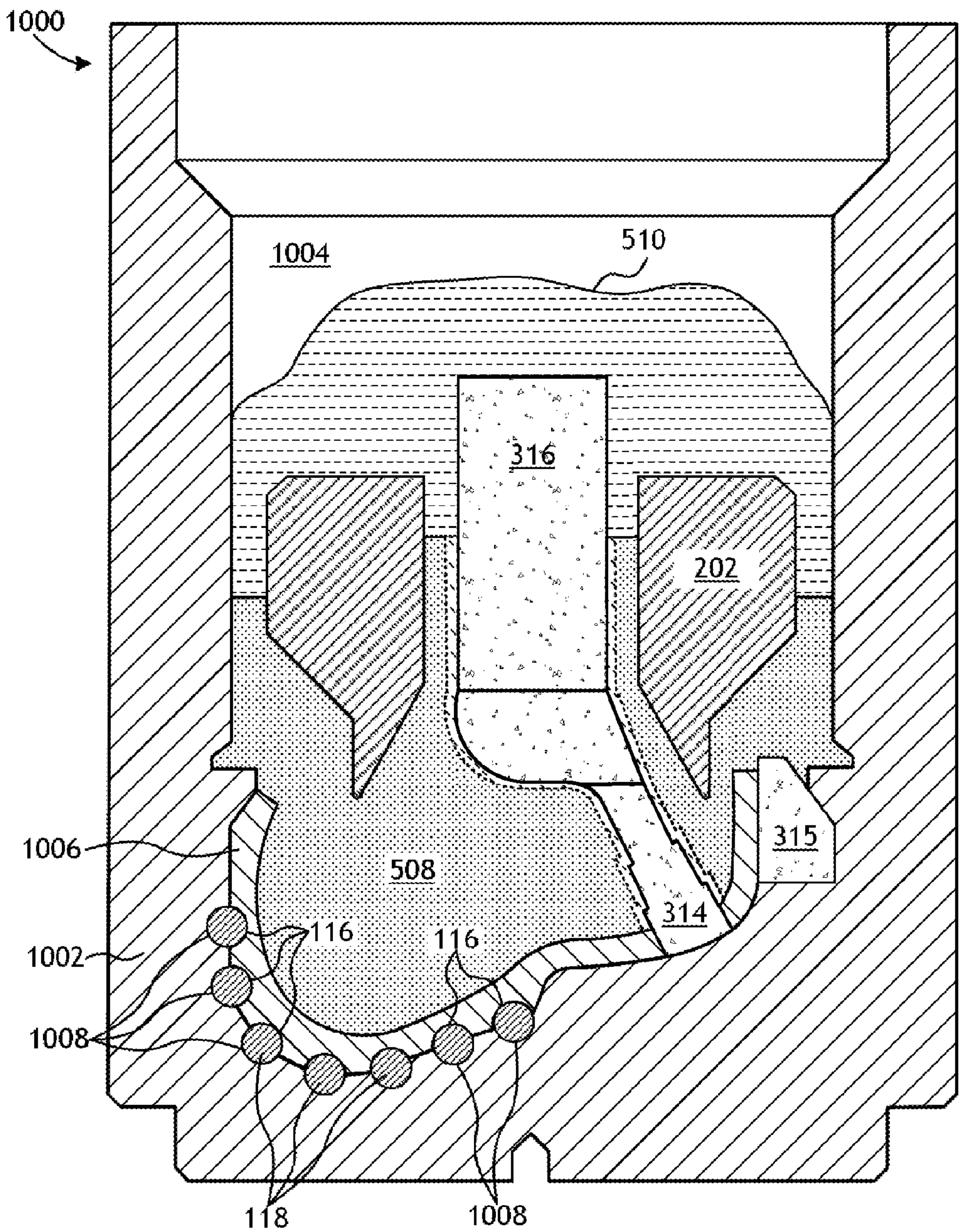


FIG. 9F


1000
1004
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316
202
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508
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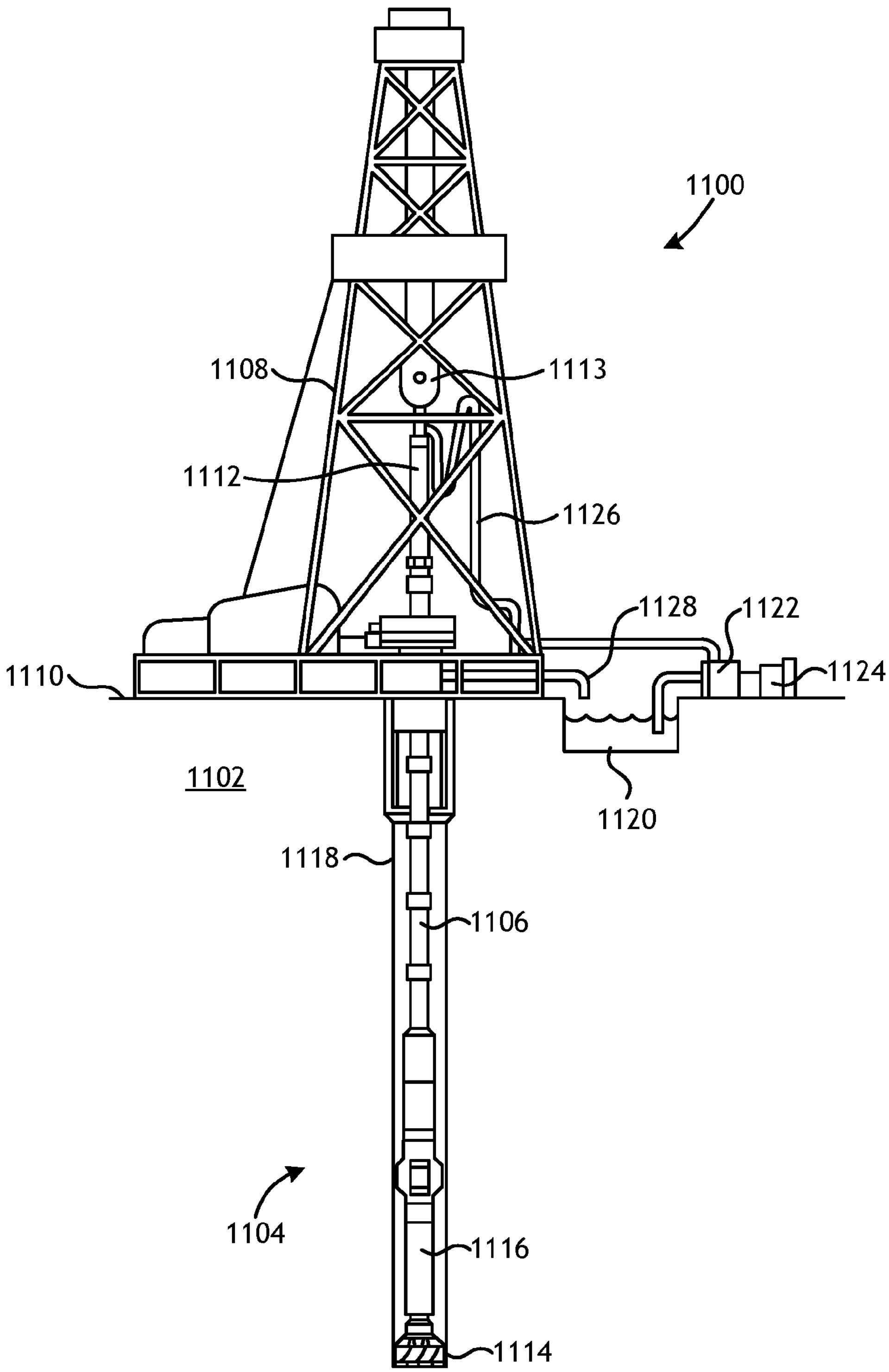
1008
118
1008

FIG. 10


1100
1108
1113
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1126
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FIG. 11

TWO-PHASE MANUFACTURE OF METAL MATRIX COMPOSITES

BACKGROUND

[0001] A wide variety of tools are commonly used in the oil and gas industry for forming wellbores, in completing drilled wellbores, and in producing hydrocarbons such as oil and gas from completed wells. Examples of such tools include cutting tools, such as drill bits, reamers, stabilizers, and coring bits; drilling tools, such as rotary steerable devices and mud motors; and other downhole tools, such as window mills, packers, tool joints, and other wear-prone tools. These tools, and several other types of tools used in applications outside the oil and gas industry, are often formed as metal-matrix composites (MMCs), and referred to herein as "MMC tools."

[0002] An MMC tool is typically manufactured by placing loose powder reinforcing material into a mold and infiltrating the powder material with a binder material, such as a metallic alloy. The various features of the resulting MMC tool may be provided by shaping the mold cavity and/or by positioning temporary displacement materials within select interior portions of the mold cavity. A quantity of the reinforcement material may then be placed within the mold cavity with a quantity of the binder material. The mold is then placed within a furnace and the temperature of the mold is increased to a desired temperature to allow the binder material to liquefy and infiltrate the matrix reinforcement material.

[0003] MMC drill bits used in the oil and gas industry are generally required to be erosion-resistant and exhibit high impact strength for long-term operation. The outer surfaces of a given MMC drill bit, for example, are commonly required to resist extreme impact loading, abrasion, and erosion, while it is desired that the central portions of the given MMC drill bit may be more ductile to prevent crack propagation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The following figures are included to illustrate certain aspects of the present disclosure, and should not be viewed as exclusive embodiments. The subject matter disclosed is capable of considerable modifications, alterations, combinations, and equivalents in form and function, without departing from the scope of this disclosure.

