(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
19 January 2017 (19.01.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/011825 A1

(51) International Patent Classification:
E21B 10/42 (2006.01) *B22F 5/00* (2006.01)
E21B 10/54 (2006.01)

(21) International Application Number:
PCT/US2016/042697

(22) International Filing Date:
18 July 2016 (18.07.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/193,145 16 July 2015 (16.07.2015) US
62/193,324 16 July 2015 (16.07.2015) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

[Continued on next page]

(54) Title: COMPOSITE DOWNHOLE TOOL

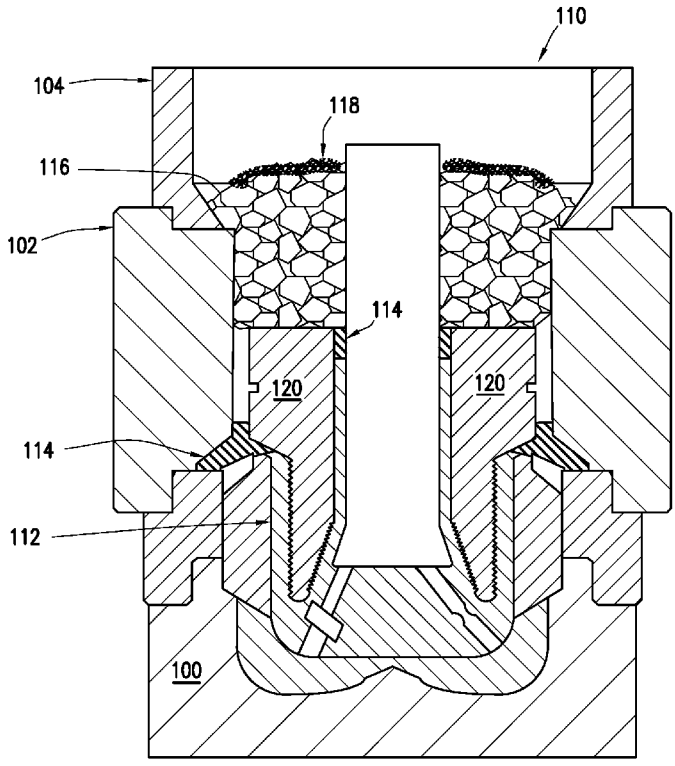


FIG. 1

(57) Abstract: A downhole cutting tool includes a body having at least 80 % of its volume made of at least one metallic region. The at least one metallic region includes a plurality of metallic particles in an infiltration binder. The infiltration binder has a melting temperature below the solidus temperature of the metallic particles. The at least one metallic region has a body hardness gradient extending at least 0.5 inches from a portion of an outer surface of the body to an interior portion of the metallic region, the body hardness gradient having a decreasing amount of carbon from the outer surface towards the interior portion. The downhole cutting tool also includes a plurality of cutting elements in cutting element pockets on the body.

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GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

COMPOSITE DOWNHOLE TOOL

CROSS REFERENCE TO RELATED APPLICATION

[0001] This Application claims the benefit to and priority of U.S. Provisional Application 62/193,145 filed on 16 July 2015 and U.S. Provisional Application 62/193,324 filed on 16 July 2015 entitled Infiltrated Cutting Tools and Related Methods, filed on the same day herewith, the entirety of which is incorporated herein by reference.

BACKGROUND

[0002] Downhole tools may be formed by infiltrating a matrix material in a mold of the tool. For example, a mold having the general negative shape of a downhole tool or component may be filled with a loose matrix material, such as a carbide powder or other cermet. A metal blank or shank may also be placed within the mold to provide reinforcement for the matrix material and for attachment to other downhole tool components. Metallic binder material (also referred to as an infiltrant or infiltration binder) may be placed over the matrix powder. The components within the mold are then heated in a furnace to the flow or infiltration temperature of the binder material, at which point the melted binder material infiltrates the matrix material. The infiltration process bonds the particles of matrix material to each other and to the other components to form a solid bit body that is relatively homogenous throughout. The sintering also causes the matrix material to bond to other structures that it contacts, such as the metal blank which may be suspended within the mold to produce the aforementioned reinforcement.

[0003] According to other methods of forming downhole tools, a body made of steel and/or other machineable material may be machined to form particular design features into the body of the tool. For example, a piece of steel may be machined to form a plurality of blades radially extending from a steel bit body, cutting element pockets machined into the blades to receive cutting elements, internal passages machined through the steel body to deliver drilling fluid, as well as other features useful in downhole drilling. A threaded pin connection may be machined from a different steel piece and welded to the end of the bit

body opposite the blades for connection to a drill string. Cutting elements may be, for example, press fitted, brazed, or mechanically secured into the cutting element pockets.

SUMMARY

[0004] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0005] In one aspect, embodiments disclosed herein relate to a downhole tool that includes a body with at least one metallic region, the at least one metallic region having a plurality of metallic particles disposed in an infiltration binder, the infiltration binder having a melting temperature below the solidus temperature of the metallic particles. The metallic region may form at least 80 % by volume of the body and at least a portion of an outer surface of the body, and the body may have a body hardness gradient extending at least 0.5 inches from the portion of the outer surface of the body to an interior portion of the metallic region, the body hardness gradient having a decreasing amount of carbon from the outer surface towards the interior portion. The downhole tool may further include a plurality of cutting elements in cutting element pockets on the body.

[0006] In another aspect, embodiments disclosed herein relate to a downhole cutting tool that includes a body with at least one metallic region, the at least one metallic region having a plurality of metallic particles disposed in an infiltration binder, the infiltration binder having a melting temperature below the solidus temperature of the metallic particles, the metallic region forming at least 80 % by volume of the body. The plurality of metallic particles may include composite metallic particles having a particle hardness gradient from the center towards the exterior of each composite metallic particle. The downhole cutting tool may further include a plurality of cutting elements in cutting element pockets on the body.

[0007] In yet another aspect, embodiments disclosed herein relate to a method of forming a downhole cutting tool body that includes providing starting materials, the starting materials having at least one metallic starting material and an infiltrant, and heating the starting materials to an infiltration temperature lower than the solidus temperature of the

at least one metallic starting material and greater than or equal to the melting temperature of the infiltrant, wherein during heating, carbon diffuses from a carbon source into the starting materials, and wherein the at least one metallic starting material and the infiltrant form at least 80 % by volume of the cutting tool body.

[0008] Other aspects and advantages of the disclosure will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF DRAWINGS

[0009] FIG. 1 is a cross sectional view of a mold assembly according to embodiments of the present disclosure.

[0010] FIG. 2 is a cross sectional view of a mold assembly according to embodiments of the present disclosure.

[0011] FIG. 3 shows a cross section of a downhole cutting tool according to embodiments of the present disclosure.

[0012] FIG. 4 shows a downhole cutting tool according to embodiments of the present disclosure.

[0013] FIG. 5 shows a downhole cutting tool according to embodiments of the present disclosure.

[0014] FIG. 6 shows an exploded view of a downhole cutting tool according to embodiments of the present disclosure.

[0015] FIG. 7 shows a downhole cutting tool body according to embodiments of the present disclosure.

[0016] FIG. 8 shows a downhole cutting tool body having cutting elements disposed thereon according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0017] Embodiments of the present disclosure relate generally to infiltration of a metallic powder to form a downhole tool. The metallic powder may be infiltrated with a low melting temperature infiltrant at temperatures below the solidus temperature of the metallic powder to prevent or inhibit the metallic powder from sintering prior to infiltration. Downhole tools may include, for example, downhole cutting tools such as drill bits, reamer blocks, or mills.

[0018] According to some embodiments, a downhole tool may be formed using a mold having the general negative shape of the tool. For example, a mold may have a negative shape of a tool body and one or more tool components or regions, such as blades or ribs extending from the tool body and/or one or more cutting elements. For a downhole cutting tool, molds including a negative shape of one or more cutting elements disposed on a cutting tool may have displacements in the shape of the cutting elements positioned within the spaces of the mold corresponding to the locations of the cutting elements. The negative shape of a mold may vary depending on the tool being formed. A mold may be made of graphite, and in some embodiments, at least a portion of the inner walls of a graphite mold may be coated, such as with a refractory metal or boron nitride, to reduce carbon additions from the graphite mold during infiltration.

[0019] Infiltration methods of the present disclosure may include filling a mold of a downhole tool with metallic material, including a metallic infiltration binder (sometimes called an infiltrant and sometimes called a binder) and a metallic starting material to be infiltrated, heating the contents of the mold to an infiltration temperature, and cooling the contents of the mold, where upon solidification, the contents form an infiltrated metallic downhole tool. As used herein, the term "starting" may be used to refer to the material that is infiltrated, while the term "infiltrant" may be used to describe the material that infiltrates the starting material. For example, a mold may be filled with a powdered metallic starting material of a metal or metal alloy. A metallic binder infiltrant may be poured over the powdered starting material and within the mold. The contents of the mold (including the powdered starting material and metallic binder infiltrant) may then be heated to an infiltration temperature that ranges from lower than the solidus temperature

of the powdered starting material to greater than or equal to the melting temperature of the metallic binder infiltrant, such that the metallic binder melts and infiltrates through the powdered starting material. By keeping the infiltration temperature lower than the solidus temperature of the starting material, the starting material may remain un-melted through the infiltration process and reduce or prevent self-sintering of the starting material. Further, infiltration methods according to embodiments of the present disclosure may include infiltrating (heating the contents of the mold to the infiltration temperature such that an infiltrant melts and infiltrates starting material) in an unpressurized environment, such as under atmospheric or ambient pressure, or in a vacuum under a low pressure environment (e.g., ranging from 10^{-3} to 10^{-11} torr or ranging from 10^{-3} to 10^{-6} torr). In some embodiments, infiltration may be carried out in a reduced oxygen environment, e.g., flushing a chamber holding the mold assembly with inert gas such as argon or nitrogen using a vacuum system or infiltrating under atmospheric pressure in an endothermic gas environment. Conducting an infiltration method of the present disclosure in a reduced oxygen environment may avoid non-wetting of the infiltrant during infiltration. The contents of the mold may then be cooled to solidify the metallic binder and form the tool.

[0020] The metallic binder infiltrant in its molten state and after it has been infiltrated and cooled may be referred to as an infiltration binder, both of which refer to a metal or an alloy infiltrant used in an infiltration process to bond together the contents of a mold. Thus, the terms "metallic binder infiltrant" and "infiltration binder" may be used interchangeably, depending on the stage of infiltration. Further, a metallic binder infiltrant may generally maintain the same composition through the infiltration process (where the metallic binder infiltrant has substantially the same composition in infiltration binder form), or the composition of the metallic binder infiltrant may alter during infiltration (where the metallic binder infiltrant has a different composition in its solidified infiltration binder form), for example, upon dissolution of one or more elements into the infiltration binder during infiltration. As used herein, the term "substantially" is used as a term of approximation, and not as a term of degree, and is intended to account for inherent, standard deviation in measured or calculated values, as would be understood by those of ordinary skill in the art.

[0021] An infiltrant (e.g., a metallic binder infiltrant or infiltration binder) may include one or more transition metals, main group metals and alloys thereof having a melting point lower than the melting point of the starting material it infiltrates. For example, copper, nickel, iron, and cobalt may be used as the major constituents in the infiltrant. Other elements, such as aluminum, manganese, chromium, zinc, tin, silicon, silver, boron, and lead, may also be present. In one particular embodiment, the infiltrant is selected from at least one of nickel, copper, and alloys thereof. The infiltrant may include, for example, a Cu-Mn-Ni alloy, a Cu-Mn-Ni-Zn, a Cu-Mn-Ni-Zn-Sn, a Cu-Mn-Ni-Sn-Zn-Fe, a Cu-Mn-Ni-Zn-Fe-Si-B-Pb-Sn alloy, a Ni-Cr-Si-B-Al-C alloy, a Ni-Al alloy, a Cu-P alloy, a Co alloy, a Fe alloy and/or other copper based alloys. The infiltrant may also be a heat treatable metal binder, *i.e.*, the properties of the metal binder improve after a subsequent heat treatment following infiltration. Heat treatable metal binders may include, for example, a Al-Cu alloy, a Al-Cu-Mg alloy, a Al-Mg-Si alloy, a Al-Zn-Mg alloy, and/or a Al-Zn-Mg-Cu alloy.

[0022] According to embodiments of the present disclosure, an infiltrant material may be selected to have a melting temperature ranging from limits of 800 °C (1,472 °F), 850 °C (1,562 °F), 900 °C (1,652 °F), 950 °C (1,742 °F), 1,000 °C (1,832 °F), 1,050 °C (1,922 °F) or 1,100 °C (2,012 °F), 1,150 °C (2,102 °F), 1,200 °C (2,192 °F), or 1,250°C (2,282°F), where any limit may be used in combination with any other limit as lower and upper limits. For example, the infiltrant material may have a melting temperature ranging from 800 °C to 1,250 °C or a melting temperature ranging from 800 °C to 950 °C.

[0023] Further, in some embodiments, an infiltrant may include a flux material provided with a metallic binder material. For example, a layer of powdered flux material may be provided over a metallic binder infiltrant. In another example, a metallic binder may be provided in the form of one or more slugs or ingots and a flux material may be coated around the metallic binder slug, or a flux material may be loaded on top of the metallic binder slug. A metallic binder slug may have various shapes, for example, spherical (or roughly spherical), cubic, or rectangular prism shaped, or irregularly shaped. The flux material may be selected based on the working temperature range of the flux and/or the melting temperature of the metallic binder, and may be provided, for example, in liquid, paste, slurry, or powder form. Non-limiting examples of flux material include boron-

based flux having a combination of one or more borates, fluorides, boron, BAg, BCuP, BCu, BNi, BAu and RBCuZn.

[0024] In embodiments having a metallic binder slug coated with a flux material, the flux material may be adhered to the surface of the metallic binder slug. For example, a flux material may be adhered to the surface of a metallic binder slug by heating the slug to a temperature sufficient to melt or partially melt the flux material upon contact with the slug surface. In such embodiments, the metallic binder slug is adherent in that the heated slug is capable of having the flux material adhere to its surface. In some embodiments, a flux material may be adhered to the surface of the metallic binder slug by using an adhesive coating, such as a fluid gel or paste, which adheres the flux material to the slug surface. An adhesive coating may be formed of a material that does not react with (or substantially react with) the metallic binder slug or flux at various temperatures (e.g., at a storage temperature and/or pre-heating temperatures) or a material that is capable of evaporating or decomposing and evaporating upon heating so that the adhesive material does not contaminate the infiltrant. For example, an adhesive coating may be formed of a viscous solvent, such as a polymeric solvent, polyether polyols, including polyether diols, polyether triols, and/or polyether tetraols), glycerol, ethylene glycol, dimethylsulfoxide, dimethylformamide, dimethylacetamide, polydimethyl siloxane, polypropylene glycol dimethylether, and a combination and/or derivative thereof. In some embodiments, the adhesive material may include a flux, such as a rosin, a modified rosin, a borate, a fluoride, and/or boron, or brown flux. The flux coating may be distributed about the surface of the binder slug in any suitable way, e.g., it may be substantially uniformly distributed about the surface of the metallic binder slug.

