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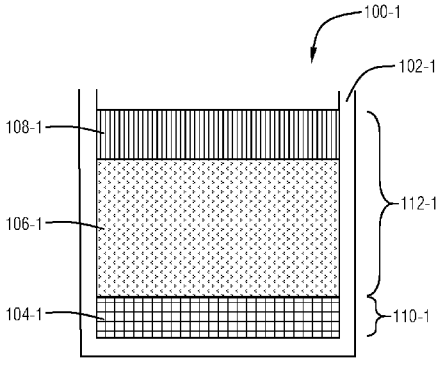


Fig. 1-1

(57) Abstract: A method of making a mill cutting structure includes combining cutting structure assembly components, including an infiltrant, a metallic starting material, and at least one pre-formed hard material body. The cutting structure assembly components are heated 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.

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TITLE

INFILTRATED CUTTING TOOLS AND RELATED METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to, and the benefit of, U.S. Patent Application Serial No. 62/193,324, filed July 16, 2015, and is related to U.S. Patent Application Serial No. 62/193,145, filed July 16, 2015, the entireties of which are incorporated herein by this reference.

BACKGROUND

Downhole milling tools used to cut casing in a downhole environment include a tubular body having a plurality of equi-azimuthally disposed blades coupled to the body. Each of the cutting blades has a forward surface facing the direction of rotation of the tool, which is dressed with a cutting material. For example, cutting elements may be attached, e.g., by brazing, to a steel cutting blade substrate at the forward surfaces of the cutting blades. Mill cutting elements may include, for example, tungsten carbide tiles, which may include a protruding ridge or chip breaker that limits the length of swarf or chip cut by the cutting edge of the element.

Downhole milling tools may be used to, for example, remove portions of or entire sections of downhole casing. For example, section milling tools may be positioned within a casing, pipe, or other tubular member to mill away a length of the tubular member, e.g., for a plug and abandon operation. Section mill cutting blades may be pivoted at one end so cutting elements at the other end may swing outwardly into engagement with the casing, pipe, or other tubular member to mill away the tubular member. As another example, window milling tools, e.g., a lead mill, may be positioned within a casing, pipe, or other tubular member and moved along a whipstock to cut an opening from the inside of the tubular member.

SUMMARY

In some aspects, embodiments disclosed herein relate to a method of making a mill, a mill blade, or other cutting structure that includes combining cutting structure assembly components that include an infiltrant, a metallic starting material, and a pre-formed hard material body. The cutting structure assembly components are heated to an infiltration temperature lower than a solidus temperature of the metallic starting material and greater than or equal to a melting temperature of the infiltrant.

In some aspects, additional embodiments disclosed herein relate to a method of making a mill cutting structure, and includes positioning pre-formed hard material bodies within a manufacturing assembly. A metallic starting material is layered within the manufacturing assembly, and on interfaces with the pre-formed hard material bodies. An infiltrant is layered on the metallic starting material. The manufacturing assembly is heated to an infiltration temperature lower than a solidus temperature of the metallic starting material and greater than or equal to a melting temperature of the infiltrant.

In some aspects, embodiments disclosed herein relate to a mill cutting structure that includes at least one cutting element coupled to a support structure. The support structure includes a plurality of

metallic particles interspersed with an infiltration binder, and the infiltration binder couples the at least one cutting element to the support structure.

In still additional aspects, embodiments disclosed herein relate to a mill cutting structure that includes at least one cutting element and a support structure having a plurality of metallic particles interspersed with an infiltration binder. The support structure may have material properties including a yield strength between 40 ksi and 70 ksi, an ultimate tensile strength between 60 ksi and 100 ksi, elongation between 5% and 16%, and hardness (as measured on the C scale of the Rockwell hardness test (HRC)) between HRC 18 and 35.

This summary is provided to introduce a selection of concepts that are further described herein, and 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.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1-1 is a cross-sectional view of a mold assembly, according to some embodiments.