[0005] FIG. **1** is a perspective view of an exemplary drill bit that may be fabricated in accordance with the principles of the present disclosure.

[0006] FIG. **2** is a cross-sectional view of the drill bit of FIG. **1**.

[0007] FIG. **3** is a cross-sectional side view of a mold assembly that may be used to fabricate the drill bit of FIGS. **1** and **2**.

[0008] FIGS. **4**A and **4**B are cross-sectional side views of an exemplary mold assembly that may be used to form an MMC tool.

[0009] FIG. **5** is a cross-sectional side view of a mold assembly and an outer shell produced during a first infiltration step.

[0010] FIG. **5**A is a cross-sectional side view of an exemplary MMC drill bit fabricated through first and second infiltration steps.

[0011] FIG. **6** is a top view of an exemplary MMC drill bit.

[0012] FIGS. **6**A-**6**F are partial cross-sectional side views of the MMC drill bit of FIG. **6**.

[0013] FIG. **7** is a top view of an additional embodiment of the MMC drill bit of FIG. **6**.

[0014] FIGS. **7**A-**7**F are partial cross-sectional side views of the additional embodiment of the MMC drill bit of FIG. **7**.

[0015] FIG. **8** is a top view of an additional embodiment of the MMC drill bit of FIG. **6**.

[0016] FIGS. **8**A-**8**F are partial cross-sectional side views of the additional embodiment of the MMC drill bit of FIG. **8**.

[0017] FIG. **9** is a top view of an additional embodiment of the MMC drill bit of FIG. **6**.

[0018] FIGS. **9**A-**9**F are partial cross-sectional side views of the additional embodiment of the MMC drill bit of FIG. **9**.

[0019] FIG. **10** is a cross-sectional side view of a mold assembly and an outer shell produced during a first infiltration step.

[0020] FIG. **11** is an exemplary drilling system that may employ one or more principles of the present disclosure.

DETAILED DESCRIPTION

[0021] The present disclosure is related to metal-matrix composite tools and, more particularly, to metal-matrix composite tools composed macroscopically of at least two different material compositions and methods of fabricating the same.

[0022] Embodiments described herein provide a manufacturing method that is capable of producing an infiltrated metal-matrix composite (MMC) tool composed macroscopically of two different material compositions. These different compositions can produce different properties in at least two different regions of the MMC tool. For example, higher stiffness, ultimate tensile strength, melting temperature, etc. can be produced along the exterior of the MMC tool with differing properties (e.g., higher toughness, lower melting temperature, etc.) within the interior of the MMC tool. Briefly, the MMC tool may be formed via a first infiltration step followed by a second infiltration step. In the first infiltration step, an outer shell for the MMC tool may be formed, and the second infiltration step may result in the formation of a reinforced composite material forming the core of the MMC tool. The outer shell may be attached to exterior portions of the interior reinforced composite material during the second infiltration step. In some embodiments, the second infiltration step may be carried out at a lower temperature than the first infiltration step that allows for simultaneous joining of cutters to the already-formed higher-melting-temperature surfaces of the outer shell.

[0023] The embodiments of the present disclosure are applicable to any tool or device formed as a metal matrix composite (MMC). Such tools or devices are referred to herein as "MMC tools" and may or may not be used in the oil and gas industry. For purposes of explanation and description only, however, the following description is related to MMC tools used in the oil and gas industry, such as drill bits, but it will be appreciated that the principles of the present disclosure are equally applicable to any type of MMC used in any industry or field, such as armor plating, automotive components (e.g., sleeves, cylinder liners, driveshafts, exhaust valves, brake rotors), bicycle frames, brake fins, aerospace components (e.g., landing-gear components, structural tubes, struts, shafts, links, ducts, waveguides, guide vanes, rotor-blade sleeves, ventral fins, actuators, exhaust structures, cases, frames), and turbopump components, without departing from the scope of the disclosure.

[0024] Referring to FIG. **1**, illustrated is a perspective view of an example MMC drill bit **100** that may be fabricated in accordance with the principles of the present disclosure. While discussed herein with reference to the MMC drill bit **100**, it will be appreciated that principles of the present disclosure may equally be applied to other MMC downhole tools including, but not limited to, oilfield drill bits or cutting tools (e.g., fixed-angle drill bits, roller-cone drill bits, coring drill bits, bi-center drill bits, impregnated drill bits, reamers, stabilizers, hole openers, cutters), non-retrievable drilling components, aluminum drill bit bodies associated with casing drilling of wellbores, drill-string stabilizers, cones for roller-cone drill bits, models for forging dies used to fabricate support arms for roller-cone drill bits, arms for fixed reamers, arms for expandable reamers, internal components associated with expandable reamers, sleeves attached to an uphole end of a rotary drill bit, rotary steering tools, logging-while-drilling tools, measurement-while-drilling tools, side-wall coring tools, fishing spears, washover tools, rotors, stators and/or housings for downhole drilling motors, blades and housings for downhole turbines, and other downhole tools having complex configurations and/or asymmetric geometries associated with forming a wellbore. Other applications of the disclosed methods and processes herein may be evident to one skilled in the art with the benefit of this disclosure.

[0025] As illustrated in FIG. **1**, the MMC drill bit **100** may include or otherwise define a plurality of cutter blades **102** arranged along the circumference of a bit head **104**. The bit head **104** is connected to a shank **106** to form a bit body **108**. The shank **106** may be connected to the bit head **104** by welding, such as using laser arc welding that results in the formation of a weld **110** around a weld groove **112**. The shank **106** may further include or otherwise be connected to a threaded pin **114**, such as an American Petroleum Institute (API) drill pipe thread.

[0026] In the depicted example, the MMC drill bit **100** includes five cutter blades **102** in which multiple recesses or pockets **116** are formed. Cutting elements **118** may be fixedly installed within each pocket **116**. This can be done, for example, by brazing each cutting element **118** into a corresponding pocket **116**. As the MMC drill bit **100** is rotated in use to drill a wellbore, the cutting elements **118** engage rock and underlying earthen materials, to dig, scrape or grind away the material of the formation being penetrated.

[0027] During drilling operations, drilling fluid or "mud" can be pumped downhole through a drill string (not shown) coupled to the MMC drill bit **100** at the threaded pin **114**. The drilling fluid circulates through and out of the MMC drill bit **100** at one or more nozzles **120** positioned in nozzle openings **122** defined in the bit head **104**. Junk slots **124** are formed between each adjacent pair of cutter blades **102**. Cuttings, downhole debris, formation fluids, drilling fluid, etc., may pass through the junk slots **124** and circulate back to the well surface within an annulus formed between exterior portions of the drill string and the inner wall of the wellbore being drilled.

[0028] FIG. **2** is a cross-sectional side view of the MMC drill bit **100** of FIG. **1**. Similar numerals from FIG. **1** that are used in FIG. **2** refer to similar components that are not described again. As illustrated, the shank **106** may be securely attached to a metal blank or mandrel **202** at the weld **110** and the mandrel **202** extends into the bit body **108**. The shank **106** and the mandrel **202** are generally cylindrical structures that define corresponding fluid cavities **204*a*** and **204*b***, respectively, in fluid communication with each other. The fluid cavity **204*b*** of the mandrel **202** may further extend longitudinally into the bit body **108**. At least one flow passageway **206** (one shown) may extend from the fluid cavity **204*b*** to exterior portions of the bit body **108**. The nozzle openings **122** (one shown in FIG. **2**) may be defined at the ends of the flow passageways **206** at the exterior portions of the bit body **108**. The pockets **116** are formed in the bit body **108** and are shaped or otherwise configured to subsequently receive the cutting elements **118** (FIG. **1**). The bit body **108** may comprise a reinforced composite material **208**.

[0029] FIG. **3** is a cross-sectional side view of a mold assembly **300** that may be used to form the MMC drill bit **100** of FIGS. **1** and **2**. As illustrated, the mold assembly **300** may include several components such as a mold **302**, a gauge ring **304**, and a funnel **306**. In some embodiments, the funnel **306** may be operatively coupled to the mold **302** via the gauge ring **304**, such as by corresponding threaded engagements, as illustrated. In other embodiments, the gauge ring **304** may be omitted from the mold assembly **300** and the funnel **306** may instead be directly coupled to the mold **302**, such as via a corresponding threaded engagement, without departing from the scope of the disclosure.

[0030] In some embodiments, as illustrated, the mold assembly **300** may further include a binder bowl **308** and a cap **310** placed above the funnel **306**. The mold **302**, the gauge ring **304**, the funnel **306**, the binder bowl **308**, and the cap **310** may each be made of or otherwise comprise graphite or alumina (Al_2O_3), for example, or other suitable materials. An infiltration chamber **312** may be defined or otherwise provided within the mold assembly **300**. Various techniques may be used to manufacture the mold assembly **300** and its components including, but not limited to, machining graphite blanks to produce the various components and thereby define the infiltration chamber **312** to exhibit a negative or reverse profile of desired exterior features of the MMC drill bit **100** (FIGS. **1** and **2**).