[0025] A flux material may be used to purify the metallic binder (e.g., by reacting with binder surface oxides to form slags) during melting and subsequent infiltration. The flux may be uniformly distributed throughout the molten infiltration binder during melting and subsequent infiltration to allow more points of contact with the binder, which allows for improved purification of the molten infiltration binder and reduced defects due to the presence of regions lacking in flux and/or regions having too much flux.

[0026] According to embodiments of the present disclosure, a metallic starting material may be infiltrated with a metallic infiltrant to form a downhole cutting tool. The metallic

starting material may include, for example, steel, alloyed steel, including iron alloyed with carbon and at least one of manganese; nickel; chromium; molybdenum; vanadium; silicon; boron; aluminum; cobalt; copper; cerium; niobium; titanium; tungsten; tin; zinc; lead; zirconium; stainless steel; cobalt; nickel; low expansion alloys, such as a Fe-Ni-Co alloy (e.g., an alloy with 29% Ni, 17% Co and remaining balance Fe), a Fe-Ni alloy (e.g., an alloy with 64% Fe and 36% Ni, an alloy with 42% Ni and remaining balance Fe), or a Fe-Ni-Cr alloy (e.g., an alloy with 42% Ni, 6% Cr, and remaining balance Fe); a refractory metal, such as tungsten, molybdenum, or vanadium; or a mixture of such metallic materials. For example, a mixture of such materials could be used having selected ratios to provide desired properties of strength and toughness for the downhole cutting tool. The metallic starting material may also include Co/Ni base alloys containing various alloying elements depending on the corrosion or wear resistance desired. Particles such as Stellite 6 powders (Stellite is a registered trademark of Kennametal Inc., Latrobe, PA), or other powders of Co alloyed with Cr, W, C, Ni, Fe, Si, Mn and/or Mo may be used. Inconel 728 powders (Inconel is a registered trademark of Huntington Alloys Corporation and is available from the Special Metals Corporation group of companies, Huntington, WV), or other powders composed of Ni alloyed with less than 35 % by mass Cr, less than 15 % by mass Fe, less than 15 % by mass Mo, less than 6 % by mass Nb, less than 20 % by mass Co, less than 1.5 % by mass Mn, less than 1 % by mass Cu, less than 2 % by mass Al, less than 3 % by mass Ti, less than 0.6 % by mass Si, less than 0.2 % by mass C, less than 0.02 % by mass S, less than 0.02 % by mass P, and/or less than 0.01 % by mass B may also be used as a starting material. According to some embodiments of the present disclosure, the metallic starting powder may be selected from one or more non-carbide forming metals or metal alloys. According to some embodiments of the present disclosure, the metallic starting material may be any suitable carburizable metal or alloy.

[0027] According to some embodiments of the present disclosure, a metallic starting material may be selected from a metal or metal alloy that has a melting temperature greater than 1,000 °C (1,832 °F), 1,050 °C (1,922 °F), 1,100° C (2,012 °F), 1,200°C (2,192 °F), 1,300° C (2,372 °F), 1,400°C (2,552 °F), or greater than 1,500°C (2,732 °F). For example, a metallic starting material may include a metal or metal alloy having a melting temperature ranging from limits of 1,050 °C (1,922 °F), 1,100 °C (2,012 °F),

1,200 °C (2,192 °F), 1,300 °C (2,372 °F), 1,400 °C (2,552 °F), 1,500 °C (2,732 °F), 1,600 °C (2,912 °F), 1,700 °C (3,092 °F), 1,800 °C (3,272 °F), 1,900 °C 3,452 °F), 2,000 °C (3,632 °F), 3,000 °C (5,432 °F), or 3,500 °C (6,332 °F), where any limit may be used as a lower limit in combination with any other limit as an upper limit. For example, the metallic starting material may have a melting temperature ranging from 1,050 °C to 3,000 °C or a melting temperature ranging from 1,100 °C to 1,300 °C.

[0028] In some embodiments, a metallic starting material powder may include a mixture of a first metallic material and a metal additive material, where the additive material may provide a desired property to the first metallic material and/or the resulting structure. For example, in some embodiments, a metallic starting material powder may include a steel metallic material mixed with an additive material, where the additive material is a powdered metal-based or non-metal material added to tailor the mechanical properties of the resultant composite and/or to reduce rust formation in the cutting tool. The metallic starting material may have a carbon content of less than 2 % by weight, less than 1 % by weight, less than 0.5 % by weight, less than 0.2 % by weight, or less than 0.1 % by weight in some embodiments. For example, a metallic starting material being infiltrated with an infiltration binder to form a downhole cutting tool may be a low carbon alloyed steel having less than 2 % by weight carbon.

[0029] Metallic starting material may be loaded into a region of a mold in powder form. The metallic starting powder may have a particle size measured in a range of mesh sizes, for example -100+320 mesh. The mesh sizes referred to herein are standard U.S. mesh sizes. For example, a standard 40 mesh screen has holes such that only particles having a dimension less than 420 μm can pass. Particles having a size larger than 420 μm are retained on a 40 mesh screen and particles smaller than 420 μm pass through the screen. Therefore, the range of particle sizes of the metallic powder may be defined by the largest and smallest grade of mesh used to screen the particles. Metallic particles in the range of -16+40 mesh (i.e., particles are smaller than the 16 mesh screen but larger than the 40 mesh screen) will contain particles larger than 420 μm and smaller than 1190 μm, whereas particles in the range of -40+80 mesh will contain particles larger than 180 μm and smaller than 420 μm. Thus, use of mesh screening may allow for an easy determination of particle size distribution. Mesh sizes for the metallic particles may

include -230+325, -200+270, -170+230, -140+200, -120+170, -100+140, -80+120, -70+100, -60+80, -50+70, -40+60, -30+40, -20+30, -10+25, etc.

[0030] Metallic starting material powder may have a mono-modal, bi-modal, or multi-modal particle size distribution, depending on the materials being used and the downhole cutting tool being formed. Further, metallic starting material powder may include particles having the same shape (e.g., spherical or irregular) or may include particles having different shapes (e.g., a combination of spherical particles and irregularly shaped particles). The shape of particles may be characterized by their "shape factor," where the shape factor ("SF") = sqrt($4\pi A$)/L, where A is the cross sectional area of the particle and L is the circumference length around the cross section. According to embodiments of the present disclosure, the shape factor of metallic starting material particles may be greater than 0.65, e.g., ranging from limits of 0.65, 0.75, 0.8, 0.85, 0.9, 0.95, or 1.0 where any limit may be used in combination with any other limit, e.g., 0.65 to 1.0 or 0.75 to 0.9.

[0031] In some embodiments, metallic starting material particles having substantially the same shape, e.g., substantially spherical particles with a shape factor ranging between 0.8 and 1.0, may be poured or otherwise placed into at least a portion of a mold (e.g., one or more selected regions, or the entire mold) of a downhole cutting tool body. The metallic starting material may have a mono-modal distribution or a bi-modal distribution. In some embodiments, upon infiltration, the portion of the downhole cutting tool body formed with particles (e.g., spherical shaped particles) having a mono- or bi-modal distribution may have a reduced mean free path and contiguity between starting material particles. As used herein, "mean free path" refers to average distance between particles of the starting material. The term "contiguity" refers to the measurement of inter-phase contact between starting material particles. For example, a contiguity of 0 % would mean that no two starting material particles are in direct contact, whereas a contiguity of about 50 % would mean that about half of the starting material particles are in contact with other starting material particles.

[0032] According to embodiments of the present disclosure, a downhole cutting tool formed of metal matrix composite material disclosed herein (metallic starting material infiltrated with a metallic infiltrant having a lower melting point than the metallic starting material) may have a mean free path between metallic starting material particles of less

than about 60 microns, e.g., between limits of 1, 5, 10, 15, 20, 25, 35, 45, 50, or 60 microns, where any limit may be used in combination with any other limit (e.g., a mean free path of 1-60 microns or a mean free path of 5-45 microns), and a contiguity of less than about 20 %, e.g., between limits of 2, 5, 10, 15, or 20 %, where any limit may be used in combination with any other limit (a contiguity of 2 to 20 % or a contiguity of 2-10 %).

[0033] FIG. 1 shows a cross sectional view of a mold assembly in an infiltration method according to embodiments of the present disclosure. The mold assembly includes a mold 100 having the general negative shape of a downhole cutting tool body and contents 110 disposed within the mold 100. A bottom funnel ring 102 and a top funnel ring 104 are fitted over the mold to funnel and hold the contents 110 within the mold. The contents 110 include a first metallic starting powder 112 and a second metallic starting powder 114 loaded around a steel blank 120, an infiltrant 116 and a flux material 118. The first and second metallic starting powders 112, 114 are made of a metal or metal alloy, e.g., low carbon alloyed steel having less than 2 % by weight carbon or other metallic starting powder types disclosed herein. In other embodiments, mold contents may include two or more different metallic starting materials (e.g., different material types, different particle sizes, different size distributions such as mono-modal and bi-modal, different shapes or combinations thereof) located in different regions of the mold to provide different material properties to the different regions of the mold. For example, a first metallic starting powder may be of a first type of metallic starting material (e.g., steel particles) having a selected particle size and size distribution and having a spherical shape, and a second metallic starting powder may be of the same or different type of metallic starting material having the same or different particle size and/or size distribution as the first metallic starting powder and having a spherical shape. A first metallic starting powder and a second metallic starting powder may have one or more property differences, for example, a difference in hardness, toughness, or erosion resistance, where the first metallic starting powder is loaded into a first region of the mold and the second metallic starting powder is loaded into the second region of the mold. In yet other embodiments, two or more different powdered metallic starting materials may be mixed together and loaded into the mold. The infiltrant 116 may be loaded (e.g., as precut chunks or binder

slugs) over the metallic starting powder 112, 114, and the flux material 118 may be poured over the infiltrant 116 (or may coat the infiltrant as described above).

[0034] The contents within the mold may then be heated to the flow or infiltration temperature of the infiltrant 116 so that the melted infiltrant material infiltrates the starting materials 112, 114 within the mold 100 and bonds particles of the starting material to each other and to any other components (e.g., a steel blank) to form a solid cutting tool body. In other words, each region of starting material within the mold (e.g., a first metallic starting powder and a second metallic starting powder) may be bonded together by the same infiltration material. In some embodiments, the infiltration material flows through the starting materials relatively homogenously so that the ratio of infiltration material to a first starting material and the ratio of infiltration material to a second starting material is substantially the same. Thus, in embodiments having two or more regions of different starting material, the starting material may be infiltrated with an infiltrant during the infiltration process, such that the different regions are integrally formed together. Likewise, embodiments having a single starting material may have an infiltrant substantially uniformly distributed throughout the starting material.

[0035] Further, in embodiments having two or more different starting materials, the infiltration temperature may be lower than the solidus temperature of each of the different starting materials and greater than or equal to the melting temperature of the infiltrant. In other embodiments having two or more different starting materials, the infiltration temperature may be lower than the solidus temperature of at least one but less than each of the starting materials, depending on the composition of the starting materials, and greater than or equal to the melting temperature of the infiltrant.

[0036] FIG. 2 shows another example of a mold assembly in an infiltration method according to embodiments of the present disclosure. The mold assembly includes a mold 100 having the general negative shape of a downhole cutting tool body and contents 110 disposed within the mold 100. A bottom funnel ring 102 and a top funnel ring 104 are fitted over the mold to funnel and hold the contents 110 within the mold. In some embodiments forming the tool body without a blank or reinforcement member, the mold 100 may have relatively taller side walls or funnel to form a relatively taller tool body, where the connection end may be machined into a threaded connection end, may be

attached to a threaded connection, or may be molded into the tool body. The contents 110 include a metallic starting powder 112, an infiltrant 116, and a flux material 118. The metallic starting powder 112 is made of a metal or metal alloy, e.g., a low carbon alloyed steel having less than 2 % by weight carbon. The infiltrant 116 may be loaded (e.g., in precut chunks) over the metallic starting powder 112, and the flux material 118 may be poured over the infiltrant 116 (or may coat the infiltrant as described above). The contents within the mold may then be heated to the flow or infiltration temperature of the infiltrant 116 so that the melted infiltrant material infiltrates the starting material 112 within the mold 100 and bonds particles of the starting material to each other to form a solid cutting tool body. Upon completion of the infiltration process, the infiltrant may be substantially uniformly distributed throughout the starting material.

[0037] According to embodiments of the present disclosure, a method of making a metallic infiltrated downhole cutting tool may include loading one or more metallic starting materials into a mold in desired locations (e.g., one starting material in the body, one starting material in the blades, etc.), adding an infiltrant (e.g., a flux-coated binder or a metallic binder) to the top of the mold, heating the resulting mold assembly to allow for infiltration of the infiltrant into the starting materials, cooling the contents of the mold to provide an in-mold cutting tool body, removing the cutting tool body from the mold to provide an out-of-mold cutting tool body, securing the cutting tool body to a connection, e.g., fitting and welding the cutting tool body to connector such as an API connector, and adding cutting elements (e.g., polycrystalline diamond (PCD) cutting elements (PDCs)) to the cutting tool body.

[0038] As used herein, a generally metallic cutting tool body refers to a downhole cutting tool body formed of one or more metallic regions, each metallic region having a substantially metallic material composition, such that at least 80 % by volume of the infiltrated portions of the metallic downhole cutting tool body has a metallic material composition with less than 3 % by weight carbon. "Metallic" regions forming generally metallic cutting tool bodies according to some embodiments of the present disclosure may include minor amounts of non-metallic materials, for example, impurities due to manufacturing conditions, interstitial alloying constituents, and/or carbon diffused from the mold during infiltration, as described below. Because non-metallic material may

enter during infiltration processes, an infiltrated region may have a greater weight % of non-metallic components than the starting material used to form such region. For example, "metallic starting material" may have at least 98 % by weight of the material composition formed of one or more metal components, while a "metallic region" formed of the metallic starting material may have at least 97 % by weight of the material composition formed of one or more metal components. In some embodiments, one or more metallic regions forming a generally metallic cutting tool body may be made by infiltrating a steel starting material (e.g., having a carbon interstitial alloying constituent of less than 1 % by weight) with a metal alloy infiltrant, where less than 1 % by weight carbon diffuses into the one or more metallic regions during infiltration, and where the one or more metallic regions have less than 0.5 % by weight of non-metal impurities.