FIG. 1-2 is a cross-sectional view of a mold assembly, according to some embodiments.

FIGS. 2-1 to 2-3 are cross-sectional views of a manufacturing assembly performing an additive manufacturing process, according to some embodiments.

FIG. 3 is a perspective view of a blade of a milling tool, according to some embodiments.

FIGS. 4-1 to 4-4 are cross-sectional views of a mill blade, according to some embodiments.

FIG. 5 shows a micrograph of a cutting element brazed to a body of a mill blade.

FIG. 6 shows a micrograph of a body integrally bonded to a cutting element through an infiltration process, according to some embodiments.

FIG. 7 is a partial cross-sectional view of a milling tool, according to some embodiments.

DETAILED DESCRIPTION

Some embodiments of the present disclosure relate generally to cutting structures, and some further embodiments relate to milling tools. Further example embodiments relate to infiltration of a metallic material. Infiltration of a metallic material may be used, for instance, to form a mill blade or other mill cutting structure supporting one or more cutting elements. A metallic material may be infiltrated with an infiltrant at temperatures below the solidus temperature of the metallic material, and above the melting temperature of the infiltrant. In some embodiments, heating the metallic material to a temperature below its solidus temperature may be performed to inhibit or even prevent the metallic material from sintering together prior to infiltration.

According to some embodiments of the present disclosure, a mill cutting structure may be made by providing at least one cutting element within a first region of a mold, which first region may correspond with a cutting portion of the mill cutting structure. The cutting structure may take any form and may include, for instance, a knife, blade, or other body that may support one or more cutting elements. As used herein, the term “cutting structure” or “mill cutting structure” may thus encompass

a body or other portion of a milling tool which supports or is coupled to one or more cutting elements, gauge protection elements, or other "pre-formed hard material bodies."

In at least some embodiments, a metallic starting material may be placed in a mold adjacent the at least one pre-formed hard material body. An infiltrant may also be placed in the mold. The contents of the mold, including the pre-formed hard material body, the metallic starting material, and the infiltrant, may be heated to an infiltration temperature, which in some embodiments may be lower than the solidus temperature of the metallic starting material and greater than or equal to the melting temperature of the infiltrant. During heating, the infiltrant may infiltrate through the metallic starting material. Depending on the heating parameters (e.g., time and temperature) and the material composition of the infiltrant, the infiltrant may infiltrate through the metallic starting material and/or the pre-formed hard material body. The infiltrant may integrate with the hard material body. Upon cooling to ambient temperature, a single-piece mill cutting structure may be formed having at least one cutting element (formed by the at least one hard material body) held at a pre-arranged position relative to a metallic support structure (formed by the infiltrated metallic starting material) having a plurality of metallic particles interspersed with an infiltration binder. The infiltration binder may attach the at least one cutting element to the support structure.

As used herein, the term "starting" may be used to refer to a material that is infiltrated, while the term "infiltrant" may be used to describe a material that infiltrates the starting material. The infiltrant in its molten state and/or after it has infiltrated the starting material and cooled may be referred to as an "infiltration binder". The infiltrant (and infiltration binder) may be a metal or an alloy infiltrant used in an infiltration process to bond together the starting material. The starting material may be contents within a mold, contents of a component formed by additive manufacturing, or the like. Thus, the terms "infiltrant" and "infiltration binder" may be used interchangeably, depending on the stage of infiltration. Further, an infiltrant (e.g., a metallic infiltrant) may generally maintain the same composition through the infiltration process. For instance, a metallic infiltrant may have substantially the same composition in infiltration binder form. In other embodiments, the composition of the binder infiltrant may be altered during infiltration, such as where a metallic infiltrant has a different composition in its solidified infiltration binder form. By way of example, one or more elements may dissolve 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, and in manufacturing tolerances, as would be understood by those of ordinary skill in the art.