[0031] Displacement materials, such as consolidated sand or graphite, may be positioned within the mold assembly **300** at desired locations to form various features of the MMC drill bit **100** (FIGS. **1** and **2**). For example, one or more consolidated legs **314** (one shown) may be positioned to correspond with desired locations and configurations of the flow passageways **206** (FIG. **2**) and their respective nozzle openings **122** (FIGS. **1** and **2**). A cylindrically-shaped central displacement **316** may be placed on the legs **314**. As will be appreciated, the number of legs **314** extending from the central displacement **316** will depend upon the desired number of flow passageways and corresponding nozzle openings **122** in the MMC drill bit **100**. Moreover, one or more junk slot displacements **315** may also be positioned within the mold assembly **300** to correspond with the junk slots **124** (FIG. **1**). Further, cutter-pocket displacements (shown as part of mold **302** in FIG. **3**) may be placed in the mold **302** to form cutter pockets **116**.

[0032] After the desired displacement materials (e.g., the central displacement **316**, the legs **314**, the junk-slot displacement **315**, etc.) are placed within the mold assembly

300, reinforcement materials **318** may then be placed within or otherwise introduced into the mold assembly **300**. The reinforcement materials **318** may include, for example, various types of reinforcing particles. Suitable reinforcing particles include, but are not limited to, particles of metals, metal alloys, superalloys, intermetallics, borides, carbides, nitrides, oxides, ceramics, diamonds, and the like, or any combination thereof.

[0033] Examples of suitable reinforcing particles include, but are not limited to, tungsten, molybdenum, niobium, tantalum, rhenium, iridium, ruthenium, beryllium, titanium, chromium, rhodium, iron, cobalt, uranium, nickel, nitrides, silicon nitrides, boron nitrides, cubic boron nitrides, natural diamonds, synthetic diamonds, cemented carbide, spherical carbides, low-alloy sintered materials, cast carbides, silicon carbides, boron carbides, cubic boron carbides, molybdenum carbides, titanium carbides, tantalum carbides, niobium carbides, chromium carbides, vanadium carbides, iron carbides, tungsten carbides, macrocrystalline tungsten carbides, cast tungsten carbides, crushed sintered tungsten carbides, carburized tungsten carbides, steels, stainless steels, austenitic steels, ferritic steels, martensitic steels, precipitation-hardening steels, duplex stainless steels, ceramics, iron alloys, nickel alloys, cobalt alloys, chromium alloys, HASTELLOY® alloys (i.e., nickel-chromium containing alloys, available from Haynes International), INCONEL® alloys (i.e., austenitic nickel-chromium containing superalloys available from Special Metals Corporation), WASPALOYS® (i.e., austenitic nickel-based superalloys), RENE® alloys (i.e., nickel-chromium containing alloys available from Altemp Alloys, Inc.), HAYNES® alloys (i.e., nickel-chromium containing superalloys available from Haynes International), INCOLOY® alloys (i.e., iron-nickel containing superalloys available from Mega Mex), MP98T (i.e., a nickel-copper-chromium superalloy available from SPS Technologies), TMS alloys, CMSX® alloys (i.e., nickel-based superalloys available from C-M Group), cobalt alloy 6B (i.e., cobalt-based superalloy available from HPA), N-155 alloys, any mixture thereof, any derivative thereof, and any combination thereof. In some embodiments, the reinforcing particles may be coated, such as diamond coated with titanium.

[0034] The mandrel **202** may be supported at least partially by the reinforcement materials **318** within the infiltration chamber **312**. More particularly, after a sufficient volume of the reinforcement materials **318** has been added to the mold assembly **300**, the mandrel **202** may then be placed within the mold assembly **300**. The mandrel **202** may include an inside diameter **320** that is greater than an outside diameter **322** of the central displacement **316**, and various fixtures (not expressly shown) may be used to position the mandrel **202** within the mold assembly **300** at a precise alignment location. The reinforcement materials **318** may then be filled to a desired level within the infiltration chamber **312**.

[0035] Binder material **324** may then be placed on top of the reinforcement materials **318**, the mandrel **202**, and the central displacement **316**. Suitable binder materials **324** include, but are not limited to, copper, nickel, cobalt, iron, aluminum, molybdenum, chromium, manganese, tin, zinc, lead, silicon, tungsten, boron, phosphorous, gold, silver, palladium, indium, any mixture thereof, any alloy thereof, and any combination thereof. Non-limiting examples of alloys of the binder material **324** may include copper-phosphorus, copper-phosphorous-silver, copper-manganese-phosphorous, copper-nickel, copper-manganese-nickel, copper-manganese-zinc, copper-manganese-nickel-zinc, copper-nickel-indium, copper-tin-manganese-nickel, copper-tin-manganese-nickel-iron, gold-nickel, gold-palladium-nickel, gold-copper-nickel, silver-copper-zinc-nickel, silver-manganese, silver-copper-zinc-cadmium, silver-copper-tin, cobalt-silicon-chromium-nickel-tungsten, cobalt-silicon-chromium-nickel-tungsten-boron, manganese-nickel-cobalt-boron, nickel-silicon-chromium, nickel-chromium-silicon-manganese, nickel-chromium-silicon, nickel-silicon-boron, nickel-silicon-chromium-boron-iron, nickel-phosphorus, nickel-manganese, copper-aluminum, copper-aluminum-nickel, copper-aluminum-nickel-iron, copper-aluminum-nickel-zinc-tin-iron, and the like, and any combination thereof. Examples of commercially-available binder materials **324** include, but are not limited to, VIRGIN™ Binder 453D (copper-manganese-nickel-zinc, available from Belmont Metals, Inc.), and copper-tin-manganese-nickel and copper-tin-manganese-nickel-iron grades 516, 519, 523, 512, 518, and 520 available from ATI Firth Sterling; and any combination thereof.

[0036] In some embodiments, the binder material **324** may be covered with a flux layer (not expressly shown). The amount of binder material **324** (and optional flux material) added to the infiltration chamber **312** should be at least enough to infiltrate the reinforcement materials **318** during the infiltration process. In some instances, some or all of the binder material **324** may be placed in the binder bowl **308**, which may be used to distribute the binder material **324** into the infiltration chamber **312** via various conduits **326** that extend therethrough. The cap **310** (if used) may then be placed over the mold assembly **300**. The mold assembly **300** and the materials disposed therein may then be preheated and subsequently placed in a furnace (not shown). When the furnace temperature reaches the melting point of the binder material **324**, the binder material **324** will liquefy and proceed to infiltrate the reinforcement materials **318**.

[0037] After a predetermined amount of time allotted for the liquefied binder material **324** to infiltrate the reinforcement materials **318**, the mold assembly **300** may then be removed from the furnace and cooled at a controlled rate. Once cooled, the mold assembly **300** may be broken away to expose the bit body **108** (FIGS. **1** and **2**). Subsequent machining and post-processing according to well-known techniques may then be used to finish the MMC drill bit **100** (FIG. **1**).

[0038] According to embodiments of the present disclosure, the MMC drill bit **100**, or any of the MMC tools mentioned herein, may be fabricated using two separate or discrete infiltration steps and thereby resulting in an MMC tool composed macroscopically of two different material compositions. These different material compositions can produce and otherwise provide different mechanical properties in at least two different regions of a given MMC tool. For example, a first infiltration step may provide the given MMC tool higher stiffness, higher ultimate tensile strength, and higher melting temperatures along the exterior or outer portions of the MMC tool. A second infiltration step may form the central portions of the MMC tool with materials exhibiting increased toughness, ductility, and a lower melting temperature. In some embodiments, the second infiltration step may be carried out at a lower temperature, which may allow for simultaneous joining or brazing of cutters (e.g., the cutting elements **118** of FIG. **1**) to the cutter pockets **116** (FIGS. **1** and **2**) formed during the first infiltration process.

[0039] Referring to FIGS. **4**A and **4**B, with continued reference to FIG. **3**, illustrated are cross-sectional side views of a portion of an exemplary mold assembly **400** that may be used to form an MMC tool, according to one or more embodiments. FIG. **4**A depicts a first mold assembly **400***a* and FIG. **4**B depicts a second mold assembly **400***b*. The mold assemblies **400***a,b* may be similar in some respects to the mold assembly **300** of FIG. **3** and therefore will be best understood with reference thereto, where like numerals represent like elements not described again. Similar to the mold assembly **300**, the mold assemblies **400***a,b* may each be used to form and otherwise fabricate an MMC drill bit, similar in some respects to the MMC drill bit **100** of FIGS. **1** and **2**. It will be appreciated, however, that variations of the mold assemblies **400***a,b* may alternatively be incorporated to form and otherwise fabricate any of the MMC tools mentioned herein using the principles discussed below.

[0040] Each mold assembly **400***a,b* may include an outer mold **402** and an inner mold **404**. While not specifically illustrated, in some embodiments, the outer mold **402** may comprise component parts similar to the mold assembly **300** of FIG. **3**, such as the mold **302**, the gauge ring **304**, the funnel **306**, etc. In the illustrated embodiment, however, the outer mold **402** is depicted as a solid monolithic mold component. Nonetheless, it will be appreciated that the outer mold **402** may alternatively be made of multiple component parts, without departing from the scope of the disclosure. Moreover, similar to the mold assembly **300**, the outer and inner molds **402**, **404** may each be made of or otherwise comprise graphite, alumina (Al_2O_3), or another suitable material.