[0039] In some embodiments, at least one region of a generally metallic cutting tool body may be formed of a non-metallic or non-metallic composite starting material. As used herein, "non-metallic" starting material may include cermet starting materials, carbide starting materials, ceramic starting materials, or other materials having greater than 10 % by weight of a non-metallic component. In other words, although non-metallic starting materials such as cermets may have metal components, they may be referred to as "non-metallic" starting materials or as forming "non-metallic" regions as they do not include a metal or metal alloy (i.e., "metallic starting material"). "Cermet" is defined herein as any metal based and/or metal bonded ceramic, and thus, may include metal carbides, metal borides, metal nitrides, or other composite material having both metal and ceramic components. Although some embodiments are described herein using cermet starting material as an example to form non-metallic regions, ceramic starting material may be used in combination with cermet starting material, or to cermet starting material, to form the non-metallic regions. Regions of a downhole cutting tool that are not formed entirely of metallic starting material or have greater than 2 % by weight carbon, such as regions formed of cermet starting materials, ceramic starting materials, and other non-metallic composite starting materials or regions having greater than 2 % by weight carbon, may be referred to herein as "non-metallic" regions.

[0040] Carbide starting material may include a powder of a single carbide material such as tungsten carbide, or it may be a mixture of more than one carbide material such as

different forms of tungsten carbide, e.g., macrocrystalline tungsten carbide, cast tungsten carbide, carburized tungsten carbide, agglomerated tungsten carbide, sintered or cemented tungsten carbide, and unsintered or pre-sintered tungsten monocarbide. In some embodiments, non-tungsten carbides of vanadium, chromium, titanium, tantalum, niobium, silicon, aluminum or other transition metal carbides may be used. In yet other embodiments, one or more of a carbide, oxide, and nitride of Group IVA, VA, or VIA metals may be used. Further, one or more additional components such as metal additives may be added to a carbide starting material. For example, a metal binder component, such as cobalt, nickel, iron, chromium, copper, molybdenum, their alloys, and combinations thereof may be mixed in with a carbide material.

[0041] In some embodiments having two or more different starting materials forming different regions of the cutting tool body, at least one starting material may be a metallic starting material made of a metal or metal alloy, e.g., a metallic composition having less than 2 % by weight carbon, and at least one starting material may include a cermet or other non-metallic material, such as tungsten carbide or other transition metal carbide. For example, in some embodiments, the cermet or other non-metallic material may be less than 10 % by volume of the total amount of starting material, less than 5 % by volume of the total amount of starting material, or less than 2 % by volume of the total amount of starting material. Additionally, in some embodiments having at least one metallic starting material and a cermet or other non-metallic starting material, at least one starting material may be a transition starting material including a mixture of metallic starting material and cermet or other non-metallic starting material, where the cermet or other non-metallic starting material and transition starting materials are less than 15 % by volume of the total amount of the starting materials. In some embodiments, a transition starting material region may have a volume between limits of 10 %, 25 %, 50 %, 75 % and 100 %, 150 %, or 200 % of the volume of the cermet starting material region, where any limit can be used in combination with any other limit (e.g., 10 % to 200 % or 10 % to 50 %).

[0042] In some embodiments having two or more different starting materials, at least one starting material may be a metallic starting material made of a metal or metal alloy having less than 2 % by weight carbon, and at least one starting material may include at least one

cermet starting material, such as a transition metal carbide, and/or at least one transition starting material such as a mixture of a cermet starting material and the metallic starting material, where the cermet starting materials (e.g., transition metal carbide) are 15 % or less, 10 % or less, 5 % or less, 2 % or less by volume of the starting material, and the metallic starting material is 85 % or more, 90 % or more, 95 % or more, or 98 % or more by volume of the starting material. In other embodiments, at least one starting material may be a metallic starting material made of a metal, metal alloy, or other metallic composition having less than 2 % by weight carbon, and at least one starting material may include at least one cermet starting material, such as a transition metal carbide, and/or at least one transition starting material such as a mixture of a cermet starting material and the metallic starting material, where the non-metallic starting materials are 20 % to 15 % by volume of the starting material, and the metallic starting material is 80 % to 100 % by volume of the starting material. Other non-metallic starting materials (included at 20 % or less by volume of the total amount of starting material) filling a mold may include, for example, carbide starting materials, such as described above, nitrides, or borides.

[0043] According to some embodiments of the present disclosure, regions of a mold may be filled with at least two different starting materials. For example, multiple metallic starting materials or at least one metallic starting material and at least one cermet starting material (e.g., a carbide starting material) and/or at least one transition starting material (e.g., one or more mixtures of the carbide and metallic starting materials) may be used, where the starting materials are selected to provide desired or particular material properties to the regions of the mold they are placed in, and where one or more metallic starting materials form 80 % or more by volume (e.g., at least 80%) of the starting material. For example, in some embodiments having regions of a mold of a downhole cutting tool filled with at least two different starting materials, including one or more metallic starting materials that are 80 % or more by volume of the starting material, a starting material having the greatest hardness or greatest wear resistance (compared with the hardness or wear resistance of the other starting materials) is positioned in one or more regions of the mold corresponding with portions of the cutting tool expected to experience the greatest amount of wear during drilling operations.

[0044] In an embodiment of preparing a mold assembly, starting material having the greatest hardness or greatest wear resistance (compared with the hardness or wear resistance of additional starting materials added to the mold) is positioned in one or more regions of a mold corresponding with portions of the cutting tool expected to experience the greatest amount of wear, and 80 % or more by volume (e.g., at least 80 %) of the total amount of starting material added in the mold includes one or more metallic starting materials (e.g., low carbon alloyed steel having less than 2 % by weight carbon). In some embodiments, a graphite mold having the general negative shape of a drill bit with a bit body and a plurality of blades extending therefrom may be used. A plurality of displacements may be placed along the inner walls of the graphite mold, including a plurality of cutter displacements along a cutting edge region of each blade portion of the mold and a plurality of wear button displacements disposed in a gage region of each blade portion of the mold. However, different molds of cutting tool bodies may have different displacements for different cutting element types or other exterior features. The mold may also define a plurality of nozzles (or nozzle displacements may be used), which form nozzle openings upon completion of the manufacturing process. The inner surfaces of the graphite mold including any displacements may be coated with boron nitride or other carburization inhibitor to reduce or prevent carbon in the graphite mold from diffusing into the mold contents during infiltration. In other embodiments, such as described below, the inner surfaces of a graphite mold may remain uncoated to allow carburization.

[0045] A carbide starting material may be loaded into portions of a prepared mold corresponding with the blade regions of the mold, such that at least a portion of the inner walls forming a top surface (corresponding with the radially outermost surface of a blade), a leading surface (corresponding with the surface of a blade facing in the direction of tool rotation), and/or a trailing surface (corresponding with the surface of a blade opposite the leading surface) of the blades have a layer of carbide starting material disposed thereon. The layer of carbide starting material may be in powdered form, slurry form, or moldable form. In some embodiments, a powdered layer of carbide starting material may be poured into the bottom of a mold in the regions forming the blades, such that the powdered layer of carbide starting material covers a portion of a blade top surface, leading surface and trailing surface and multiple cutter displacements. For example, the layer of powdered carbide starting material may have a thickness of about 1

inch (as measured at the thickest portion of the layer) to cover at least one cutter displacement. In other embodiments, moldable carbide starting material may be layered in regions of the mold corresponding with one or more blades, for example, along portions covering one or more cutter displacements, along portions covering the entire or part of the leading surface of the blade, or along portions of the blade corresponding with regions experiencing the greatest amount of wear during drilling operations.

[0046] A layer of cermet or other non-metallic starting material (e.g., tungsten carbide powder or a moldable carbide material) may be disposed in various regions of a mold of a downhole cutting tool having a selected thickness. The thickness of the layer may be designed to be thick enough to cover a cutter displacement (such that the layer forms a cutter pocket) but also be in a small enough quantity that the amount of metallic starting material added to the mold may be 80 % or more by volume (e.g., at least 80 %) of the starting material. For example, according to some embodiments of the present disclosure, a carbide starting material may be in a region of a cutting tool mold such that upon infiltration, the carbide starting material forms a carbide region defining at least a portion of a cutting element pocket, where the carbide region may have a thickness extending from the outer surface of the cutting tool to greater than the diameter of at least one of the cutting tool cutting elements and up to two times the diameter of the at least one cutting element.

[0047] FIG. 3 shows a cross sectional view of a portion of a downhole cutting tool 300 formed using metallic infiltration methods according to embodiments of the present disclosure. The cutting tool 300 was formed by applying a layer of a cermet starting material along an inner wall of a mold corresponding with an outer surface of the cutting tool having cutting elements disposed thereon and filling the remaining regions of the mold with a metallic starting material. In other embodiments, other non-metallic starting material may be applied along an inner wall of a mold. An infiltrant was infiltrated through the metallic starting material and the cermet starting material to integrally form together a cermet region 310 and a metallic region 320 of the cutting tool. The cermet region 310 may have a thickness 315 measured between the outermost surface 302 of the cutting tool 300 to an interface 304 between the cermet region 310 and metallic region 320 (e.g., where the thickness is measured perpendicular to the blade top). The cermet

region thickness 315 may fully cover any adjacent cutting element 330 or other cutting tool component, e.g., nozzle bores and gage elements (such that the cutting element 330 or cutting tool component does not interface with the metallic region), and may, for example, have a thickness greater than or equal to the diameter of an adjacent cutting element 330, and may be up to two times the diameter of the adjacent cutting element 330.

[0048] According to some embodiments of the present disclosure, a non-metallic starting material (e.g., cermet or carbide starting material) may be in regions of a mold along its inner walls, where the non-metallic starting material has a thickness measured perpendicularly from the inner wall of at least 0.125 in (3.175 mm), e.g., ranging from limits of 0.125 in (3.175 mm), 0.25 in (6.35 mm), 0.5 in (12.7 mm), 1 in (25.4 mm), 1.5 in (38.1 mm), 2 in (50.8 mm), 2.5 in (63.5 mm), or 3 in (76.2 mm), where any limit may be used in combination with any other limit (e.g., 0.125 in to 3 in or 0.25 in to 2 in). The thickness may be selected based on a variety of factors including the size and shape of the tool, its application, and the location of the non-metallic starting material layer.

[0049] Additionally, in some embodiments, one or more layers of transition starting material may be added between a layer of a cermet starting material and a metallic starting material, where each layer of transition starting material may have a thickness measured perpendicularly from the adjacent layer of starting material of at least 0.125 in (3.175 mm), e.g., ranging from limits of 0.125 in (3.175 mm), 0.25 in (6.35 mm), 0.5 in (12.7 mm), 0.8 in (20.3 mm), 1 in (25.4 mm), or 1.5 in (38.1 mm), where any limit may be used in combination with any other limit (e.g., 0.125 in to 1.5 in or 0.125 in to 1 in). A layer of transition starting material may have a thickness greater than, equal to, or less than the thickness of an adjacent layer of non-metallic starting material. The thickness of the transition starting material layer may be selected based on a variety of factors, such as the location within the cutting tool body. In some embodiments, more than one layer of transition starting material may be added between a layer of a non-metallic starting material and a metallic starting material, where the total thickness of the layers of transition starting material is greater than, equal to, or less than the thickness of the cermet starting material layer. In yet other embodiments, a layer of transition starting material may be disposed along (and adjacent to) the inner wall of a mold in selected

regions, e.g., along portions covering one or more cutter displacements, along portions covering the entire or part of the leading surface of the blade, or along portions of the blade corresponding with regions experiencing the greatest amount of wear during drilling operations.

[0050] According to embodiments of the present disclosure, a core (e.g., a sand core) may be positioned in connection with the nozzle displacements positioned in a mold for forming a cutting tool body, where upon completing the manufacturing process, the core and nozzle displacements form fluid passages through the cutting tool body. A core may be added before any starting material is poured into the mold, or the core may be added after one or more layers of starting material is poured into the mold, where the one or more layers do not completely cover the nozzle displacements. In embodiments having one or more layers of starting material poured into a mold prior to adding a core, the one or more layers of starting material may be positioned in the mold such that the tops of the nozzle displacements are exposed to contact with the core.

[0051] One or more powdered metallic starting materials may be poured into the mold and around the core, where the metallic starting material forms the majority of the contents of the mold. For example, in some embodiments, metallic starting material may be poured over one or more carbide or other non-metallic starting material regions and around a core, where the metallic starting material forms the majority of the contents of the mold, or all starting material poured in the mold and around the core may be metallic starting material. Once the starting material is loaded into the mold, a funnel ring (which may be formed of more than one piece or integrally formed as a single piece) may be fitted around the opening of the mold. In some embodiments, a funnel ring may be fitted around the opening of a mold prior to loading the starting material. An infiltrant may then be loaded into the funnel ring over the metallic starting material, forming a mold assembly. In some embodiments, a flux material may also be added over the infiltrant (or as described above, with the infiltrant) to form the mold assembly.

[0052] Once a mold assembly is completed, i.e., all of the contents are loaded into the mold, the contents of the mold (including any carbide starting material, metallic starting material, and infiltrant) may be heated to an infiltration temperature that is greater than or equal to the melting temperature of the infiltrant and less than the solidus temperature of

the starting materials, such that the infiltrant melts and infiltrates the starting materials. The contents of the mold may then be cooled to form a downhole cutting tool body such as a drill bit.

[0053] The process for removing the core to expose one or more fluid passages may be performed, in part, with the infiltration process, or may be performed after completion of the infiltration process. For example, in embodiments having a core with its shape held by a resin or organic binder, the high temperature during infiltration may burn out at least a portion of the resin or organic binder, thereby degrading the structure of the core. As another example, in some embodiments, a core mold may be removed after infiltration by mechanical means or by a combination of chemical and mechanical means. As yet another example, some embodiments may have the core removed after infiltration by chemically breaking down the bonds formed by a resin or organic binder used to hold the shape of the core to degrade the structure of the core. When sufficient degradation of the core structure occurs, the core may be removed by shaking or scooping out the remaining core material.

[0054] Further, according to embodiments of the present disclosure, a mold assembly may not include use of a blank (or shank or shaft). Instead, powdered starting materials may fill the entire mold, with the exception of mold components, which may include, for example, cutting element displacements, nozzle displacements, and a core. In embodiments formed according to methods of the present disclosure that do not include a blank, a threaded connection may be welded directly to an upper portion of the cutting tool, or a threaded connection may be machined into the upper portion of the cutting tool. In some embodiments formed according to methods of the present disclosure that include a blank (the blank is disposed in the mold and surrounded by starting material for infiltration), a threaded connection, such as an American Petroleum Institute (API) connection, may be formed on or welded to the blank. For example, in embodiments having a blank, after the infiltration process, a protruding section of the blank may be welded to a threaded connection. The threaded connection may have a tapered portion that may be threaded onto a drilling string.