An infiltrant (e.g., a metallic infiltrant or infiltration binder) may include one or more transition metals, main group metals, or alloys thereof, although any suitable infiltration material or family of infiltration materials may be used. The infiltrant may have a melting point lower than the melting point of a starting material it infiltrates. For example, one or more of copper, nickel, iron, or cobalt may a

major constituent in the infiltrant. Other elements, such as one or more of aluminum, manganese, chromium, zinc, tin, silicon, silver, boron, or lead may also be present. In some embodiments, the infiltrant may nickel, copper, or alloys of nickel and/or copper. The infiltrant may include, for example, a Cu-Mn-Ni alloy, a Cu-Mn-Ni-Zn alloy, a Cu-Mn-Ni-Zn-Sn alloy, a Cu-Mn-Ni-Sn-Zn-Fe alloy, 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, a Cu alloy, a Ni alloy, other alloys, or combinations of one or more of the foregoing. The infiltrant may be a heat treatable metal binder in some embodiments. For instance, the properties of the metal binder may improve after a subsequent heat treatment following infiltration. Heat treatable metal binders may include, for example, Al-Cu alloys, Al-Cu-Mg alloys, Al-Mg-Si alloys, Al-Zn-Mg alloys, Al-Zn-Mg-Cu alloys, other alloys, and combinations of one or more of the foregoing.

According to some embodiments of the present disclosure, a selected infiltrant material may have a melting temperature within a range having lower and/or upper limits including one of more of 800 °C (1470 °F), 850 °C (1560 °F), 900 °C (1650 °F), 950 °C (1740 °F), 1000 °C (1830 °F), 1050 °C (1920 °F), 1100 °C (2010 °F), 1150 °C (2100 °F), 1200 °C (2190 °F), 1250 °C (2280°F), or values therebetween. In other embodiments, the melting temperature of the infiltrant may be less than 800 °C (1470 °F) or greater than 1250 °C (2280°F).

Further, in some embodiments, an infiltrant may include a flux material. The flux material may be provided with a metallic binder material. For example, a layer of powdered flux material may be provided over a layer of metallic binder infiltrant. In another example, a metallic binder may be provided in the form of one or more slugs, ingots, or the like, and a flux material may be coated around the metallic binder, loaded on top of the metallic binder slug, encased within the metallic binder, or otherwise included with the metallic binder. A metallic binder slug, ingot, or the like may have any of various shapes. By way of illustration, a metallic binder may be formed to be spherical (or generally spherical), cubic, or rectangular prism shaped, or have another symmetrical or geometric shape. The metallic binder may also be irregularly shaped in some embodiments. The flux material may, in some embodiments, 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, powder, or other forms. Non-limiting examples of flux material include boron-based flux having a combination of one or more borates and fluorides, boron, BAg, BCuP, BCu, BNi, BAu, and RBCuZn.

In embodiments having a metallic binder coated with a flux material, the flux material may be adhered to the surface of the metallic binder. For example, a flux material may be adhered to the surface of a metallic binder by heating the metallic binder slug, ingot, or other structure to a temperature sufficient to melt or partially melt the flux material in contact with one or more surfaces of the metallic binder. In such embodiments, the metallic binder may be adherent in that the heated metallic binder may be 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 by using an adhesive coating, such

as a fluid gel or paste, which adheres the flux material to the surface of the metallic binder. An adhesive coating may be formed of a material that does not react with (or substantially react with) the metallic binder or flux at various temperatures (e.g., at a storage temperature and/or pre-heating temperatures) or a material that is capable of evaporating, decomposing, or otherwise dissipating 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 (e.g., polyether polyols, polyether diols, polyether triols, polyether tetraols), glycerol, ethylene glycol, dimethylsulfoxide, dimethylformamide, dimethylacetamide, polydimethyl siloxane, polypropylene glycol dimethylether, other materials, and combinations or derivatives of one or more of the foregoing. In some embodiments, the adhesive material may include a flux, such as a rosin, a modified rosin, a borate, a fluoride, boron, brown flux, other materials, or combinations of one or more of the foregoing. The flux may be substantially uniformly distributed about one or more surfaces (e.g., exterior surfaces) of the metallic binder.