[0041] The outer mold **402** may generally define the infiltration chamber **312** and the inner mold **404** may be disposable within the infiltration chamber **312** such that a gap **406** is defined between an inner surface **408***a* of the outer mold **402** and an outer surface **408***b* of the inner mold **404**. In some embodiments, for instance, one or more standoffs or spacers (not shown) may extend between the outer and inner molds **402**, **404** to hold or maintain the inner mold **404** offset from the outer mold **402** and thereby generate the gap **406**. In such embodiments, the spacers may or may not be dissolvable during the infiltration steps discussed below. In other embodiments, the gap **406** may be formed by coupling the inner mold **404** to a centering fixture (not shown) that precisely aligns the inner mold **404** within the outer mold **402**.

[0042] The gap **406** may exhibit a predetermined depth or thickness **410** that corresponds to a desired thickness of an outer shell to be formed via a first infiltration process or step. As described below, the outer shell may form and otherwise provide all or a portion of the bottom and side surfaces of the MMC tool being fabricated. The thickness **410** may vary at select locations of the gap **406**, depending on the application and/or the particular material used to fabricate the outer shell. In some embodiments, for instance, the thickness **410** may vary across selective portions or locations along the gap **406** to coincide with selective regions of the bottom and side surfaces of the MMC tool.

[0043] In some embodiments, one or both of the outer and inner molds **402**, **404** may provide and otherwise define various features or designs to be molded in the outer shell. For instance, in embodiments where the mold assemblies **400***a,b* are configured to fabricate an MMC drill bit, the outer mold **402** may define a plurality of protrusions **412** on the inner surface **408***a* to correspond with the recesses or pockets **116** (FIGS. **1** and **2**) formed on the outer surface of an MMC drill bit. Moreover, in some embodiments, the outer surface **408***b* of the inner mold **404** may vary and otherwise define macroscopic undulations, crenellations, steps, waves, dimples, recesses, protrusions, nubs, fins, threads, miters, dovetails, knurling, or any type of protrusion and/or recess, as discussed in more detail below. In other embodiments, however, the outer surface **408***b* of the inner mold **404** may be generally smooth, as illustrated.

[0044] Referring specifically to the mold assembly **400***b* of FIG. **4**B, in one or more embodiments, the inner mold **404** may accommodate various displacement materials that may be placed within the infiltration chamber **312** at desired locations to form various features of the MMC tool. In such embodiments, the inner mold **404** may comprise two or more component parts, or may alternatively comprise a monolithic part machined to accommodate the desired displacement materials. In embodiments where the mold assembly **400***b* is configured to fabricate an MMC drill bit, the consolidated legs **314** (one shown) and the central displacement **316** may be positioned to correspond with the flow passageways **206** (FIG. **2**) and the fluid cavity **204***b* (FIG. **2**), respectively. In other embodiments, however, the legs **314** and the central displacement **316** may be omitted for the first infiltration step, as in the mold assembly **400***a*, and otherwise positioned in the infiltration chamber **312** during the second infiltration step.

[0045] Once the inner mold **404** is suitably arranged within the outer mold **402**, and the displacement materials (if used) are placed within the infiltration chamber **312** at desired locations, a first reinforcement material **414** may be loaded into the gap **406**. During a first infiltration step, the first reinforcement material **414** may be infiltrated with a first binder material (not shown), which may comprise similar materials as the binder material **324** of FIG. **3**. The amount of the first binder material used in the assemblies **400***a,b* should be at least enough to infiltrate the first reinforcement material **414**.

[0046] The first reinforcement material **414** may comprise reinforcing particles similar to those listed above for the reinforcement materials **318**. In some embodiments, the first reinforcement material **414** may comprise reinforcing particles that, upon being infiltrated by the first binder material, may result in an outer shell exhibiting optimized mechanical properties such as, but not limited to, wear resistance, erosion resistance, abrasion resistance, increased stiffness (elastic modulus), hardness (i.e., resistance to plastic deformation), yield strength, ultimate tensile strength, fatigue life, lubricity (i.e., reduced friction), hydrophobicity, anti-balling characteristics, surface roughness, and surface energy. Suitable reinforcing particles for the first reinforcement material **414** may include, but are not limited to, particles of metals, metal alloys, superalloys, intermetallics, borides, carbides, nitrides, oxides, ceramics, diamonds, and the like, or any combination thereof. In at least one embodiment, the first reinforcement material **414** may comprise a carbide powder (e.g., tungsten carbide, titanium carbide, tantalum carbide, etc.) and the first binder material may comprise a copper or nickel alloy. In such embodiments, the first infiltration process may result in an outer shell that is stiff or hard.

[0047] Suitable metals that may be used as the reinforcing particles of the first reinforcement material **414** include, but are not limited to, transition metals (e.g., iridium, rhenium, ruthenium, tungsten, molybdenum, hafnium, chromium, manganese, rhodium, iron, cobalt, titanium, niobium, osmium, palladium, platinum, zirconium, nickel, copper, scandium, tantalum, vanadium, yttrium), post-transition metals (e.g., aluminum and tin), semi-metals (e.g., boron and silicon), alkaline-earth metals (e.g., beryllium and magnesium), lanthanides (e.g., lanthanum and ytterbium), non-metals (e.g., carbon, nitrogen, and oxygen), any alloy thereof, and the like.

[0048] Suitable metal alloys that may be used as the reinforcing particles of the first reinforcement material **414** include alloys that contain chromium, carbon, molybdenum, manganese, nickel, cobalt, tungsten, niobium, tantalum, vanadium, silicon, copper, and iron, which may produce a wear-resistant, erosion-resistant, abrasion-resistant, or hard outer shell. Using iridium, rhenium, ruthenium, tungsten, molybdenum, beryllium, chromium, rhodium, iron, cobalt, nickel, and alloys thereof may prove advantageous since such metals exhibit a relatively high modulus of elasticity, and may therefore produce a stiff, outer shell. For example, alloying nickel with vanadium, chromium, molybdenum, tantalum, tungsten, rhenium, osmium, or iridium increases the elastic modulus of the resulting alloy.

[0049] The formation of ceramic materials (e.g., carbides, borides, nitrides, and oxides) in the outer shell may produce beneficial changes in any of the desired properties mentioned above. The in-situ formation of carbides, borides, nitrides, and oxides may be achieved by including carbon, boron, nitrogen, and oxygen in the first binder material or the reinforcing particles. In particular, carbides may be formed by using molybdenum, tungsten, chromium, titanium, niobium, vanadium, tantalum, zirconium, hafnium, manganese, iron, nickel, boron, and silicon in the first binder material or the reinforcing particles of the first reinforcement material **414**. Borides may be formed by using titanium, zirconium, hafnium, vanadium, niobium, tantalum, chromium, molybdenum, tungsten, iron, cobalt, nickel, and lanthanum in the first binder material or the reinforcing particles of the first reinforcement material **414**. Nitrides may be formed by using boron, silicon, aluminum, iron, nickel, scandium, yttrium, titanium, vanadium, chromium, zirconium, molybdenum, tungsten, tantalum, hafnium, manganese, and niobium in the first binder material or the reinforcing particles of the first reinforcement material **414**. Oxides may be formed by using silicon, aluminum, yttrium, zirconium, and titanium in the first binder material or the reinforcing particles of the first reinforcement material **414**.

[0050] Intermetallics may also prove advantageous since the formation of such materials in the outer shell may produce beneficial changes in any of the desired properties mentioned above. Suitable intermetallics that may be used as the reinforcing particles of the first reinforcement material **414** include both stoichiometric and non-stoichiometric phases that are formed between two metallic elements. Examples of elements that form refractory aluminum-based intermetallics include boron, carbon, cobalt, chromium, copper, iron, hafnium, iridium, manganese, molybdenum, niobium, nickel, palladium, platinum, rhenium, ruthenium, scandium, tantalum, titanium, vanadium, tungsten, and zirconium. Other examples of refractory intermetallic systems include silver-titanium, silver-zirconium, gold-hafnium, gold-manganese, gold-niobium, gold-scandium, gold-tantalum, gold-titanium, gold-thulium, gold-vanadium, gold-zirconium, boron-chromium, boron-manganese, boron-molybdenum, boron-niobium, boron-neodymium, boron-ruthenium, boron-silicon, boron-titanium, boron-vanadium, boron-tungsten, boron-yttrium, beryllium-copper, beryllium-iron, beryllium-niobium, beryllium-nickel, beryllium-palladium, beryllium-titanium, beryllium-vanadium, beryllium-tungsten, beryllium-zirconium, any combination thereof, and the like.

[0051] To facilitate the first infiltration process or step, the mold assemblies **400***a,b* and their contents may be preheated and subsequently placed in a furnace to liquefy the first binder material, which then proceeds to infiltrate the first reinforcement material **414**. After a predetermined amount of time allotted for the liquefied first binder material to infiltrate the first reinforcement material **414**, the mold assemblies **400***a,b* may then be removed from the furnace and cooled at a controlled rate. Once cooled, the inner mold **404** may be removed to expose an outer shell for the MMC tool in preparation for a second infiltration step. The outer shell may comprise portions of the bottom and/or the sides of the MMC tool. In some embodiments, as described below, the outer mold **402** may also be removed and the outer shell may either be placed in a new or second outer mold or otherwise be used itself as an outer mold for the second infiltration step.