[0055] FIGS. 4 and 5 show an example of a drill bit 400 having a bit body 402 with a cutting end 404 formed according to embodiments of the present disclosure. An upper

portion 406 is formed opposite the cutting end 404 during formation of the drill bit 400, for example, by infiltrating a metallic starting material according to embodiments of the present disclosure. A pin connection 410 may be welded to the upper portion 406, forming a weld joint 412, where the pin connection 410 has a threaded end for connection to a drill string or other downhole drilling component. The weld joint 412 may then be machined to form a smooth connection 414 between the upper portion 406 and the pin connection 410.

[0056] In other embodiments, a connection end may be mechanically secured to a bit head or other downhole cutting tool. For example, FIG. 6 shows an exploded view of a multi-component downhole cutting tool 600, including a bit head 610, an upper section (or connection component) 620, and a locking ring 630, where the bit head 610 is formed according to embodiments of the present disclosure. Although a bit head 610 is shown in the example of FIG. 6, other downhole cutting tools may be used, for example, including other types of bits, such as a roller-cone bit, an underreamer, a stabilizer (e.g., a stabilizer sleeve), a concentric hole opener, a housing on a motor, or the like. The bit head 610 has a bit body 612 and a plurality of blades 614 extending therefrom (which support a plurality of cutting elements 615 secured within pockets formed in the blades 614). At least 80 % by volume of the bit head 610 is made of an infiltrated metallic material having less than 2 % by weight carbon. A bore is formed at least partially (or completely) through the bit body 612. The inner surface of the bore has a plurality of threads that are configured to engage corresponding threads (service threads) formed on the outer surface of the shaft 624 of the upper section 620. The threaded shaft 624 may provide an axial preload or tension in the connection with the bit head 610. However, in other embodiments, configurations other than threads may be used on the shaft 624 and/or inner surface adjacent the bore of the bit head 610 to, for instance, provide a similar preload. For example, a quick lock configuration may be used.

[0057] The upper section 620 is shown as a connection pin that may be configured to couple to a drill string. It may be appreciated, however, that although the upper section 620 is shown as a connection pin, other components are also contemplated, e.g., a drill pipe, a drill string, a coiled tubing, a wireline, a drill collar, a stabilizer sleeve, an internal portion in a larger tool, similar downhole tool components, or combinations thereof. The

upper section 620 may include a head 622 having a shaft 624 extending from one end and a connection end 628 extending opposite the shaft 624. The shaft 624 and connection end 628 may include threads about a circumference. As shown, the head 622 has a greater cross-sectional length (e.g., diameter) than the shaft 624. A bore 626 may extend through the head 622 and/or the shaft 624. The diameter of the bore 626 may vary along the length of the upper section 620. The inner surface of the head 622 that defines the bore 626 may include a plurality of threads formed thereon for connecting to another component, such as a drill string or other downhole tool. The head 622 may have one or more grooves 623 formed in the outer surface. At least one groove 623 may be formed around a portion of the circumference of the head 622. In another embodiment, a single groove may be formed around the entire circumference of the head 622. The (radial) depth of the groove 623 may vary along the circumference of the head 622. In some embodiments, the groove 623 may facilitate mating of the downhole tool 610 to a drill string, other downhole tool, or other tubular.

[0058] The locking ring 630 may be configured to mechanically rotationally lock to the bit head 610 and to connect to the upper section 620 with a weld, or braze, or other suitable adhesive or mechanical lock. In some embodiments, the weld may not be necessary. The locking ring 630 may have a body 632 sized to have similar dimensions to dimensions of the bit head 610 and/or upper section 620. For example, an outer diameter of the body 632 may be substantially similar to an outer diameter of the upper section 620. The locking ring 630 may be disposed between the bit head 610 and the upper section 620. In at least one embodiment, the locking ring 630 may be or serve as a stabilizer. The locking ring 630 may have an annular body 632. The body 632 may have an axial bore 634 formed therethrough, where the bore 634 may be arranged and designed to have the shaft 624 of the upper section 620 extend therethrough. The locking ring 630 may be made of the same material as the bit head 610 and/or the upper section 620, or the locking ring 630 may include a different material. In at least one embodiment, the locking ring 630 may include steel or another weldable material. For example, the locking ring 630 may be made from a nickel-chromium-molybdenum alloy steel such as AISI 43XX steel (e.g., 4340 steel) or a low carbon alloyed steel.

[0059] A first axial surface of the locking ring 630 may be substantially planar, flat, or smooth, and may be positioned adjacent to and abut an axial surface of the upper section

620 (e.g., the steel connection pin) when the downhole tool 600 is assembled. A second, opposing axial surface of the locking ring 630 may have one or more indentations or axial recesses (e.g., castellations) 636 formed into the annular body 632. At least one axial recess 636 may be arranged and designed to receive a corresponding axial protrusion (e.g., castellation) 616 of the bit head 610 therein. As shown, each axial recess 636 is arranged and designed to receive its corresponding axial protrusion 616. The axial recesses 636 may be circumferentially-offset from one another around the second axial surface of the locking ring 630. Likewise, the second axial surface of the locking ring 636 may have the one or more axial protrusions extending therefrom, and the outer axial surface of the bit head 610 may have one or more corresponding indentations or recesses formed therein. In other words, the configuration of the axial protrusions and the recesses may be reversed and/or the second axial surface of the locking ring and the outer axial surface of the bit head 610 may each have both axial protrusions and axial recesses. In operation, the second axial surface of the locking ring 630 may be placed in contact with the outer axial surface of the bit head 610. More particularly, the axial protrusions (whether on the outer axial surface of the bit head 610, on the second axial surface of the locking ring 630, or both) are aligned with and inserted into the corresponding axial recesses 636 (whether in the second axial surface of the locking ring 630, on the outer axial surface of the bit head 610, or both). The contact between the angled surfaces of the axial protrusions 616 and the angled surfaces of the axial recesses 636 may prevent or limit circumferential movement between the locking ring 630 and the bit head 610. With the first axial surface of the locking ring 630 (i.e., the flat surface) abutting the upper section 620, the locking ring 630 and the upper section 620 may be welded, brazed, or otherwise affixed together. In at least one embodiment, the locking ring 630 and the upper section 620 may be welded together via electronic welding (e.g., metal arc welding) using any suitable weld material. It may be appreciated that the order of assembly described above is merely illustrative, and the upper section, the bit head 610, and the locking ring 630 may be assembled in a different order.

[0060] A downhole cutting tool formed according to embodiments of the present disclosure may be a drill bit having a bit body with blades extending therefrom, which support PDC cutters (or other cutting elements) which, in turn, perform the downhole cutting operation. PDC cutters may be bonded to the body in pockets formed in the

blades. For example, FIGS. 7 and 8 show a picture of a drill bit 700 formed according to embodiments of the present disclosure. The drill bit 700 includes a bit body 702 and a plurality of blades 704 extending radially outward from a bit centerline. A plurality of pockets 706 are formed along a top surface of each blade 704. A cutting element 708 may be disposed in each of the pockets 406 and brazed within the pockets 706.

[0061] According to embodiments of the present disclosure, a method of forming a downhole cutting tool body may include pouring contents within a mold, the contents including an infiltrant and at least one metallic starting material having a composition with at least 98 weight % of at least one metal or metal alloy, and heating the contents of the mold to an infiltration temperature lower than the solidus temperature of the at least one metallic starting material and greater than or equal to the melting temperature of the infiltrant, where the at least one metallic starting material and the infiltrant form at least 80 % by volume of the infiltrated cutting tool body. In some embodiments, the contents of the mold may also include a carbide starting material in a layer along at least a portion of an inner wall of the mold, the carbide starting material forming less than 10 % by volume of the starting materials. For example, the carbide starting material may be along a portion of a mold inner wall corresponding with at least one cutting element pocket. In some embodiments, the contents of the mold may also include at least one transition starting material adjacent to the layer of the carbide starting material, the at least one transition starting material and carbide starting material forming less than 15 % by volume of the starting materials.

[0062] In some embodiments, a mold of a downhole cutting tool may have the general negative shape of at least one blade extending from a tool body, where a portion of the blade region may be filled with a cermet or other non-metallic starting material, e.g., one or more powdered transition metal carbides such as tungsten carbide and optionally, mixed with one or more metal powders selected from Group VIII of the Periodic Table. For example, a powdered mixture of cermet starting material may be poured into selected regions of the mold having the negative shape of a blade, where the cermet starting material forms a layer lining at least a portion of the inner wall of the mold corresponding with the at least one blade. At least one metallic starting material may be loaded into the mold over the cermet starting material, or at least one transition layer including a mixture

of the cermet material and a metallic starting material may be loaded between the cermet starting material layer and the metallic starting material. An infiltrant may then be placed over the starting material in the mold, and the contents within the mold may then be heated in a furnace to the flow or infiltration temperature of the infiltrant, at which point the melted infiltrant infiltrates the starting material, including the metallic starting material and the cermet starting material. Once cooled, the infiltrant material may form an infiltration binder phase, binding together the cermet material and metallic material. The infiltration process that occurs during heating bonds the particles of cermet material and the metallic material to each other and to the other contents in the mold to form a solid bit body that has a relatively homogeneous dispersion of infiltrant throughout.

[0063] One or more cermet, ceramic, or other non-metallic composite starting materials may be provided as a powder mixture, a paste or slurry, or as a moldable material. As used herein, a moldable material refers to a material that is combined as a premixed paste with a binder (e.g., an organic binder) so that the material has an increased viscosity. By using a paste-like mixture of carbides, optional metal powders, and binder, the mixture may possess structural cohesiveness that can be used to form selected regions of a cutting tool having a desired material make-up. Additionally, the material may be formable or moldable, similar to clay, which may allow for the material to be shaped to have the desired thickness, shape, contour, etc., when placed or positioned in a mold. Further, as a result of the structural cohesiveness, when placed in a mold, the material may hold in place (e.g., without encroaching the opposing portion of the mold cavity). To be moldable, such materials may have a viscosity of at least about 250,000 cP. However, in other embodiments, the materials may have a viscosity of at least 1,000,000 cP, at least 5,000,000 cP in another embodiment, or at least 10,000,000 cP in yet another embodiment (e.g., a viscosity of 250,000 cP to 10,000,000 cP). Further, the material may be designed to possess sufficient viscidity and adhesive strength so that it can adhere to a mold wall (e.g., a surface wall) during the manufacturing process, without moving. For example, it may be spread on or stuck to a surface of a graphite mold, and the mold may be vibrated or turned upside down without the material falling. Thus, in some embodiments, for a given material, the adhesive strength should be greater than the weight of the material per given contact area (with the mold) of the material. In some

embodiments, once such moldable materials are adhered to the particular desired vertical or upside down surfaces, the remaining portions of the mold may be filled with powdered starting materials. For example, in some embodiments, a moldable cermet starting material may be adhered along the mold inner walls defining at least one blade, and in some embodiments, a moldable cermet starting material may be adhered along a portion of the mold inner walls defining at least one blade, such as the mold inner walls defining a top surface of the blade, a portion of a leading surface of the blade, and/or a portion of a trailing surface of the blade, and the remaining portions of the mold may be filled with powdered starting materials, e.g., metallic starting material and optionally one or more layers of transition starting material layered between the metallic starting material and the moldable cermet starting material. The entire mold contents may then be infiltrated using an infiltration binder (by heating the mold contents to a temperature over the melting point of the infiltration binder and below the solidus temperature of any metallic starting material).

[0064] Use of moldable materials may also allow for precision/controllability in the thickness of the layers/regions. That is, by using a moldable material, the material may be shaped or cut into the desired shape or thickness using a sharp blade or rolling pin. Thus, such techniques may allow for formation of a layer having a relatively uniform thickness, *i.e.*, within ± 20 % variance. However, in other embodiments, the thickness may have a variance within ± 15 %, ± 10 %, or ± 5 %. In yet other embodiments, a tapered layer may be desired, with precision of the taper (rate of taper) and thickness of various regions of the tapered layer being similarly achievable.

[0065] According to embodiments of the present disclosure, one or more layers of transition starting material may be between an outer layer of starting material (e.g., a carbide, ceramic, cermet or other non-metallic composite starting material) and metallic starting material. The layers of transition starting material may be formed of varying mixtures of the outer layer material and the metallic material, such that a gradient of the outer layer material is formed across an opposing gradient of metallic starting material.

[0066] In some embodiments, one or more layers of transition starting material may include particles of metallic starting material that are coated with a non-metallic (e.g., cermet or ceramic) starting material. For example, one or more transition layers may

include particles of steel, low expansion alloy, or other metallic starting material listed above, where the metallic particles each have a coating of non-metallic material deposited thereon, e.g., a cermet such as a metal carbide coating or a coating of one or more non-metallic starting materials listed above. Coating methods that may be used to coat particles of metallic starting material may include, but are not limited to, chemical vapor deposition (CVD), physical vapor deposition (PVD) or atomic layer deposition (ALD). In embodiments having more than one transition layer, the transition layer adjacent a non-metallic starting material (or adjacent to the outermost layer in embodiments having a transition material mixture as the outermost layer) may have a composition including a larger relative ratio of non-metallic material to metallic material than the transition layer adjacent the metallic starting material. For example, the transition layer adjacent an outermost layer of cermet starting material may have metallic particles coated with relatively thicker cermet material coatings or may have a relatively larger ratio of cermet material particles mixed with metallic particles than the transition layer adjacent the metallic starting material.

[0067] In some embodiments, layers of transition starting material may be formed with starting materials or combinations of starting materials having a coefficient of thermal expansion between that of an outermost layer of starting material and a metallic starting material forming an inner region of a cutting tool, where transition starting materials may or may not include the same starting materials forming the outermost layer and metallic inner region. For example, a transition starting material may be layered between a carbide starting material outermost layer and a metallic starting material core to provide a gradient of coefficient of thermal expansion between the carbide and metallic starting materials. In some embodiments, a gradient of coefficient of thermal expansion may be formed through a transition starting material outermost layer, a metallic starting material core or inner layer, and one or more additional transition starting material layers disposed between the outermost layer and the core or inner layer of a cutting tool body. In some embodiments, forming one or more transition layers integrally (using a single infiltrant metal or alloy) between an outermost layer of a tool body at least partially formed of non-metallic starting material (e.g., a cermet starting material outermost layer or a transition starting material outermost layer having a mixture of non-metallic and metallic starting material) and an inner layer or core formed of metallic starting material may improve the

strength of the connection between the outermost layer and core, thereby reducing the incidence of cracking or spalling of the outermost layer when compared with conventionally formed steel cutting tools having hardfacing deposited on one or more outer surfaces.