A flux material may be used to purify a metallic or other binder (e.g., by reacting with binder surface oxides to form slags) during melting and subsequent infiltration. The flux may be uniformly distributed throughout molten infiltration binder during melting and subsequent infiltration to allow increased points of contact with the binder. Increased contact with the binder may allow 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.

According to some embodiments, a metallic starting material may be infiltrated with a metallic infiltrant to form at least a portion of a mill cutting structure. For instance, the metallic starting material may be infiltrated to form a support structure for one or more cutting elements. The metallic starting material may include, for example, steel or 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, or zirconium). The metallic starting material may include stainless steel, cobalt, nickel, or low expansion alloys (e.g., 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 58% Fe and 42% Ni), or a Fe-Ni-Cr alloy (e.g., an alloy with 42% Ni, 6% Cr, and remaining balance Fe)). The metallic starting material may include refractory metals (e.g., tungsten, molybdenum, or vanadium), or a mixture of metallic materials (including one or more of those disclosed herein) having selected ratios to provide desired properties of strength and/or toughness for a milling tool or a downhole cutting tool. The metallic starting material may include Co/Ni base alloys containing various alloying elements depending on the corrosion or wear resistance requirements. Particles such as STELLITE 6® powders, or other materials/powders composed of Co alloyed with one or more of Cr, W, C, Ni, Fe, Si, Mn, or Mo, or INCONEL 728® alloy powders, or other powders or materials composed of Ni alloyed with, for example, one or more of less than 35% by weight Cr, less than 15% by weight Fe, less than 15% by weight Mo, less than 6% by weight Nb,

less than 20% by weight Co, less than 1.5% by weight Mn, less than 1% by weight Cu, less than 2% by weight Al, less than 3% by weight Ti, less than 0.6% by weight Si, less than 0.2% by weight C, less than 0.02% by weight S, less than 0.02% by weight P, or less than 0.01% percent by weight B are also some examples of some suitable starting materials. According to some embodiments of the present disclosure, the metallic starting powder or material 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.

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 1000 °C (1830 °F), 1050 °C (1920 °F), 1100 °C (2010 °F), 1200 °C (2190 °F), 1300 °C (2370 °F), 1400 °C (2550 °F), or 1500 °C (2730 °F). For example, a metallic starting material may include a metal or metal alloy having a melting temperature within a range having lower and/or upper limits including any of 1050 °C (1920 °F), 1100 °C (2010 °F), 1200 °C (2190 °F) 1300 °C (2370 °F), 1400 °C (2550 °F), 1500 °C (2730 °F), 1600 °C (2910 °F), 1700 °C (3090 °F), 1800 °C (3270 °F), 1900 °C (3450 °F), 2000 °C (3630 °F), 3000 °C (5430 °F), or 3500 °C (6330 °F), where any value may be used as a lower or upper limit. In other embodiments, the melting temperature of the metallic starting material may be less than 1000 °C (1830 °F) or greater than 3500 °C (6330°F).

In some embodiments, a metallic starting material may include a mixture of a first metallic material and an additive material. The additive material may provide a desired property to the first metallic material. 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 or to reduce rust formation in the milling/cutting, or other downhole tool. A 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 metal infiltrant to form a support structure of a mill cutting structure may be low carbon alloyed steel having a carbon content of less than 2% percent by weight.