[0052] Referring now to FIG. **5**, illustrated is a cross-sectional side view of a mold assembly **500** that may be used for facilitating a second infiltration step for an MMC tool, according to one or more embodiments. Similar to the mold assemblies **400***a,b* of FIGS. **4**A and **4**B, the mold assembly **500** may be used to form and otherwise fabricate an MMC drill bit, similar in some respects to the MMC drill bit **100** of FIGS. **1** and **2**. It will be appreciated, however, that variations of the mold assembly **500** may alternatively be incorporated to form and otherwise fabricate any of the MMC tools mentioned herein, without departing from the scope of the disclosure. Nonetheless, for purposes of discussion, the mold assembly **500** will be described herein as forming an MMC drill bit.

[0053] As illustrated, the mold assembly **500** may comprise an outer mold **502** that defines an infiltration chamber **504**. An outer shell **506** previously produced during the above-described first infiltration step may be positionable within the outer mold **502**. In some embodiments, the outer mold **502** may be the same as the outer mold **402** of FIGS. **4**A and **4**B and, therefore, the outer shell **506** may be produced in situ within the outer mold **502** during the first infiltration step, after which the inner mold **404** (FIGS. **4**A and **4**B) may be removed. In other embodiments, however, the outer mold **502** may be different from the outer mold **402** and otherwise configured to receive the outer shell **506** following the above-described first infiltration step.

[0054] As illustrated, the outer shell **506** may extend across portions of the bottom and/or the sides of the MMC tool being fabricated. In some embodiments, as shown in dashed lines, the outer shell **506** may further extend along exterior portions of the legs **314** (one shown) and the central displacement **316**, if used during the first infiltration process. In such embodiments, the displacement materials for the legs **314** and the central displacement **316** may be retained in place for both the first and second infiltration processes. In other embodiments, however, the legs **314** and the central displacement **316**, or any other type of displacement material (e.g., the junk slot displacements **315**), may be added to the mold assembly **500** following the first infiltration process. In such embodiments, the outer mold **502** may be configured to hold the displacement materials with respect to the outer shell **506** during the second infiltration process. As illustrated, the mandrel **202** may also be positioned within the infiltration chamber **504** and may also be held in place with respect to the outer shell **506** during the second infiltration process.

[0055] As illustrated, the outer mold **502** may be configured to cover and otherwise extend past top portions of the outer shell **506**. As will be appreciated, this may prove advantageous in allowing for the formation of a smooth transition surface between the outer shell **506** and the mandrel **202** following the second infiltration step and accomplished during post-processing machining. Alternatively, the outer mold **502** may allow the formation of material outside of the outer shell **506**. In such embodiments, the material formed outside of the outer shell **506** may be removed during post-processing machining.

[0056] After the desired displacement materials have been installed within the mold assembly **500** and situated with respect to the outer shell **506**, a second reinforcement material **508** may then be introduced into the mold assembly **500**. Similar to the first reinforcement material **414** of FIGS. **4**A and **4**B, the second reinforcement material may comprise reinforcing particles similar to the reinforcement materials **318** of FIG. **3**. A second binder material **510** may then be introduced into the mold assembly **500** for infiltrating the second reinforcement material **508** during a second infiltration process. The second binder material **510** may comprise materials similar to the binder material **324** of FIG. **3**, but may be different than the first binder material used during the above-described first infiltration step. In some embodiments, as illustrated, the second binder material **510** may be placed on top of the second reinforcement material **508**, the mandrel **202**, and the central displacement **316**. In other embodiments, however, the mold assembly **500** may further include the binder bowl **308** (FIG. **3**) and the second binder material **510** may alternatively be placed in the binder bowl **308** for the second infiltration step.

[0057] During the second infiltration step, the mold assembly **500** may be introduced into a furnace to increase the temperature of the mold assembly **500** and its contents. When the furnace temperature reaches the melting point of the second binder material **510**, the second binder material **510** will liquefy and proceed to infiltrate the second reinforcement material **508**. After a predetermined amount of time allotted for the liquefied second binder material **510** to infiltrate the second reinforcement material **508**, the mold assembly **500** may then be removed from the furnace and cooled at a controlled rate. Once cooled, the mold assembly **500** may be broken away to expose the MMC tool for machining and post-processing to finish the MMC tool.

[0058] The temperature of the second infiltration step may be less than the temperature of the first infiltration step used to form the outer shell **506**. As will be appreciated, this may be required so as to not re-liquefy the outer shell **506** although some diffusion, alloying, or reactions between the outer shell **506** and the remaining portions of the MMC tool may occur to enhance the bond. The first and second reinforcing materials **414**, **508** may comprise the same or different material compositions, but the second binder material **510** may be different than the first binder material used to form the outer shell **506**. In such embodiments, the second binder material **510** may be configured to melt at a lower temperature to facilitate the second infiltration process.

[0059] In some embodiments, and prior to undertaking the second infiltration process, a material coating **512** may be deposited on the inner surface of the outer shell **506**. The material coating **512** may be configured to promote adhesion between outer shell **506** and the second reinforcing material **508** during the second infiltration process. The material coating **512** may comprise any material suitable for diffusion or dissolution into or alloying or reaction with the second binder material **510** during the second infiltration process including, but not limited to, transition metals (e.g., iridium, rhenium, ruthenium, tungsten, molybdenum, hafnium, chromium, manganese, rhodium, iron, cobalt, titanium, niobium, osmium, palladium, platinum, zirconium, nickel, copper, scandium, tantalum, vanadium, yttrium), post-transition metals (e.g., aluminum and tin), semi-metals (e.g., boron and silicon), alkaline-earth metals (e.g., beryllium and magnesium), lanthanides (e.g., lanthanum and ytterbium), nonmetals (e.g., carbon, nitrogen, and oxygen), any alloy thereof, and the like. In particular, reactive metals, such as titanium, chromium, vanadium, niobium, zirconium, and hafnium, any alloy thereof, and the like, may drastically increase the strength of the resulting bond between the outer shell **506** and the reinforced composite material **208** to be formed during the second infiltration step.

[0060] The material coating **512** may be deposited on the outer shell **506** using any known process including, but not limited to, physical vapor deposition, chemical vapor deposition, sputtering, pulsed laser deposition, chemical solution deposition, plasma enhanced chemical vapor deposition, cathodic arc deposition, electrohydrodynamic deposition (i.e., electrospray deposition), ion-assisted electron-beam deposition, electrolytic plating, electroless plating, thermal evaporation, spin coating, dipping portions of the outer shell **506** in a molten metal bath, and forming and placing foils. In some embodiments, the material coating **512** may be formed under a controlled atmosphere such as high vacuum and/or inert atmosphere during the deposition process.

[0061] In some embodiments, the outer mold **502** may not be required for the second infiltration process. Rather, the outer shell **506** itself may instead be used as a type of mold for loading the second reinforcement materials **508** and the second binder material **510**. In such embodiments, the second infiltration step may be undertaken entirely within the outer shell **506**. However, an outer mold and/or fixture (not shown) may be required to maintain the outer shell **506** in place while it is being loaded with the second reinforcement materials **508** and the second binder material **510** in preparation for the second infiltration step, and also to prevent the second binder material **510** from potentially spilling over to the outside. In other embodiments, the outer mold **502** may be limited to the area between the outer shell **506** and the mandrel **202** to prevent overflow of the second reinforcement materials **508** and the second binder material **510**. In such embodiments, the outer mold **502** may interface directly with the mandrel **202** or maintain a space between mandrel **202** and the outer mold **502**, as shown in FIG. **5**.

[0062] FIG. **5**A illustrates a cross-sectional side view of an exemplary MMC drill bit **514** fabricated through the above-described first and second infiltration steps, according to one or more embodiments. The MMC drill bit **514** may be similar in some respects to the MMC drill bit **100** of FIG. **2** and therefore will be best understood with reference thereto, where like numerals represent like elements not described again. As illustrated, the MMC drill bit **514** may include the bit head **108**, which provides two macroscopically different regions generated through the first and second infiltration steps described herein, respectively. For instance, the bit head **108** includes the outer shell **506** formed during the first infiltration step and attached to exterior portions of the reinforced composite material **208** formed during the second infiltration step. As illustrated, in some embodiments, the outer shell **506** may extend along all or a portion of the fluid cavity **204***b* and the flow passageways **206**, without departing from the scope of the disclosure.

[0063] Referring now to FIG. **6** and FIGS. **6**A-**6**F, illustrated are a top view and partial cross-sectional side views, respectively, of an exemplary MMC drill bit **600**, according to one or more embodiments. The MMC drill bit **600** may be similar in some respects to the MMC drill bits **100** and **514** of FIGS. **1**-**2** and **5**A, respectively, and therefore may be best understood with reference thereto, where like numerals will represent like components not described again in detail. As illustrated in FIG. **6**, for instance, the MMC drill bit **600** may include a plurality of cutter blades **102** (six shown) and cutting elements **118** fixedly installed within corresponding pockets **116** defined in the cutter blades **102**. Nozzle openings **122** are also defined within the junk slots **124** between adjacent pairs of cutter blades **102**.

[0064] Similar to the MMC drill bit **514** of FIG. **5**A, the MMC drill bit **600** may be manufactured via the first and second infiltration steps described herein. FIGS. **6**A-**6**F are partial cross-sectional side views of the MMC drill bit **600** as taken along the lines indicated in FIG. **6**, and each depict an outer shell **602** extending along some or all of the bottom and sides of the MMC drill bit **600** and otherwise attached to exterior portions of a reinforced composite material **604**. The outer shell **602** may be similar to the outer shell **506** described above and otherwise fabricated through a first infiltration step. Moreover, the reinforced composite material **604** may be similar to the reinforced composite material **208** of FIG. **5**A and otherwise fabricated through a second infiltration step following the first infiltration step, and may otherwise comprise the second reinforcement material **508** (FIG. **5**) as infiltrated by the second binder material **510** (FIG. **5**).