[0068] In some embodiments, infiltration methods disclosed herein may be used to form a generally metallic downhole cutting tool body (where one or more metallic regions having less than 3 % by weight carbon form at least 80 % by volume of the tool body) in a single infiltration process, without additional processing, e.g., machining, such as cutting element pocket machining, or hardfacing. For example, instead of hardfacing an outer surface of a cutting tool body, a downhole cutting tool may be formed according to embodiments disclosed herein to have a carbide material region formed integrally with the tool body along at least a portion of its outer surface, the carbide material region forming at least a portion of a cutting element pocket. Doing so may prevent or inhibit thermal oxidation of the metallic inner region of the cutting element pocket. However, although in some embodiments additional processing steps are not needed, other embodiments may have include processing steps for forming the tool body, such as heat treating the tool body or machining (e.g., machining threads into a connection end, machining the cutting element pockets to a given surface roughness, etc.).

[0069] According to embodiments of the present disclosure, a downhole cutting tool may have a body and a plurality of cutting elements disposed thereon, where the body has at least one metallic region with a metallic composition having at least 97 weight % a metal or metal alloy and at least a first metallic phase disposed in an infiltration binder, the infiltration binder having a melting temperature below the solidus temperature of the first metallic phase. The at least one metallic region may form at least 80 % by volume of the tool body.

[0070] In embodiments having less than 100 % by volume of the tool body formed of one or more metallic regions, the remaining non-metallic regions may include a cermet material region, e.g., a carbide region, forming at least a portion of an outer surface of the body, such as at least a portion of at least one cutting element pocket or at least a portion of a gage region (i.e., the region defining the outermost diameter of the tool body). The

carbide region may have a carbide phase disposed in the infiltration binder. In some embodiments, the non-metallic regions may include a transition region formed of one or more mixtures of a non-metallic material, such as a cermet and a metallic material disposed in the infiltration binder. In some embodiments, a transition region may be formed integrally with and disposed between a non-metallic region and a metallic region, where the transition region is formed from the infiltrant forming the cutting tool body and a mixture of material forming the metallic region and material forming the non-metallic region. In some embodiments, a transition region may be formed integrally with and disposed between a non-metallic (e.g., cermet) region and a metallic region, where the transition region has a coefficient of thermal expansion between the coefficients of thermal expansion of the non-metallic region and the metallic region.

[0071] According to some embodiments of the present disclosure, starting material may be built into a structure using additive manufacturing, such as 3D printing, robot casting, or simultaneous casting, prior to infiltrating the starting material structure to form one or more starting material regions. For example, an additive manufacturing assembly including a deposition device may be used to form a starting material structure by depositing sequential volumes or layers of starting material in designated regions. A binder or adhesive may be used to bind the multiple sequential layers together to form the starting material structure. For example, the binder may be mixed within the starting material prior to being deposited by the deposition device, the binder may be applied through a separate nozzle of the deposition device and simultaneously applied with the starting material, or a layer of the binder may be deposited between layers of the starting material. Suitable binders may include organic binders, such as waxes, resins or other organic compounds, synthetic waxes, sodium silicate, acrylic copolymers, arabic gum, portland cement and the like.

[0072] Upon forming a starting material structure using additive manufacturing, the starting material structure may be infiltrated, as described herein. For example, a starting material structure having at least one region formed with a metallic starting material may be infiltrated with an infiltrant by heating the infiltrant to an infiltration temperature lower than the solidus temperature of the metallic starting material and greater than or equal to the melting temperature of the infiltrant, such that the infiltrant infiltrates through the

starting material structure. Optionally, the starting material structure may be infiltrated in the presence of a carbon source, such as graphite. For example, the starting material structure may be surrounded (at least partially) by a graphite powder, or in some embodiments, the starting material structure corresponding to the blades (or another region of the structure) may be surrounded by a graphite powder. A starting material structure formed using additive manufacturing may form one or more regions of a downhole cutting tool body.

[0073] An additive manufacturing assembly may be any suitable device capable of fabricating a starting material structure, or for forming the mold in which starting material is infiltrated, using a CAD or other model as a template or guide. Suitable commercially available additive manufacturing assemblies capable of assembling starting material structures or molds include S-MAX, S-PRINT, M-PRINT, and/or M-FLEX, which are available from The ExOne Company, located in North Huntingdon, Pennsylvania.

[0074] Downhole cutting tools formed according to embodiments of the present disclosure may have improved material properties from integrally forming different regions together and from the infiltration of a metallic region, for example, reduced phase transition induced strain during subsequent heat treatment and thermal cycles (e.g., post-infiltration brazing processes), improved combination of toughness and strength, and improved corrosion/erosion resistance. For example, a fixed cutter drill bit downhole cutting tool may be formed according to methods disclosed herein, where a cermet region is formed integrally with a metallic region during a single infiltration process along at least a portion of the outer surfaces forming blades extending from the bit body, and where the metallic region forms at least 80 % by volume of the bit. By forming the bit with a single infiltration process according to embodiments of the present disclosure, the bit may have relatively taller blades having improved strength and toughness of the metallic bit body when compared with conventionally formed matrix fixed cutter bits, as well as, improved erosion and corrosion resistance from the cermet region integrally formed with the metallic region when compared with conventionally hardfaced steel downhole cutting tools.

[0075] According to embodiments of the present disclosure, a downhole cutting tool may have a body and a plurality of cutting elements in cutting element pockets. At least 80 % by volume of the body may be formed of one or more metallic regions having a metallic composition with at least 97 weight % of one or more metals or metal alloys. One or more of the metallic regions may have a yield strength ranging from 40 to 80 ksi, an ultimate tensile strength ranging from 60 to 120 ksi, an elongation ranging from 2 to 10 %, and a Charpy impact ranging from 3 to 20 ft-lb. In some embodiments, the body may also have a cermet region (e.g., a carbide region) integrally formed with the metallic region(s) and extending inward a thickness from an outer surface of the body, the cermet region forming less than 10 % by volume of the body. For example, the cermet region may form at least a portion of at least one cutting element pocket, where the thickness of the cermet region is greater than the diameter of at least one of the cutting elements and up to two times the diameter of the at least one cutting element, and/or the cermet region may form at least a portion of a gage region of the body. In some embodiments, the cutting tool may also have a threaded upper section having a threaded connection end and a threaded shaft extending opposite from the threaded connection end and a locking ring positioned between the body and the threaded upper section, where the threaded shaft may extend through an axial bore of the locking ring and threadably engage a threaded bore formed in the body.

[0076] Depending on the metallic starting material used to form one or more metallic regions of downhole cutting tools according to embodiments of the present disclosure, an infiltrated metallic downhole cutting tool body may have one or more metallic regions having a yield strength ranging from 40 to 80 ksi, an ultimate tensile strength ranging from 60 to 120 ksi, an elongation ranging from 2 to 10 %, and a Charpy impact ranging from 1 to 20 ft-lb. In some embodiments, an infiltrated metallic downhole cutting tool body may have one or more metallic regions having a yield strength ranging from about 70 to 160 ksi, an ultimate tensile strength ranging from about 90 to 170 ksi, an elongation ranging from about 19 to 28 %, and a Charpy impact ranging from about 75 to 140 ft-lb.

[0077] Further, by infiltrating a metallic starting material with a relatively low melting temperature infiltrant to form a downhole cutting tool according to embodiments of the present disclosure, self-sintering of the metallic starting material may be suppressed and

the particle size of the metallic starting material may be preserved. When self-sintering occurs, metallic starting particles sinter together and the infiltrant may not infiltrate around individual particles of the metallic starting material. Thus, rather than forming an infiltrated metallic material microstructure (particles of metallic starting material disposed in a matrix of infiltration binder) according to embodiments of the present disclosure, a non-uniform microstructure including partially sintered together particles of the metallic starting material may be formed.

[0078] In some embodiments, low temperature infiltration may be conducted in a carbon rich environment such as in a graphite mold or a mold made with carbon containing material, to provide a reduction environment for infiltration as well as a carbon source for carburization to form a hard outer layer. The region having carbon diffused therein during carburization (thereby creating a region relatively rich in carbon compared to regions not affected by the carburization) may be referred to as a carbon affected zone ("CAZ"). By using low infiltration temperatures according to embodiments of the present disclosure, the CAZ may have increased hardness (from the carbon diffused therein), thereby providing the cutting tool with an integrally formed hard outer shell, while also maintaining toughness and ductility from the infiltrated metallic composition (from the temperature being low enough to avoid formation or precipitation of carbides).

[0079] According to embodiments of the present disclosure, a CAZ may have up to a 50 times increase in the weight percent of carbon based on the total weight of the CAZ over the weight percent of carbon in the starting material forming the CAZ based on the total weight of the CAZ. In other words, upon carburizing (diffusing carbon into a starting material region during the infiltration process disclosed herein) a region of starting material having a first amount of carbon, a resulting CAZ may have up to 50 times more carbon than the first amount of carbon. In some embodiments, a CAZ may have a starting weight percent of carbon and an ending weight percent of carbon, based on the total weight of the CAZ, ranging from limits of 0 wt%, greater than 0 wt%, 0.1 wt%, 0.2 wt%, 0.5 wt%, 1 wt%, 2 wt%, 3 wt%, 4 wt%, 5 wt%, 5.5 wt%, 6 wt%, or 6.7 wt%, where any limit may be used in combination with any other limit (e.g., a starting carbon weight percent of 0 wt% and an ending carbon weight percent of 5 wt% or a starting carbon weight percent of 0.2 wt% and an ending carbon weight percent of 4 wt%). The carbon

weight percent increase from the starting weight percent of carbon to the ending weight percent of carbon in the CAZ, based on the total weight of the CAZ, may range from limits of 1.5 times, 5 times, 10 times, 15 times, 20 times, 25 times, 30 times, 40 times, or 50 times, where any limit may be used in combination with any other limit (e.g., the weight percent of carbon may be increased by 1.5 times to 30 times, or 5 times to 25 times). For example, the starting carbon in the CAZ may be 0.2 wt% based on the total weight of the CAZ, and the ending carbon in the CAZ after carburization may be 3 wt%, an increase of 15 times; or in one embodiment, the starting carbon in the CAZ may be 3.0 wt% based on the total weight of the CAZ, and the ending carbon in the CAZ after carburization may be 4.5 wt%, an increase of about 1.5 times. In addition, the increase of carbon weight percent in the CAZ may be compared to the region adjacent to the CAZ, as it should be approximately equal to the starting amount of carbon in the CAZ. As such, in one embodiment, the ending carbon in the CAZ after carburization may be 3 wt%, based on the total weight of the CAZ, and the carbon weight percent outside the CAZ may be 0.2 wt% based on the total weight of that region, an increase of about 30 times. Further, according to embodiments of the present disclosure, a CAZ may be formed along one or more outer regions of a generally metallic cutting tool body according to embodiments of the present disclosure, where the CAZ may have a material composition including greater than 2 wt% carbon based on the total weight of the CAZ. In some embodiments having one or more CAZs with a composition including greater than 2 wt% carbon, the one or more CAZs may form less than 20 vol% of the infiltrated metallic cutting tool body.

[0080] Carburization from a carbon containing mold material or other carbon source to the mold contents may be controlled by controlling the variables of the infiltration process, including the heating time and the heating temperature, as well as the initial material composition of the mold and contents of the mold. For example, initial carbon concentration in the starting material being infiltrated and the temperature may influence the rate of carbon transport, and the carbon concentration of the mold material and heating time may effect how much carbon is transported. According to some embodiments of the present disclosure, parameters of infiltrating a generally metallic cutting tool body, including starting material composition (e.g., amount of carbon initially

present in the starting material), mold composition (e.g., amount and/or structure of carbon in the mold material), infiltration temperature (including any intermediate temperatures the mold assembly is heated to for carbon diffusion), and time the mold assembly is heated to selected temperatures, may be designed to control the depth of diffusion (and thus the depth of the CAZ from the outer surface of the cutting tool body) and the amount of carbon that diffuses into the starting material, which may provide a selected hardness to the CAZ. According to some embodiments of the present disclosure, a CAZ may extend a depth of at least 0.05 inches from an outer surface of a cutting tool body. In some embodiments, the CAZ may extend a depth ranging from limits of 0.03 inches (0.762 mm), 0.05 inches (1.27 mm), 0.1 inches (2.54 mm), 0.25 inches (6.35 mm), 0.5 inches (12.7 mm), 0.6 inches (15.24 mm), 0.75 inches (19.05 mm), 1 inch (25.4 mm), or greater than 1 inch (25.4 mm), where any limit may be used in combination with any other limit (e.g., 0.03 in to 1 in or 0.05 in to 0.75 in).

[0081] In some embodiments, carburization may be controlled so that the CAZ includes composite metallic particles with a gradient hardness from the center towards the outer boundary of each composite metallic particle. For example, a metallic starting material may be selected where upon diffusion of carbon from the mold the surface of metallic particles in the metallic starting material reacts with the carbon, thereby carburizing the outer boundary of the metallic particles. Upon completion of the infiltration process, such surface reacted metallic particles form the composite metallic particles having a gradient hardness from the center towards the outer boundary of each composite metallic particle. In other words, metallic particles of metallic starting material may become composite metallic particles after carburization from the infiltration process. Composite metallic particles may include, for example, austenite, martensite, and other carbon steel phases.

[0082] For example, according to some embodiments, a downhole cutting tool body may be formed by infiltrating metallic starting material (having a composition with at least 98 weight % of at least one metal or metal alloy) with an infiltrant at an infiltration temperature less than the solidus temperature of the metallic starting material and greater than the melting temperature of the infiltrant. The metallic starting material may be loaded into at least one region of a graphite mold of the cutting tool body such that the at

least one region of metallic starting material forms at least 80 % by volume of the mold and where the metallic starting material is disposed adjacent to at least a portion of the mold inner walls. During infiltration, carbon from the graphite mold may diffuse into the metallic starting material adjacent to the mold inner walls to create a CAZ. The CAZ formed along the outer surface of the infiltrated metallic material may have a hardness greater than that of the infiltrated metallic material located interior to the CAZ. While the formation of a CAZ has been described with respect to powdered starting materials placed in a mold, the formation of a CAZ may also occur when starting materials are printed as described above and surrounded with a carbon source, such as a graphite powder.