According to some embodiments of the present disclosure a metallic starting material may be loaded in powder form into a region of a mold. Optionally, the mold may include one or more pre-formed hard material bodies, and the metallic starting material may be placed at least partially around the pre-formed hard material bodies. In some embodiments, the metallic starting powder may have a particle size measured in a range of mesh sizes (e.g, -100+320 mesh). The term "mesh" actually refers to the size of the wire mesh used to screen the particles. For example, "40 mesh" indicates a wire mesh screen with 40 holes per linear inch, where the holes are defined by the crisscrossing strands of wire in the mesh. The hole size is determined by the number of meshes per inch and the wire size. Mesh sizes referred to herein are standard U.S. mesh sizes. For example, a standard 40 mesh screen has holes

such that particles having a dimension less than 420 μm can pass through the mesh screen while particles having dimensions greater than 420 μm are restricted from passing through, and are retained on the mesh 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 efficient determination of particle size distribution. Example mesh sizes for particles (e.g., metallic starting material particles/powders) 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.

In some embodiments, no particles with dimensions outside the specified mesh size may be included in the starting material. In other embodiments, however, some particles outside the specified mesh size may be included. For instance, in some embodiments, fewer than 20%, fewer than 10%, fewer than 5%, fewer than 2%, fewer than 1%, fewer than 0.5%, fewer than 0.1%, or fewer than 0.01% of the total particles may be outside the specified mesh size.

Metallic starting material particles may have a mono-modal, bi-modal, or multi-modal particle size distribution, depending on the materials being used and the mill cutting structure support being formed. Further, metallic starting material 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." The shape factor (SF) may be determined by the expression:

$$SF = \frac{\sqrt{4\pi A}}{L}$$

where A is the cross-sectional area of the particle and L is the circumference length around the cross-section. According to some embodiments of the present disclosure, the shape factor of metallic starting material particles may be greater than 0.65. For instance, the shape factor of metallic starting material particles may be within a range having lower and/or upper limits including any of 0.65, 0.75, 0.8, 0.85, 0.9, 0.95, or 1.0, where any value may be a lower or upper limit. In other embodiments, the shape factor may be less than 0.65.

In some example 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 over or around one or more pre-formed hard material bodies. For instance, the metallic starting material particles may be placed in one or more selected regions of a mold, or within the entire mold and around or over one or more pre-formed hard material bodies of a mill cutting structure. Further, metallic starting material having spherical or otherwise shaped particles may have a mono-modal or bi-modal distribution. In such embodiments,

upon infiltration, a portion of the mill (e.g., a mill cutting support structure) formed with 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 50% would mean that half of the starting material particles are in contact with other starting material particles.

According to some embodiments of the present disclosure, a mill cutting structure formed as disclosed herein may be formed of a metal matrix composite material (e.g., a metallic starting material infiltrated with a metallic infiltrant having a lower melting point than the metallic starting material). The mill cutting structure may have a mean free path between metallic starting material particles of less than 60 microns (μm). For instance, the mean free path between metallic starting material particles may be within a range having lower and/or upper limits including any of 1 μm, 5 μm, 10 μm, 15 μm, 20 μm, 25 μm, 35 μm, 45 μm, 50 μm, or 60 μm, where any value may be a lower or upper limit. In other embodiments, the mean free path between metallic starting material particles may be less than 1 μm or greater than 60 μm. In some embodiments, the contiguity of the metallic starting material particles may be less than 20%, and within a range having lower and/or upper limits including any of 2%, 5%, 10%, 15%, 20% percent, or any value therebetween. In other embodiments, the contiguity may be less than 2% or more than 20%.

The metallic starting material may be positioned adjacent to at least one hard material body to form one or more metal matrix composite regions of a mill cutting structure support. One or more metal matrix composite regions, i.e., regions formed of metallic starting material infiltrated with an infiltrant having a lower melting point than the metallic starting material, may form, for example, greater than 80% by volume, greater than 90% by volume, greater than 95% by volume, or even 100% by volume of a mill cutting structure support. In some embodiments, the metal matrix composite regions may be less than 80% by volume of the mill cutting support structure.