[0065] The partial cross-sectional side views of FIGS. **6**A-**6**F also depict the mandrel **202** and a fluid cavity **608**, and FIGS. **6**A, **6**D, and **6**F each depict flow passageways **610** extending from the fluid cavity **608** and terminating in nozzle openings **122**. The fluid cavity **608** and the flow passageways **610** may be similar to the fluid cavity **204***b* and flow passageways **206** of FIG. **5**A, and therefore may be defined using the central displacement **316** and legs **314** of FIGS. **3**, **4**A-**4**B or **5**.

[0066] The thickness of the outer shell **602** may correspond to the thickness **410** of the gap **406** of FIGS. **4**A and **4**B. Accordingly, in some embodiments, the thickness of the outer shell **602** may be uniform or constant about the outer portions of the MMC drill bit **600**. In other embodiments, however, the thickness of the outer shell **602** may vary at select locations, such as an increased thickness at or near the cutter blades **102**, as shown in FIGS. **6**B and **6**E.

[0067] As indicated above, the outer shell **602** may be made of a variety of materials configured to provide desired surface properties to the MMC drill bit **600**. More particularly, the outer shell **602** may be made of materials that may promote wear resistance, erosion resistance, abrasion resistance, increased stiffness (elastic modulus), hardness (i.e., resistance to plastic deformation), yield strength, ultimate tensile strength, fatigue life, lubricity (i.e., reduced friction), hydrophobicity, anti-balling characteristics, surface roughness, and surface energy.

[0068] In some embodiments, the inner surface of the outer shell **602** may be generally smooth, as shown in FIGS. **6**A, **6**C, **6**D, and **6**F. In other embodiments, however, the inner surface of the outer shell **602** may comprise macroscopic surface features **612**, as shown in FIGS. **6**B and **6**E. The surface features **612** may comprise, but are not limited to, small-scale undulations, crenellations, steps, waves, dimples, recesses, protrusions, nubs, fins, threads, miters, dovetails, knurling, any combination thereof, and the like. Such surface features **612** may be formed in the inner mold **404** (FIGS. **4**A and **4**B) or formed into the outer shell **602** after manufacture, such as by shot peening, machining, and the like, and may expose sides, vertices, edges, and the like of the first reinforcement material **414** (FIGS. **4**A and **4**B) to enhance bonding between the outer shell **602** and the reinforced composite material **604**. The surface features **612** may correspond to geometries of the outer shell **602** (e.g., cutter pockets) or may be formed in otherwise smooth surfaces or surfaces whose features do not correspond to the geometries of the outer shell **602**.

[0069] As will be appreciated, the surface features **612** may prove advantageous in increasing the bonding surface area between the outer shell **602** and the reinforced composite material **604**, and increasing the surface area may promote adhesion and enhance shearing strength between the two macroscopic regions. Moreover, varying the bonding area between the outer shell **602** and the reinforced composite material **604** may prove advantageous in helping to prevent the outer shell **602** from being torqued off and otherwise disengaged from the reinforced composite material **604** during operational use of the MMC drill bit.

[0070] Referring now to FIG. **7** and FIGS. **7**A-**7**F, illustrated are a top view and partial cross-sectional side views, respectively, of another embodiment of the MMC drill bit **600** of FIG. **6**, according to one or more embodiments. FIGS. **7**A-**7**F are partial cross-sectional side views of the MMC drill bit **600** as taken along the lines indicated in FIG. **7** and each depict the outer shell **602** extending along some or all of the bottom and sides of the MMC drill bit **600** and otherwise attached to exterior portions of the reinforced composite material **604**. Unlike the embodiment shown in FIGS. **6**A-**6**F, however, the outer shell **602** is depicted as extending up along at least a portion of the flow passageways **610** and the fluid cavity **608**, as shown in FIGS. **7**A, **7**D and **7**F.

[0071] In such embodiments, the legs **314** and central displacement **316** of FIGS. **3**, **4**A-**4**B, and **5** may have been used during the first infiltration process. As will be appreciated, having the outer shell **602** extend along the flow passageways **610** and the fluid cavity **608** may provide the flow passageways **610** and the fluid cavity **608** with greater wear and erosion resistance. The reinforced composite material **604** may provide compliance and toughness between the outer shell **602** where it extends along the flow passageways **610** and the fluid cavity **608**.

[0072] Referring now to FIG. **8** and FIGS. **8**A-**8**F, illustrated are a top view and partial cross-sectional side views, respectively, of another embodiment of the MMC drill bit **600** of FIG. **6**, according to one or more embodiments. FIGS. **8**A-**8**F are partial cross-sectional side views of the MMC drill bit **600** as taken along the lines indicated in FIG. **8** and each depict the outer shell **602** extending along some or all of the bottom and sides of the MMC drill bit **600** and otherwise attached to exterior portions of the reinforced composite material **604**. Unlike the embodiment shown in FIGS. **6**A-**6**F or FIGS. **7**A-**7**F, however, the outer shell **602** is much thicker to the point that the region below the fluid cavity **608** is completely filled with the material of the outer shell **602**, as shown in FIGS. **8**A, **8**D and **8**F. As indicated above, the thickness of the outer shell **602** may correspond to the thickness **410** of the gap **406** of FIGS. **4**A and **4**B, which, in this case, may vary to displace the reinforced composite material **604** from the region below the fluid cavity **608**. Such embodiments may be easier to manufacture, as the inner mold **404** (FIGS. **4***a* and **4**B) is easier to break out of the outer shell **602** for the second infiltration process. Furthermore, the inner surface of the outer shell **602** may be far enough from the cutter pockets **116** to produce a fairly smooth surface.

[0073] Referring now to FIG. **9** and FIGS. **9**A-**9**F, illustrated are a top view and partial cross-sectional side views, respectively, of another embodiment of the MMC drill bit **600** of FIG. **6**, according to one or more embodiments. FIGS. **9**A-**9**F are partial cross-sectional side views of the MMC drill bit **600** as taken along the lines indicated in FIG. **9** and each depict the outer shell **602** extending along some or all of the bottom and sides of the MMC drill bit **600** and otherwise attached to exterior portions of the reinforced composite material **604**. Unlike the embodiment shown in FIGS. **6**A-**6**F, **7**A-**7**F, or **8**A-**8**F, however, the outer shell **602** in FIGS. **9**A-**9**F is depicted as being formed primarily at the cutting blades **102**, as shown in FIGS. **9**B and **9**E. In FIGS. **9**A, **9**C, and **9**D, the outer shell **602** may correspond to the principal blade, in this case, the blade shown in FIG. **9**B. In other cases, the material of the outer shell **602** shown in FIGS. **9**A, **9**C, and **9**D may connect the blades together. Accordingly, the first infiltration process described above may result in the outer shell **602** comprising a plurality of component parts, where each component part corresponds to a given cutting blade **102**. During the second infiltration process, the component parts of the outer shell **602** at each cutting blade **102** may be coupled to the reinforced composite material **604**, such as through diffusion or the like, as in the previous embodiments. Further, such embodiments could be amenable to batch processing, wherein each blade section of the outer shell **602** is formed in a smaller mold **402** such that blade sections for multiple bits could be processed in one heating cycle.

[0074] Referring now to FIG. **10**, illustrated is a cross-sectional side view of another mold assembly **1000** that may be used for facilitating a second infiltration step for an MMC tool, according to one or more embodiments. The mold assembly **1000** may be similar in some respects to the mold assembly **500** of FIG. **5** and, therefore, may be used to form and otherwise fabricate an MMC drill bit. As illustrated, the mold assembly **1000** may comprise an outer mold **1002** that defines an infiltration chamber **1004**, and an outer shell **1006** produced during the first infiltration step may be positionable within the outer mold **1002**. In the illustrated embodiment, the outer mold **1002** receives the outer shell **1006**, which may have been fabricated in another outer mold (e.g., the outer mold **402** of FIGS. **4**A and **4**B) via the first infiltration step.

[0075] Moreover, the outer mold **1002** may include and otherwise define a plurality of cavities **1008** configured to receive a corresponding plurality of cutting elements **118** and suitable attachment material (not shown), such as braze paste or braze foil. Due its complicated contours, the outer mold **1002** may be composed of multiple pieces or component parts that can be assembled about the outer shell **1006** in a predetermined order to allow for complete assembly. The cutting elements **118** and attachment material may be positioned within the cavities **1008** prior to positioning the outer shell **1006** within the outer mold **1002**. As illustrated, the outer shell **1006** may include a plurality of pockets **116** molded therein during the first infiltration process and otherwise configured to align with the cutting elements **118** when positioned within the outer mold **1002**. During the second infiltration process, the cutting elements **118** may be joined to the outer shell **1006** at the pockets **116**. As indicated above, the second infiltration process may be undertaken at a temperature that is lower than that of the first infiltration process, but sufficiently high to braze the cutting elements **118** to the pockets **116**. As will be appreciated, this may prove advantageous in eliminating human interaction in attaching the cutting elements **118** to the pockets **116**, since they will all be attached in-situ during the second infiltration step.