[0083] The size and hardness of the composite metallic particles in the CAZ is at least partly a function of infiltration temperature and time. In some embodiments, the hardness of the composite metallic particles in the CAZ ranges from between 1.1 and 2.5 times greater than the hardness of the material in an interior region of an infiltrated metallic body (e.g., on the HRc scale), or from 1.1 to 2.1 times greater, or from 1.2 to 1.6 times greater. For example, in one embodiment, the hardness in the CAZ may range from about 30.5 to 40.0 HRc and the hardness in the interior region may range from about 19.5 to 20.0 HRc (e.g., the CAZ is 1.5 to 2.1 times harder than the interior region on the HRc scale). In another embodiment, the hardness in the CAZ may range from about 29.0 to 30.0 HRc and that in the interior region is 24.5 to 25.5 HRc (e.g., the CAZ is 1.1 to 1.2 times harder than the interior region on the HRc scale). According to some embodiments of the present disclosure, the hardness in a CAZ may range from 15 to 45 HRc, from 20 to 40 HRc, or from 25 to 35 HRc.

[0084] According to embodiments of the present disclosure, metallic starting material (and non-carburized infiltrated metallic particles) may have a hardness ranging from limits of 50, 80, 100, 200, 300, 400, or 800 HV, where any limit can be used in combination with any other limit (e.g., 50 to 800 HV or 80 to 300 HV). After carburization from infiltration, composite metallic particles may have a hardness ranging from limits of 100, 200, 300, 400, 500, 750, or 1000 HV, where any limit can be used in combination with any other limit (e.g., 100 to 1000 HV or 100 to 750 HV). Composite metallic particles having a particle hardness gradient (with a decreasing hardness from the particle's

exterior surface toward its center) may have a hardness ratio of the hardness at the exterior to the hardness at the center that ranges from greater than 1/1 to 10/1, 2/1 to 10/1, 2/1 to 8/1, greater than 2/1 to 10/1, greater than 2/1 to 8/1, or 3/1 to 5/1. According to embodiments of the present disclosure, composite metallic particles may have a particle hardness gradient, where a center hardness ranges from limits of 50, 80, 100, 200, 300, 400, or 800 HV, where any limit can be used in combination with any other limit (e.g., 50 to 800 HV or 80 to 800 HV), an exterior hardness ranging from limits of 100, 200, 300, 400, 500, 750, or 1000 HV, where any limit can be used in combination with any other limit (e.g., 100 to 1000 HV or 300 to 750 HV), and the hardness decreases from the exterior hardness to the center hardness. For example, composite metallic particles may have a particle hardness gradient with a center hardness ranging between 80 and 200 HV, an exterior hardness ranging between 500 and 1000 HV, and a decreasing hardness from the exterior hardness to the center hardness.

[0085] By using infiltration methods of the present disclosure to form downhole cutting tool bodies, material properties of the infiltrated metallic cutting tool body may be designed and selected for different regions of the cutting tool body and/or different applications. For example, the material properties of the infiltrated metallic cutting tool body may be designed by selecting the starting material composition (e.g., starting materials having a selected initial amount of carbon), the type of mold used to hold the starting materials (e.g., mold made with carbon containing material such as graphite or graphite and sand, or a mold having at least a portion of its inner walls coated with a high temperature refractory layer prior to pouring the contents within the mold), the infiltration temperature (including intermediate temperatures between a lowest starting temperature and a highest infiltration temperature, e.g., an intermediate temperature for carburization of a portion of the starting material), and the duration of heating the mold and its contents at selected temperatures.

[0086] In some embodiments, a downhole cutting tool body may have at least one metallic region, the at least one metallic region having a plurality of metallic particles disposed in an infiltration binder and the infiltration binder having a melting point lower than the melting point of the plurality of metallic particles, with the hardness of the plurality of metallic particles ranging between 100 and 1000 HVN, where the mean free path between

the plurality of metallic particles is less than 60 microns, and the contiguity between the plurality of metallic particles is less than 20 %. In some embodiments, a generally metallic cutting tool body may have at least one outer region having a material composition including a plurality of hard particles with a hardness of greater than 1200 HVN in an infiltration binder. Hard particles having a hardness of greater than 1200 HVN may include cermets, ceramics, carbides, and other composite materials described herein as non-metallic composite material. For example, in some embodiments, a generally metallic cutting tool body may include at least one carbide region having a material composition including a plurality of carbide particles disposed in the infiltration binder used to infiltrate the cutting tool body, where the at least one carbide region forms less than 10 % by volume of the body. In some embodiments, at least one carbide region may form at least a portion of at least one cutting element pocket formed in the cutting tool body, where the carbide region may have a thickness greater than a diameter and up to two times the diameter of the cutting element in the cutting element pocket. In some embodiments, a generally metallic cutting tool body may include a transition region formed integrally with and disposed between at least one carbide region and at least one metallic region, where the transition region has a coefficient of thermal expansion between the coefficients of thermal expansion of the carbide region and the metallic region.

[0087] Regions of a generally metallic cutting tool body may be designed to have selected material compositions, e.g., metallic regions, transition regions, carbide regions and other non-metallic composite regions such as described herein, such that desired material properties are provided to the different regions of the cutting tool body. For example, a generally metallic cutting tool body may include at least one metallic region having a yield strength ranging from 40 to 80 ksi, an ultimate tensile strength ranging from 60 to 120 ksi, an elongation ranging from 2 to 10 %, and a Charpy impact ranging from 3 to 20 ft-lb. In some embodiments, the generally metallic cutting tool body may also include a hard outer region made of one or more non-metallic composite regions, transition regions or CAZs, such as described above, to provide one or more outer regions of the cutting tool body (e.g., at least a portion of a cutting element pocket wall, an outer surface of a blade, or an outer surface at a gage of the cutting tool body) with increased hardness.

[0088] Table 1 shows the material properties of three examples of tool bodies.

Table 1

	Matrix Body	Composite body	4130 Steel body
Transverse rupture strength ("TRS") (ksi)	128-145	122	-
UTS (ksi)		61	98
Elongation (%)	-	11	26
Young's modulus (x10^6 psi)	44	23	30
Hardness (HRc)	38	22.5	12
Charpy (ft.lbs)		4	135
Fracture toughness ("K_{IC}") (ksi.$in^{1/2}$)	18	17	
Wear - B611 (1000rev/cc)	1.1	1.2	2.1
Erosion 70°- G76	0.26	0.27	0.09
Erosion 30°- G76	0.24	0.28	0.05

[0089] The matrix body in Table 1 was formed of a conventionally infiltrated tungsten carbide matrix material, where a majority of a mold was filled with tungsten carbide particles and infiltrated with a metallic infiltrant. The composite body in Table 1 was formed according to embodiments of the present disclosure, where a majority of a mold was filled with metallic starting material particles and infiltrated with a metallic infiltrant. The 4130 steel body in the table above was machined from a piece of conventionally formed 4130 steel. As shown, the composite body formed according to embodiments of the present disclosure may show material property characteristics similar to both matrix material bodies (e.g., transverse rupture strength) and steel bodies (e.g., ultimate tensile strength).

[0090] Although just a few embodiments have been described in detail above, those skilled in the art will appreciate that many modifications are possible in the example embodiments without materially departing from the apparatus, systems, and methods disclosed herein. Accordingly, such modifications are intended to be included within the scope of this disclosure. Additionally, it should be understood that references to "one embodiment" or "an embodiment" of the present disclosure are not intended to be

interpreted as excluding the existence of additional embodiments that also incorporate the recited features. For example, any element described in relation to an embodiment herein may be combinable with any element of any other embodiment described herein.

[0091] In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not just structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke means-plus-function for any limitations of any of the claims herein, except for those in which the claim expressly uses the words 'means for' together with an associated function. Each addition, deletion, and modification to the embodiments that fall within the meaning and scope of the claims is to be embraced by the claims.

CLAIMS

What is claimed is:

1. A downhole tool, comprising:
   a body having at least 80 % of its volume comprising at least one metallic region, the at least one metallic region comprising:
   a plurality of metallic particles disposed in an infiltration binder; and
   the infiltration binder having a melting temperature below the solidus temperature of the metallic particles,
   the body having a body hardness gradient extending at least 0.5 inches from a portion of an outer surface of the body to an interior portion of the metallic region, the body hardness gradient having a decreasing amount of carbon from the outer surface towards the interior portion of the metallic region; and
   a plurality of cutting elements in cutting element pockets on the body.

2. The downhole tool of claim 1, wherein the mean free path between the plurality of metallic particles is less than 60 micons.

3. The downhole tool of claim 1, wherein the contiguity between the plurality of metallic particles is less than 20 %.

4. The downhole tool of claim 1, wherein the plurality of metallic particles forming the body hardness gradient comprises composite metallic particles having a particle hardness gradient from the center towards the exterior of each composite metallic particle.

5. The downhole tool of claim 1, wherein the plurality of metallic particles have a mono-modal or bi-modal distribution.

6. The downhole tool of claim 1, wherein the plurality of metallic particles have a substantially spherical shape with a shape factor ranging between 0.8 and 1.0.

7. The downhole tool of claim 1, further comprising:

an upper section having a threaded connection end and a threaded shaft extending opposite the threaded connection end; and

a locking ring between the body and the upper section, the locking ring including an axial bore,

wherein the threaded shaft extends through the axial bore and threadably engages a threaded bore in the body.

8. A downhole cutting tool, comprising:

a body comprising at least one metallic region, the at least one metallic region comprising:

a plurality of metallic particles disposed in an infiltration binder,

the plurality of metallic particles comprising composite metallic particles, each composite metallic particle having a particle hardness gradient from the center towards the exterior,

the infiltration binder having a melting temperature below the solidus temperature of the metallic particles, and

the metallic region forming at least 80 % by volume of the body; and

a plurality of cutting elements in cutting element pockets on the body.

9. The downhole cutting tool of claim 8, wherein the particle hardness gradient of the composite metallic particles has a center hardness ranging between 80 and 200 VHN, an exterior hardness ranging between 500 and 1000 VHN, and a decreasing hardness from the exterior hardness to the center hardness.

10. The downhole cutting tool of claim 8, wherein a hardness ratio of the hardness at the exterior of the composite metallic particles to the hardness at the center of the composite metallic particles ranges from greater than 2/1 to 10/1.

11. The downhole cutting tool of claim 8, further comprising at least one outer region forming an outer surface of the body, the at least one outer region comprising a plurality of hard particles with a hardness of greater than 1200 HVN disposed in the infiltration binder.

12. The downhole cutting tool of claim 8, further comprising at least one carbide region at an outer surface of the body, the at least one carbide region comprising a plurality of carbide particles disposed in the infiltration binder, the at least one carbide region forming less than 10 % by volume of the body.

13. The downhole cutting tool of claim 12, wherein the at least one carbide region forms at least a portion of at least one of the cutting element pockets and has a thickness greater than a diameter and up to two times the diameter of the cutting element disposed in the at least one cutting element pocket.

14. The downhole cutting tool of claim 12, further comprising a transition region formed integrally with and between the at least one carbide region and the at least one metallic region, the transition region having a coefficient of thermal expansion between the coefficients of thermal expansion of the carbide region and the metallic region.

15. A method of forming a downhole cutting tool body, comprising:
providing starting materials, the starting materials comprising:
at least one metallic starting material; and
an infiltrant; and
heating the starting materials to an infiltration temperature lower than the solidus temperature of the at least one metallic starting material and greater than or equal to the melting temperature of the infiltrant;
wherein during heating, carbon diffuses from a carbon source into the starting materials; and
wherein the at least one metallic starting material and the infiltrant form at least 80 % by volume of the downhole cutting tool body.

16. The method of claim 15, wherein the starting materials further comprises a carbide starting material disposed in a layer forming at least a portion of an outer surface of blades of the downhole cutting tool body, the carbide starting material forming less than 10 % by volume of the starting materials.

17. The method of claim 16, wherein the starting materials further comprise at least one transition starting material adjacent to the layer of the carbide starting material, the at

least one transition starting material and carbide starting material forming less than 15 % by volume of the starting materials.

18. The method of claim 16, wherein the outer surface corresponds with at least one cutting element pocket.

19. The method of claim 15, wherein the starting materials are placed in a mold and the mold comprises the carbon source.