In some example embodiments of mill cutting structures (e.g., mill cutting structures formed entirely of one or more cutting elements arranged on a support), a mold having the negative shape of the mill cutting structure may have one or more pre-formed hard material bodies loaded therein. For instance, the pre-formed hard material bodies may be in a position corresponding with a cutting portion of the mill cutting structure. The entire remainder of the mold is optionally filled with metallic starting material and an infiltrant (and optionally metal additive material and/or flux). In such embodiments, the resulting mill cutting structure support may have its entire volume formed of a metal matrix composite material of embodiments of the present disclosure. In some embodiments, less than the entire remainder of a mold may be filled with metallic starting material and an infiltrant (and optionally metal additive material and/or flux) over and/or around one or more pre-formed hard material bodies.

In some embodiments, additional components or one or more transition layers of carbide powder of a mill cutting structure may be added to the mold.

The term "hard material body" may be used in description of the process or method of making a mill cutting structure, or the result of such process. In some embodiments, upon formation of the mill cutting structure, the hard material body may be referred to as a "cutting element." Thus, the terms "hard material body" and "cutting element" may be used interchangeably, depending on the stage of infiltration. A gauge protection element may also be a hard material body in some embodiments. A cutting element (or pre-formed hard material body) may be formed from a hard material, for example, a carbide material such as a metal carbide (e.g., tungsten carbide or titanium carbide), a diamond material (e.g., synthetic diamond or thermally stable polycrystalline diamond ("TSP")), or other ultrahard material such as cubic boron nitride ("CBN"), etc. For example, according to embodiments of the present disclosure, cutting elements may be formed of at least one of WC, TiC, TaC, NbC, diamond, CBN, other ultrahard materials, and mixtures thereof, such as WC(TiCTaCNbC), with a suitable binder material, such as cobalt. In embodiments having tungsten carbide cutting elements, the mill cutting structure may be formed by loading one or more tungsten carbide pre-formed hard material bodies into a mold or other support for facilitating formation of the cutting structure. The tungsten carbide pre-formed hard material bodies may be pre-formed by sintering tungsten carbide, e.g., crushed or cast tungsten carbide, with a binder, e.g., cobalt binder, into a desired shape. Other embodiments may use different types of transition metal carbide and/or different types of binder to form sintered carbide pre-formed hard material bodies, which may act as the cutting elements of an infiltrated mill cutting structure.

Infiltration methods of the present disclosure may include providing metallic material, including a metallic infiltrant and a metallic starting material to be infiltrated, adjacent to one or more pre-formed hard material bodies, heating the metallic material and pre-formed hard material body assembly to an infiltration temperature, and cooling the assembly, where upon solidification, the assembly forms a mill cutting structure having one or more cutting elements arranged on a metal matrix composite support (the metallic starting material infiltrated with the infiltrant). For example, the assembly may be provided in a mold, where the mold has one or more pre-formed hard material bodies set on or therein, and is filled with a powdered metallic starting material fully or partially including a metal or metal alloy. A metallic starting material having a metal or metal alloy composition (e.g., steel or other metal alloys having less than 2% by weight carbon or other metallic starting materials including those described herein) may in some embodiments form greater than 80% by volume, greater than 90% by volume, greater than 95% by volume, or even 100% by volume of the starting material to be infiltrated in methods of making a mill cutting structure by infiltration according to some embodiments of the present disclosure. For example, in some embodiments, prior to infiltration, an entire volume of a mill cutting structure may be formed of metallic starting material (not including any pre-formed hard

material bodies). In the same or other embodiments, prior to infiltration, an entire volume of one or more regions of a mill cutting structure may be formed of metallic starting material (not including any pre-formed hard material bodies). In still other embodiments, less than the entire volume of a mill cutting structure (or a region thereof) may be formed of metallic starting materials.