[0076] Referring now to FIG. **11**, illustrated is an exemplary drilling system **1100** that may employ one or more principles of the present disclosure. Boreholes may be created by drilling into the earth **1102** using the drilling system **1100**. The drilling system **1100** may be configured to drive a bottom hole assembly (BHA) **1104** positioned or otherwise arranged at the bottom of a drill string **1106** extended into the earth **1102** from a derrick **1108** arranged at the surface **1110**. The derrick **1108** includes a kelly **1112** and a traveling block **113** used to lower and raise the kelly **112** and the drill string **1106**.

[0077] The BHA **1104** may include a drill bit **1114** operatively coupled to a tool string **1116** which may be moved axially within a drilled wellbore **1118** as attached to the drill string **1106**. The drill bit **1114** may be fabricated and otherwise created in accordance with the principles of the present disclosure and, more particularly, with two macroscopic regions formed during first and second infiltration steps. During operation, the drill bit **1114** penetrates the earth **1102** and thereby creates the wellbore **1118**. The BHA **1104** provides directional control of the drill bit **1114** as it advances into the earth **1102**. The tool string **1116** can be semi-permanently mounted with various measurement tools (not shown) such as, but not limited to, measurement-while-drilling (MWD) and logging-while-drilling (LWD) tools, that may be configured to take downhole measurements of drilling conditions. In other embodiments, the measurement tools may be self-contained within the tool string **1116**, as shown in FIG. **11**.

[0078] Fluid or "mud" from a mud tank **1120** may be pumped downhole using a mud pump **1122** powered by an adjacent power source, such as a prime mover or motor **1124**. The mud may be pumped from the mud tank **1120**, through a stand pipe **1126**, which feeds the mud into the drill string **1106** and conveys the same to the drill bit **1114**. The mud exits one or more nozzles arranged in the drill bit **1114** and in the process cools the drill bit **1114**. After exiting the drill bit **1114**, the mud circulates back to the surface **1110** via the annulus defined between the wellbore **1118** and the drill string **1106**, and in the process, returns drill cuttings and debris to the surface. The cuttings and mud mixture are passed through a flow line **1148** and are processed such that a cleaned mud is returned down hole through the stand pipe **1126** once again.

[0079] Although the drilling system **1100** is shown and described with respect to a rotary drill system in FIG. **11**, those skilled in the art will readily appreciate that many types of drilling systems can be employed in carrying out embodiments of the disclosure. For instance, drills and drill rigs used in embodiments of the disclosure may be used onshore (as depicted in FIG. **11**) or offshore (not shown). Offshore oil rigs that may be used in accordance with embodiments of the disclosure include, for example, floaters, fixed platforms, gravity-based structures, drill ships, semi-submersible platforms, jack-up drilling rigs, tension-leg platforms, and the like. It will be appreciated that embodiments of the disclosure can be applied to rigs ranging anywhere from small in size and portable, to bulky and permanent.

[0080] Further, although described herein with respect to oil drilling, various embodiments of the disclosure may be used in many other applications. For example, disclosed methods can be used in forming tools for use in drilling for mineral exploration, environmental investigation, natural gas extraction, underground installation, mining operations, water wells, geothermal wells, and the like. Further, embodiments of the disclosure may be used in weight-on-packers assemblies, in running liner hangers, in running completion strings, etc., without departing from the scope of the disclosure.

[0081] Embodiments disclosed herein include:

[0082] A. A method for fabricating a metal-matrix composite (MMC) tool that includes positioning an inner mold within an outer mold and thereby defining a gap between the inner and outer molds, loading a first reinforcement material into the gap, infiltrating the first reinforcement material at a first temperature with a first binder material and thereby forming an outer shell, removing the inner mold and loading a second reinforcement material at least partially into the outer shell, and infiltrating the second reinforcement material at a second temperature with a second binder material and thereby forming a reinforced composite material, wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material, and wherein the outer shell is attached to exterior portions of the reinforced composite material.

[0083] B. A metal-matrix composite (MMC) tool that includes a reinforced composite material forming a core of the MMC tool and having an exterior, and an outer shell attached to at least a portion of the exterior and being harder than the reinforced composite material, wherein the outer shell is formed during a first infiltration step where a first binder material infiltrates a first reinforcement material at a first temperature, the first reinforcement material being loaded into a gap defined between an inner mold and an outer mold, wherein the reinforced composite portion is formed after the outer shell and during a second infiltration step where a second binder material infiltrates a second reinforcement material at a second temperature, the second reinforcement material being loaded at least partially into the outer shell, and wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material.

[0084] C. A drilling assembly that includes a drill string extendable from a drilling platform and into a wellbore, a drill bit attached to an end of the drill string, and a pump fluidly connected to the drill string and configured to circulate a drilling fluid to the drill bit and through the wellbore. The drill bit may include a reinforced composite material forming a core of the drill bit and having an exterior, and an outer shell attached to at least a portion of the exterior and being harder than the reinforced composite material, wherein the outer shell is formed during a first infiltration step where a first binder material infiltrates a first reinforcement material at a first temperature, the first reinforcement material being loaded into a gap defined between an inner mold and an outer mold, wherein the reinforced composite portion is formed after the outer shell and during a second infiltration step where a second binder material infiltrates a second reinforcement material at a second temperature, the second reinforcement material being loaded at least partially into the outer shell, and wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material.

[0085] Each of embodiments A, B, and C may have one or more of the following additional elements in any combination: Element 1: further comprising varying a thickness of the gap and thereby varying a thickness of the outer shell at select regions. Element 2: wherein positioning the inner mold within the outer mold further comprises positioning one or more displacements within the outer mold to form one or more features while infiltrating the first reinforcement material at the first temperature. Element 3: wherein loading the second reinforcement material at least partially into the outer shell is preceded by positioning one or more displacements within the outer shell to form one or more features while infiltrating the second reinforcement material at the second temperature. Element 4: wherein the outer mold is a first outer mold and wherein loading the second reinforcement material at least partially into the outer shell is preceded by removing the outer shell from the first outer mold, and positioning the outer shell in a second outer mold. Element 5: wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements are disposed in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and wherein infiltrating the second reinforcement material at the second temperature further comprises attaching the plurality of cutting elements to the plurality of pockets. Element 6: wherein an attachment material is disposed in the plurality of cavities with the plurality of cutting elements, and wherein attaching the plurality of cutting elements to the plurality of pockets comprises brazing the plurality of cutting elements to the plurality of pockets with the attachment material. Element 7: wherein loading the second reinforcement material at least partially into the outer shell is preceded by depositing a material coating on at least a portion of an inner surface of the outer shell. Element 8: wherein loading the second reinforcement material at least partially into the outer shell is preceded by forming one or more surface features on at least a portion of an inner surface of the outer shell.

[0086] Element 9: wherein the MMC tool is a tool selected from the group consisting of an oilfield drill bit or cutting tool, a non-retrievable drilling component, an aluminum drill bit body associated with casing drilling of wellbores, a drill-string stabilizer, a cone for roller-cone drill bits, a model for forging dies used to fabricate support arms for roller-cone drill bits, an arm for fixed reamers, an arm for expandable reamers, an internal component associated with expandable reamers, a sleeve attachable to an uphole end of a rotary drill bit, a rotary steering tool, a logging-while-drilling tool, a measurement-while-drilling tool, a side-wall coring tool, a fishing spear, a washover tool, a rotor, a stator and/or housing for downhole drilling motors, blades for downhole turbines, armor plating, an automotive component, a bicycle frame, a brake fin, an aerospace component, a turbopump component, and any combination thereof. Element 10: wherein the first and second binder materials comprise a material selected from the group consisting of copper, nickel, cobalt, iron, aluminum, molybdenum, chromium, manganese, tin, zinc, lead, silicon, tungsten, boron, phosphorous, gold, silver, palladium, indium, any mixture thereof, any alloy thereof, and any combination thereof. Element 11: wherein the first and second reinforcement materials comprise reinforcing particles selected from the group consisting of a metal, a metal alloy, a superalloy, an intermetallic, a boride, a carbide, a nitride, an oxide, a ceramic, a diamond, and any combination thereof. Element 12: wherein a thickness of the outer shell varies. Element 13: wherein the outer mold is a first outer mold and the outer shell is positioned in a second outer mold for the second infiltration step. Element 14: wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements and attachment material are disposable in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and wherein the plurality of cutting elements are attached to the plurality of pockets during the second infiltration step. Element 15: wherein a material coating is applied to at least a portion of an inner surface of the outer shell prior to loading the second reinforcement material at least partially into the outer shell. Element 16: wherein the material coating comprises a material selected from the group consisting of a transition metal, a post-transition metal, a semi-metal, an alkaline-earth metal, a lanthanide, a non-metal, and any alloy thereof. Element 17: wherein the MMC tool is a drill bit that defines one or more flow passageways and a fluid cavity, and wherein the outer shell extends along at least a portion of one or both of the one or more flow passageways and the fluid cavity. Element 18: wherein the outer shell has an inner surface attached to the portion of the exterior of the reinforced composite material, and wherein the inner surface defines one or more surface features. Element 19: wherein the MMC tool is a drill bit that provides a plurality of cutter blades, and wherein the outer shell comprises a plurality of component parts each positioned at a corresponding cutter blade.