20. The method of claim 15, wherein the heating is conducted in a vacuum.

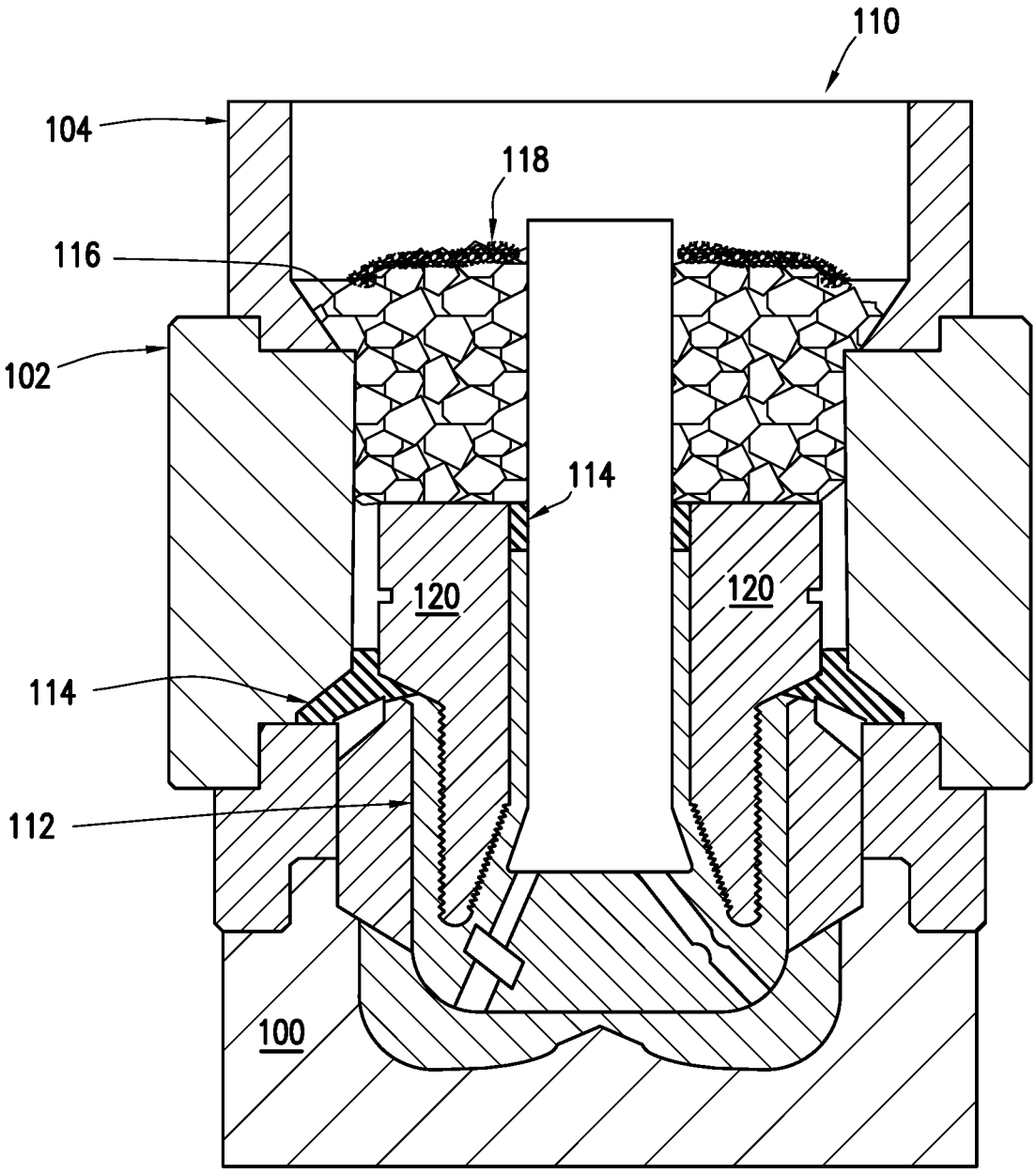


FIG. 1

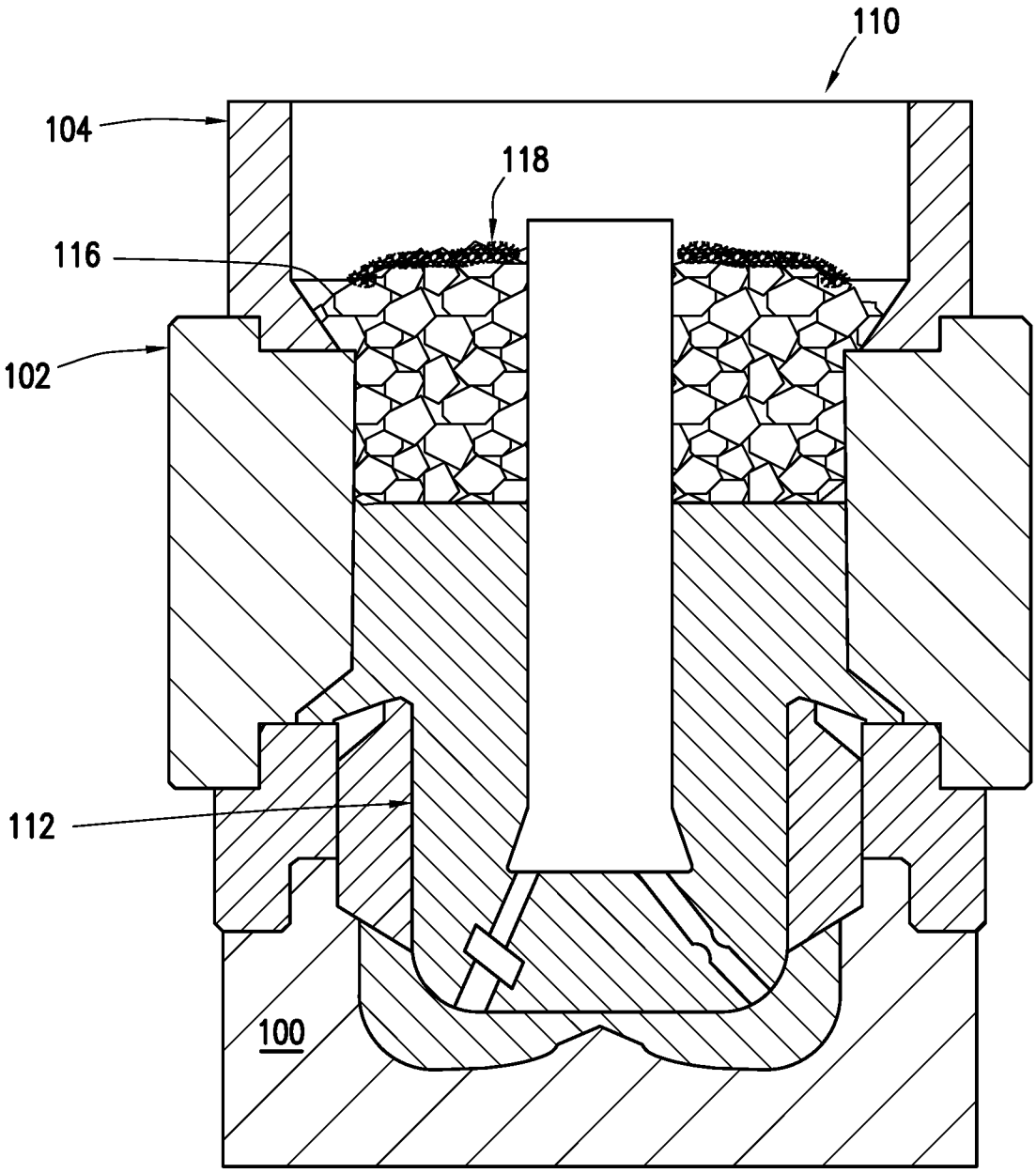


FIG. 2

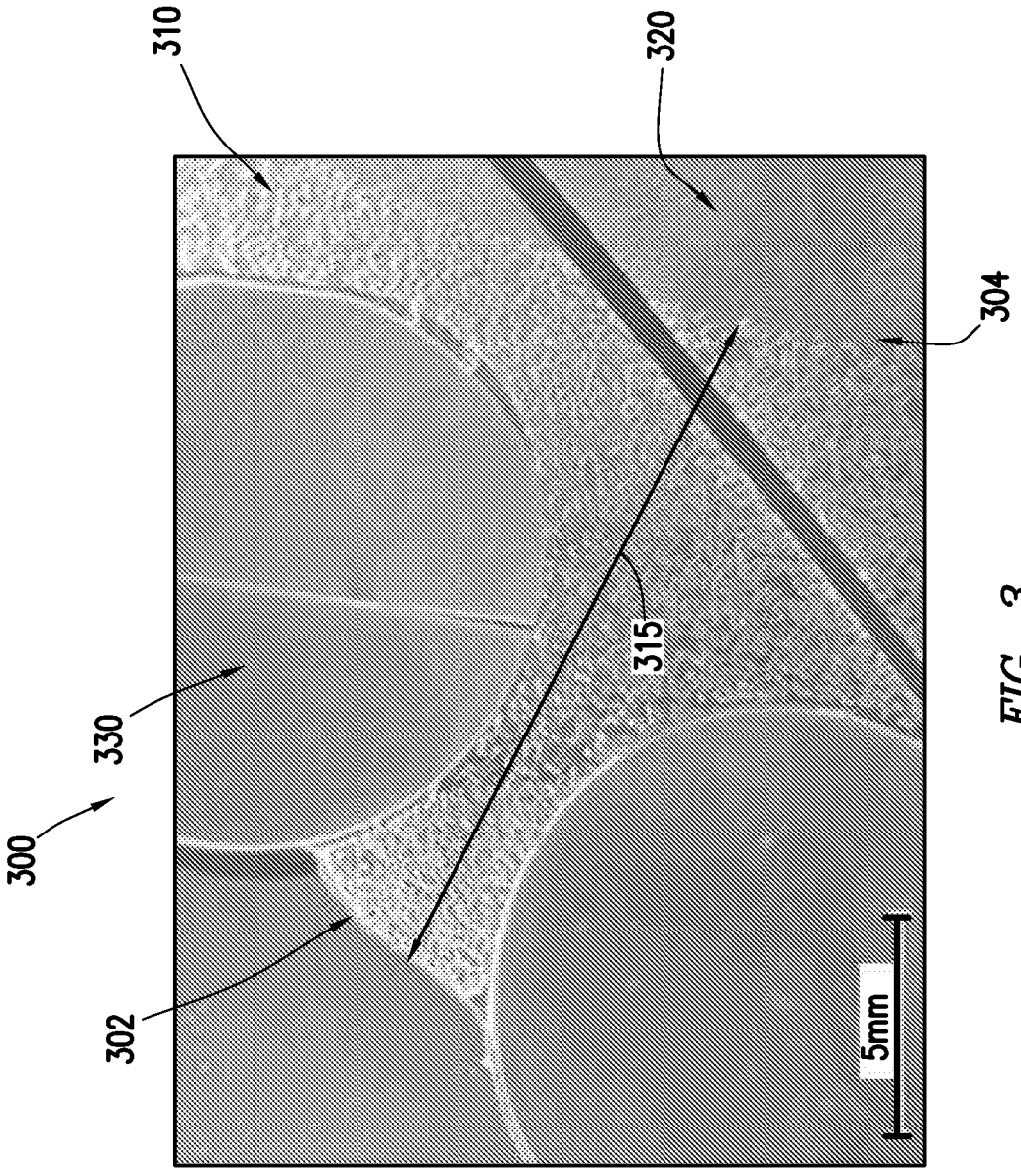


FIG. 3

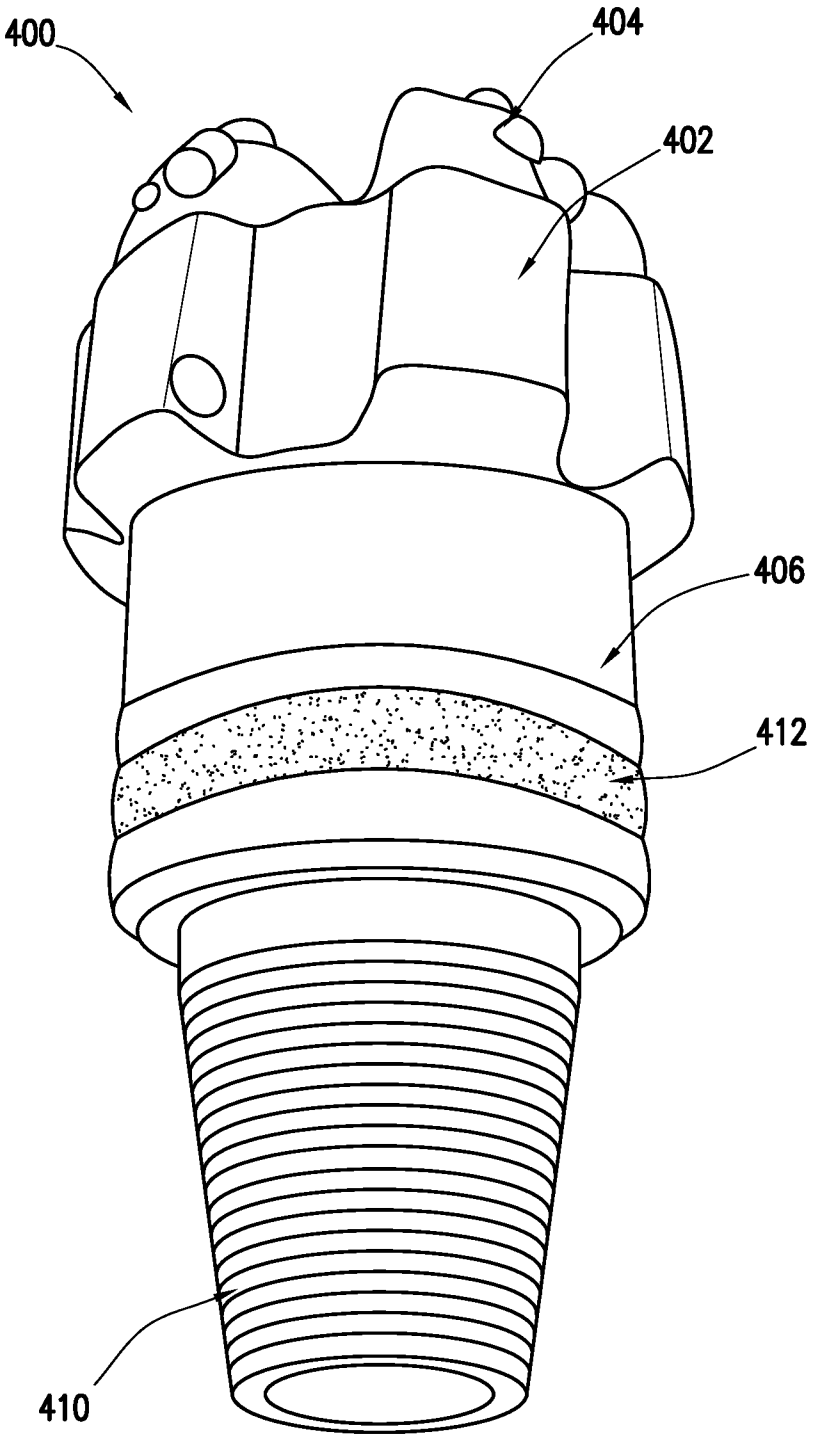


FIG. 4

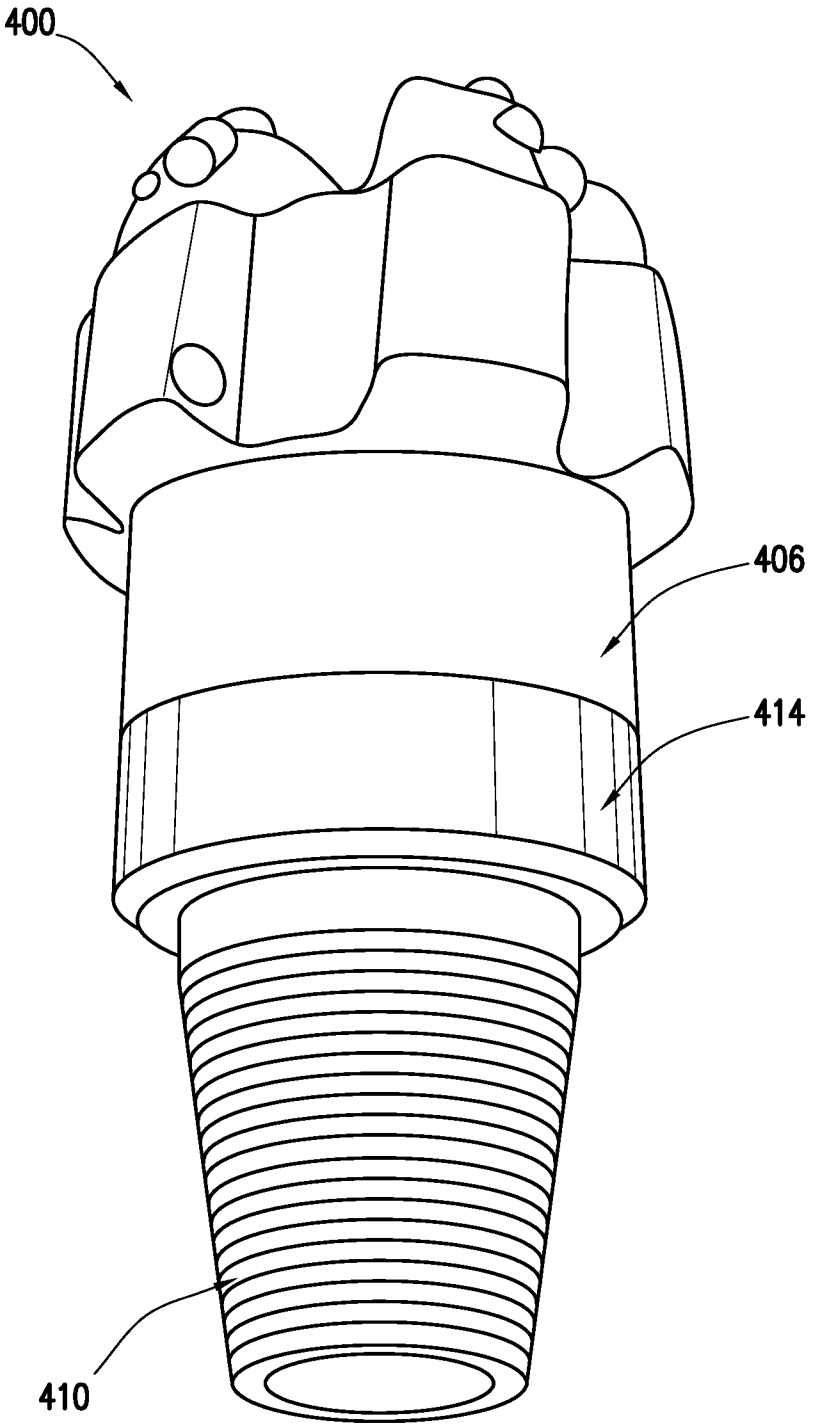


FIG. 5

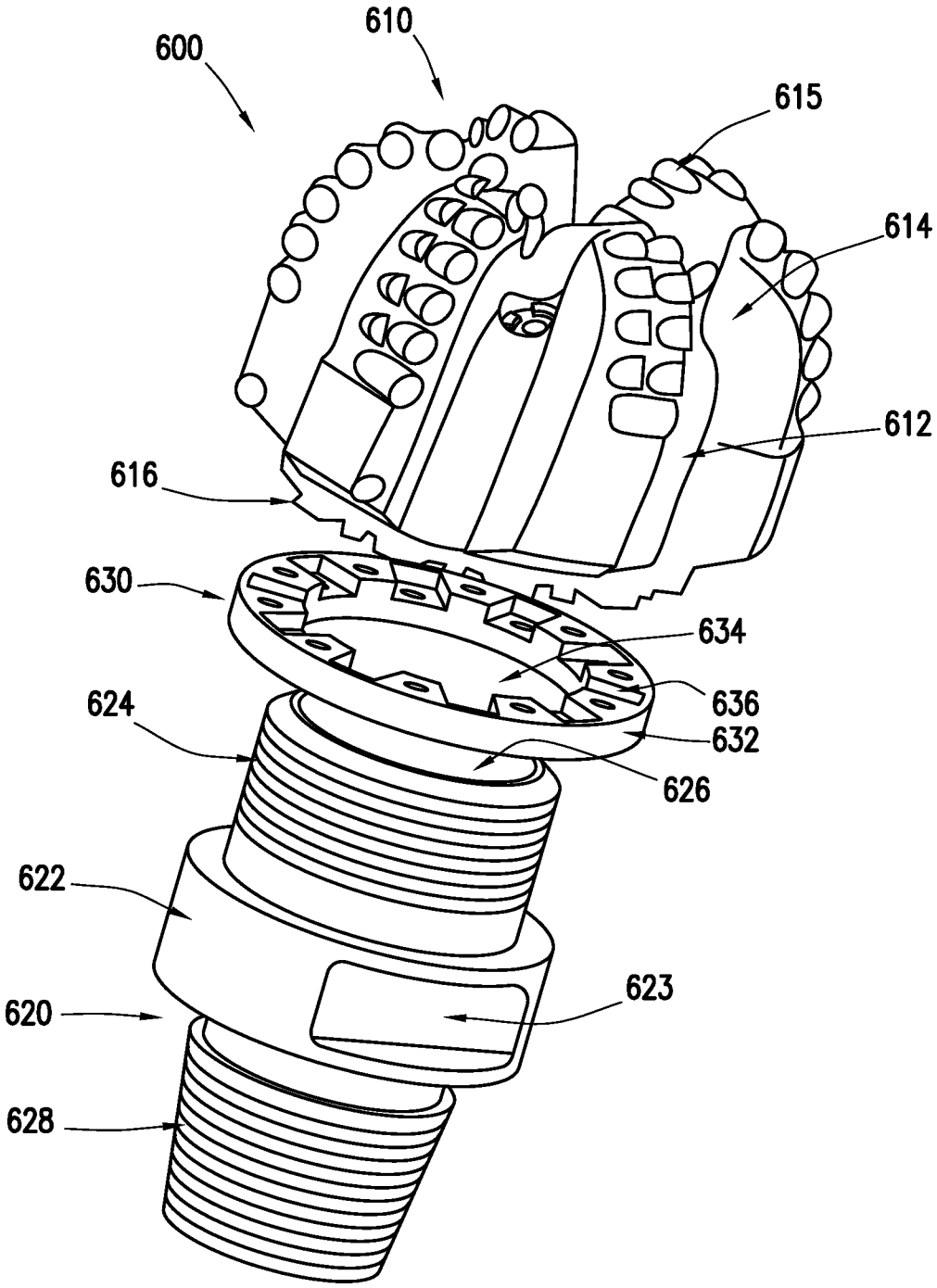


FIG. 6

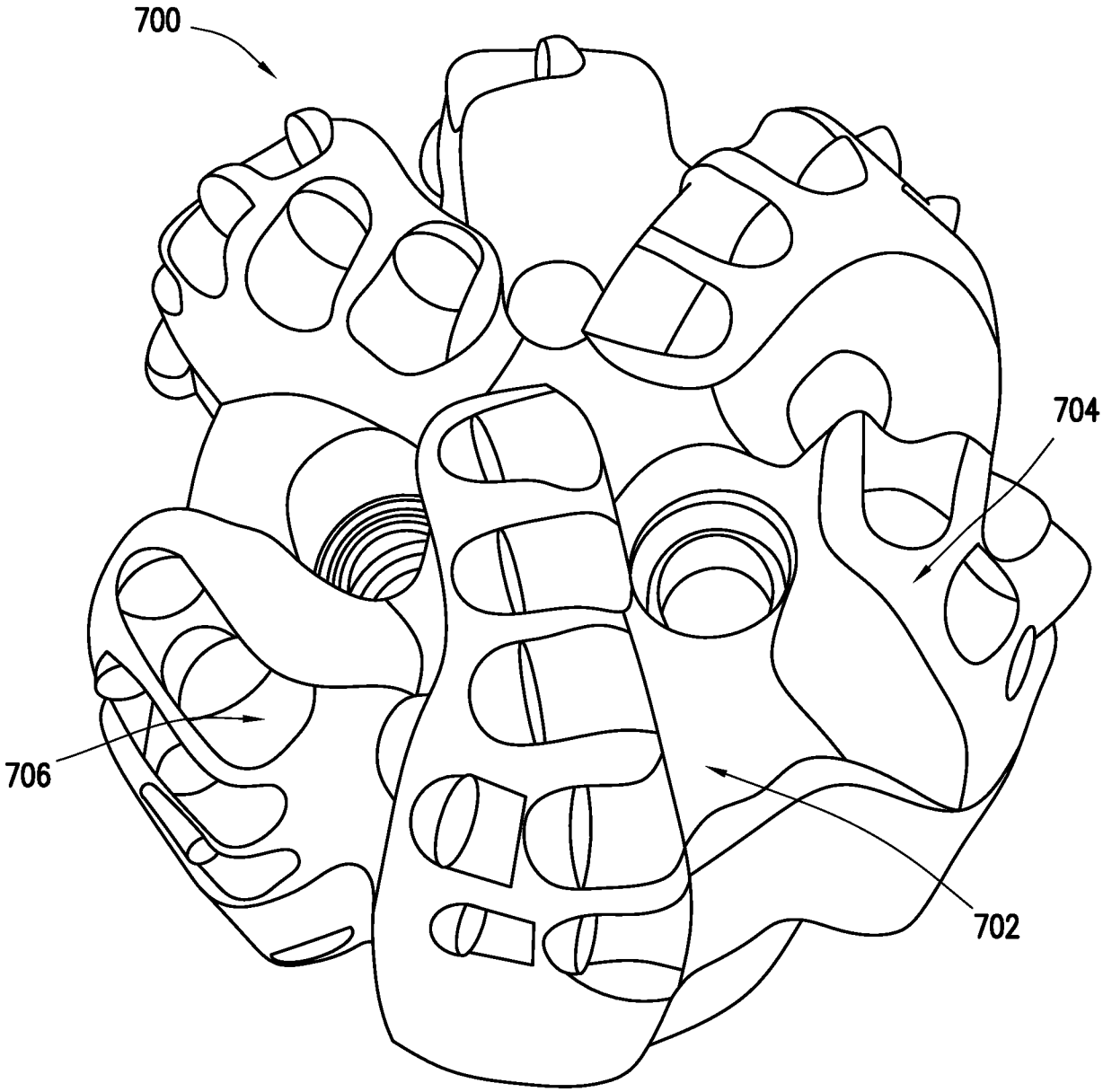


FIG. 7

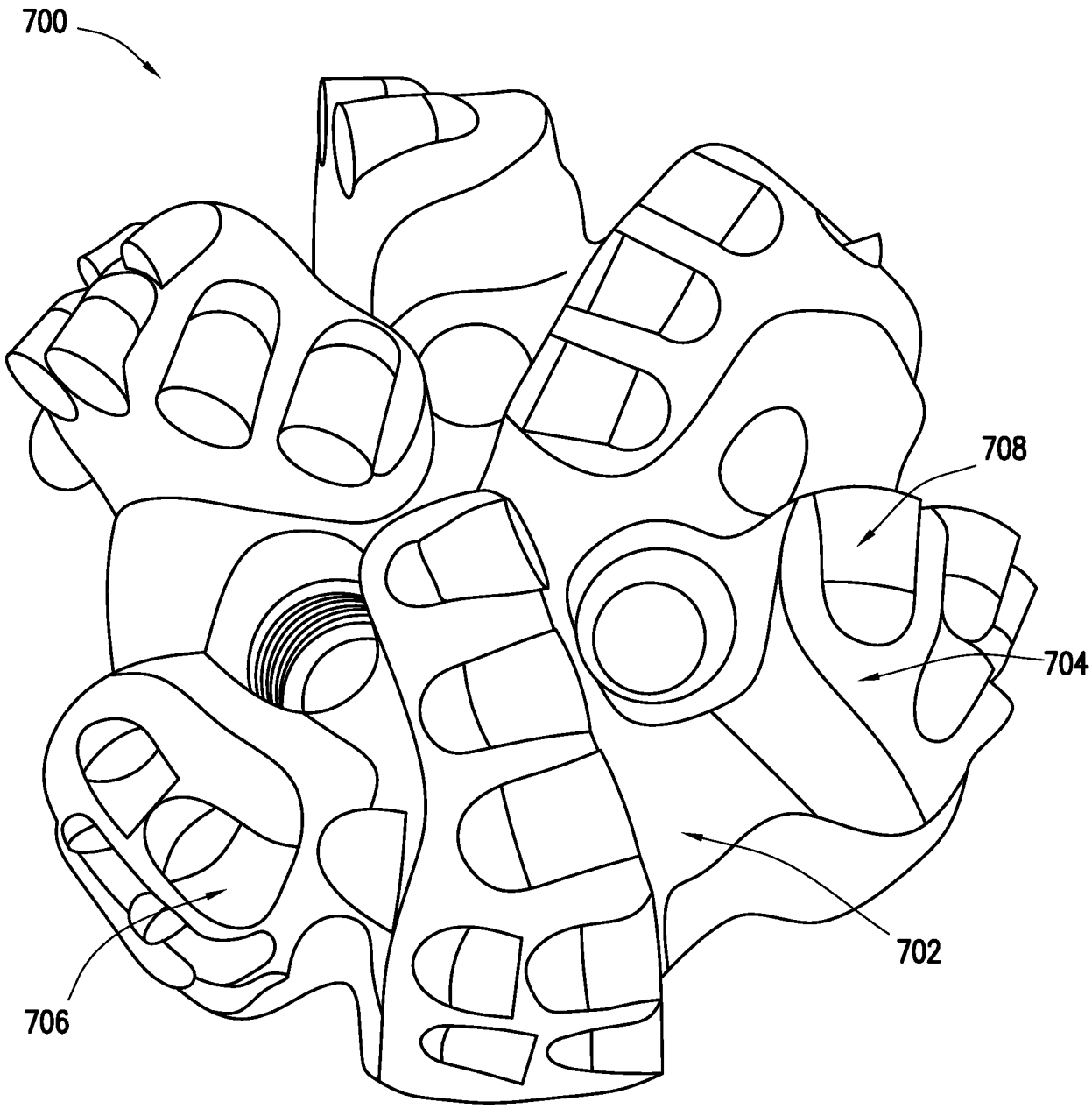


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/042697

A. CLASSIFICATION OF SUBJECT MATTER

E21B 10/42(2006.01)i, E21B 10/54(2006.01)i, B22F 5/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B 10/42; B22D 27/02; E21B 10/46; B22D 13/00; B23D 77/00; E21B 12/00; E21B 10/50; B24D 3/06; B24D 18/00; B22D 19/16; E21B 10/54; B22F 5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: downhole tool, metallic material, infiltration binder, solidus temperature, hardness, mold, carbon

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010-0278604 A1 (GLASS et al.) 04 November 2010 See paragraphs [0031], [0043], [0052]-[0054], [0062]-[0063], [0072]-[0074], [0078] and figures 1-2.	8-14
Y		1-7,15-20
Y	US 2010-0236834 A1 (XIA et al.) 23 September 2010 See paragraph [0058].	1-7,15-20
Y	WO 2015-023925 A1 (SMITH INTERNATIONAL, INC.) 19 February 2015 See paragraphs [0028], [0031] and figure 2.	7
Y	US 2012-0240476 A1 (MIRCHANDANI et al.) 27 September 2012 See paragraph [0064], claims 39, 46, and figures 2-4.	20
A	US 8991471 B2 (CHENG et al.) 31 March 2015 See abstract, claim 1, and figure 5.	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 October 2016 (14.10.2016)	**14 October 2016 (14.10.2016)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/042697

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