[0087] Element 20: wherein a thickness of the outer shell varies. Element 21: wherein the outer mold is a first outer mold and the outer shell is positioned in a second outer mold for the second infiltration step, wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements and attachment material are disposable in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and wherein the plurality of cutting elements are attached to the plurality of pockets during the second infiltration step. Element 22: wherein a material coating is applied to at least a portion of an inner surface of the outer shell prior to loading the second reinforcement material at least partially into the outer shell. Element 23: wherein the drill bit defines one or more flow passageways and a fluid cavity, and wherein the outer shell extends along at least a portion of one or both of the one or more flow passageways and the fluid cavity.

[0088] By way of non-limiting example, exemplary combinations applicable to A, B, and C include: Element 4 with Element 5; Element 5 with Element 6; Element 13 with Element 14; and Element 15 with Element 16.

[0089] Therefore, the disclosed systems and methods are well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed above are illustrative only, as the teachings of the present disclosure may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered, combined, or modified and all such variations are considered within the scope of the present disclosure. The systems and methods illustratively disclosed herein may suitably be practiced in the absence of any element that is not specifically disclosed herein and/or any optional element disclosed herein. While compositions and methods are described in terms of "comprising," "containing," or "including" various components or steps, the compositions and methods can also "consist essentially of" or "consist of" the various components and steps. All numbers and ranges disclosed above may vary by some amount. Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range is specifically disclosed. In particular, every range of values (of the form, "from about a to about b," or, equivalently, "from approximately a to b," or, equivalently, "from approximately a-b") disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. Moreover, the indefinite articles "a" or "an," as used in the claims, are defined herein to mean one or more than one of the elements that it introduces. If there is any conflict in the usages of a word or term in this specification and one or more patent or other documents that may be incorporated herein by reference, the definitions that are consistent with this specification should be adopted.

[0090] As used herein, the phrase "at least one of" preceding a series of items, with the terms "and" or "or" to separate any of the items, modifies the list as a whole, rather than each member of the list (i.e., each item). The phrase "at least one of" allows a meaning that includes at least one of any one of the items, and/or at least one of any combination of the items, and/or at least one of each of the items. By way of example, the phrases "at least one of A, B, and C" or "at least one of A, B, or C" each refer to only A, only B, or only C; any combination of A, B, and C; and/or at least one of each of A, B, and C.

What is claimed is:

1. A method for fabricating a metal-matrix composite (MMC) tool, comprising:
 positioning an inner mold within an outer mold and thereby defining a gap between the inner and outer molds;
 loading a first reinforcement material into the gap;
 infiltrating the first reinforcement material at a first temperature with a first binder material and thereby forming an outer shell;
 loading a second reinforcement material at least partially into the outer shell; and
 infiltrating the second reinforcement material at a second temperature with a second binder material and thereby forming a reinforced composite material, wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material, and wherein the outer shell is attached to exterior portions of the reinforced composite material.

2. The method of claim 1, further comprising varying a thickness of the gap and thereby varying a thickness of the outer shell at select regions.

3. The method of claim 1, wherein positioning the inner mold within the outer mold further comprises positioning one or more displacements within the outer mold to form one or more features while infiltrating the first reinforcement material at the first temperature.

4. The method of claim 1, wherein loading the second reinforcement material at least partially into the outer shell is preceded by positioning one or more displacements within the outer shell to form one or more features while infiltrating the second reinforcement material at the second temperature.

5. The method of claim 1, wherein the outer mold is a first outer mold and wherein loading the second reinforcement material at least partially into the outer shell is preceded by:
 removing the outer shell from the first outer mold; and
 positioning the outer shell in a second outer mold.

6. The method of claim 5, wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements are disposed in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and wherein infiltrating the second reinforcement material at the second temperature further comprises attaching the plurality of cutting elements to the plurality of pockets.

7. The method of claim 6, wherein an attachment material is disposed in the plurality of cavities with the plurality of cutting elements, and wherein attaching the plurality of cutting elements to the plurality of pockets comprises brazing the plurality of cutting elements to the plurality of pockets with the attachment material.

8. The method of claim 1, wherein loading the second reinforcement material at least partially into the outer shell is preceded by depositing a material coating on at least a portion of an inner surface of the outer shell.

9. The method of claim 1, wherein loading the second reinforcement material at least partially into the outer shell is preceded by forming one or more surface features on at least a portion of an inner surface of the outer shell.

10. A metal-matrix composite (MMC) tool, comprising:
 a reinforced composite material forming a core of the MMC tool and having an exterior; and
 an outer shell attached to at least a portion of the exterior and being harder than the reinforced composite material,
 wherein the outer shell is formed during a first infiltration step where a first binder material infiltrates a first reinforcement material at a first temperature, the first reinforcement material being loaded into a gap defined between an inner mold and an outer mold,
 wherein the reinforced composite portion is formed after the outer shell and during a second infiltration step where a second binder material infiltrates a second reinforcement material at a second temperature, the second reinforcement material being loaded at least partially into the outer shell, and
 wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material.

11. The MMC tool of claim 10, wherein the MMC tool is a tool selected from the group consisting of an oilfield drill bit or cutting tool, a non-retrievable drilling component, an aluminum drill bit body associated with casing drilling of wellbores, a drill-string stabilizer, a cone for roller-cone drill bits, a model for forging dies used to fabricate support arms for roller-cone drill bits, an arm for fixed reamers, an arm for expandable reamers, an internal component associated with expandable reamers, a sleeve attachable to an uphole end of a rotary drill bit, a rotary steering tool, a logging-while-drilling tool, a measurement-while-drilling tool, a side-wall coring tool, a fishing spear, a washover tool, a rotor, a stator and/or housing for downhole drilling motors, blades for downhole turbines, armor plating, an automotive component, a bicycle frame, a brake fin, an aerospace component, a turbopump component, and any combination thereof.

12. The MMC tool of claim 10, wherein the first and second binder materials comprise a material selected from the group consisting of copper, nickel, cobalt, iron, aluminum, molybdenum, chromium, manganese, tin, zinc, lead, silicon, tungsten, boron, phosphorous, gold, silver, palladium, indium, any mixture thereof, any alloy thereof, and any combination thereof.

13. The MMC tool of claim 10, wherein the first and second reinforcement materials comprise reinforcing particles selected from the group consisting of a metal, a metal alloy, a superalloy, an intermetallic, a boride, a carbide, a nitride, an oxide, a ceramic, a diamond, and any combination thereof.

14. The MMC tool of claim 10, wherein a thickness of the outer shell varies.

15. The MMC tool of claim 10, wherein the outer mold is a first outer mold and the outer shell is positioned in a second outer mold for the second infiltration step.

16. The MMC tool of claim 15, wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements and attachment material are disposable in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and wherein the plurality of cutting elements are attached to the plurality of pockets during the second infiltration step.

17. The MMC tool of claim 10, wherein a material coating is applied to at least a portion of an inner surface of the outer shell prior to loading the second reinforcement material at least partially into the outer shell.

18. The MMC tool of claim **17**, wherein the material coating comprises a material selected from the group consisting of a transition metal, a post-transition metal, a semi-metal, an alkaline-earth metal, a lanthanide, a non-metal, and any alloy thereof.

19. The MMC tool of claim **10**, wherein the MMC tool is a drill bit that defines one or more flow passageways and a fluid cavity, and wherein the outer shell extends along at least a portion of one or both of the one or more flow passageways and the fluid cavity.

20. The MMC tool of claim **10**, wherein the outer shell has an inner surface attached to the portion of the exterior of the reinforced composite material, and wherein the inner surface defines one or more surface features.

21. The MMC tool of claim **10**, wherein the MMC tool is a drill bit that provides a plurality of cutter blades, and wherein the outer shell comprises a plurality of component parts each positioned at a corresponding cutter blade.

22. A drilling assembly, comprising:

a drill bit attached to an end of a drill string; and

a pump fluidly connected to the drill string and configured to circulate a drilling fluid to the drill bit and through the wellbore, wherein the drill bit comprises:

a reinforced composite material forming a core of the drill bit and having an exterior; and

an outer shell attached to at least a portion of the exterior and being harder than the reinforced composite material,

wherein the outer shell is formed during a first infiltration step where a first binder material infiltrates a first reinforcement material at a first temperature, the first reinforcement material being loaded into a gap defined between an inner mold and an outer mold,

wherein the reinforced composite portion is formed after the outer shell and during a second infiltration step where a second binder material infiltrates a second reinforcement material at a second temperature, the second reinforcement material being loaded at least partially into the outer shell, and

wherein the second temperature is lower than the first temperature and the second binder material is different from the first binder material.

23. The drilling assembly of claim **22**, wherein a thickness of the outer shell varies.

24. The drilling assembly of claim **22**,

wherein the outer mold is a first outer mold and the outer shell is positioned in a second outer mold for the second infiltration step,

wherein the second outer mold defines a plurality of cavities and a corresponding plurality of cutting elements and attachment material are disposable in the plurality of cavities and alignable with a plurality of pockets defined in an outer surface of the outer shell, and

wherein the plurality of cutting elements are attached to the plurality of pockets during the second infiltration step.

25. The drilling assembly of claim **22**, wherein a material coating is applied to at least a portion of an inner surface of the outer shell prior to loading the second reinforcement material at least partially into the outer shell.

26. The drilling assembly of claim **22**, wherein the drill bit defines one or more flow passageways and a fluid cavity, and wherein the outer shell extends along at least a portion of one or both of the one or more flow passageways and the fluid cavity.

27. The drilling assembly of claim **22**, wherein the drilling assembly is used in an offshore drilling system.

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