In some embodiments, a metallic binder infiltrant may be poured over the powdered starting material and within the mold, placed as solid blocks or as a powder into the mold, or otherwise added to the metallic starting materials in the mold. The contents of the mold (including the hard material bodies, powdered starting material, and metallic binder infiltrant) may then be heated to an infiltration temperature. The infiltration temperature may be between the solidus temperature of the powdered metallic starting material and the melting temperature of the metallic binder infiltrant, such that the infiltrant melts and infiltrates through the powdered metallic starting material. By keeping the infiltration temperature lower than the solidus temperature of the starting material (which may be higher than the melting temperature of the metallic binder infiltrant), the starting material may remain un-melted through the infiltration process, which in some embodiments may reduce or even prevent self-sintering of the starting material.

Infiltration methods according to some embodiments of the present disclosure may also or instead include infiltrating a mill cutting structure or other contents of a mold (e.g., by heating the contents of a mold to an infiltration temperature such that an infiltrant melts and infiltrates starting material) in an unpressurized environment. The unpressurized environment may be under atmospheric or ambient pressure, or in a vacuum under a low pressure environment. For instance, the unpressurized or low pressure environment may be at a pressure having lower or upper limits including any one or more of 10^{-3} torr, 10^{-4} torr, 10^{-5} torr, 10^{-6} torr, 10^{-8} torr, 10^{-10} torr, 10^{-11} torr, or values therebetween. In some embodiments, infiltration may be carried out in a reduced oxygen environment, e.g., flushing a chamber holding a mold assembly with inert gas such as argon or nitrogen using a vacuum system. In other embodiments, infiltration may occur by infiltrating under atmospheric pressure in an endothermic gas environment. Heating may be performed using a variety of techniques and equipment, including vacuum heating, microwave furnace heating, induction heating, or other direct or indirect heating. Infiltrating according to embodiments of the present disclosure in a reduced oxygen environment may avoid non-wetting of the infiltrant during infiltration. Following an infiltration process, contents of a mold may then be cooled to solidify the metallic binder and form the mill body. In other embodiments, and as discussed in greater detail herein, an infiltration process may include additive manufacturing or other manufacturing techniques that may or may or may not include a mold.

Turning now to FIG. 1-1, a cross-sectional view of a mold assembly 100-1 for use in an infiltration process is shown according to some embodiments of the present disclosure. The mold assembly 100-1 may include a mold 102-1 having the general negative shape of a mill cutting structure and contents 104-1, 106-1, 108-1 provided therein. For example, FIG. 1-1 shows the cross-section of a mold 102-1

having a negative shape of a mill cutting structure with a cutting region 110-1 and a support region 112-1. In some embodiments, the cutting region 110-1 include one or more pre-formed hard material bodies 104-1 having a predetermined size and shape. The one or more pre-formed hard material bodies 104-1 may be positioned within the cutting region 110-1 of the mold 102-1, and located at positions corresponding to the locations of where the cutting elements are to be positioned in a milling cutting structure. One or more regions of metallic starting material 106-1 may be placed or otherwise loaded into the mold 102-1 and located adjacent the pre-formed hard material body 104-1. As shown, the metallic starting material 106-1 may interface with the pre-formed hard material body 104-1. In some embodiments, the interface may be planar along a single surface of the pre-formed hard material body 104-1; however, in other embodiments, the metallic starting material 106-1 may interface along more than one surface of a hard material body (e.g., to partially surround a hard material body on multiple sides or surfaces, and potentially each surface other than a cutting surface). Further, in some embodiments, metallic starting material 106-1 may interface along one or more non-planar surfaces of a pre-formed hard material body 104-1 (e.g., to form a curved or other non-planar interface, to form an interlocking geometry interface, etc.).

In at least some embodiments, an infiltrant 108-1 may be placed or otherwise loaded into the mold 102-1 and optionally layered or otherwise positioned over the metallic starting material 106-1. In some embodiments, the infiltrant 108-1 may be a metallic infiltrant. Optionally, flux (not shown) may be provided with or in addition to the infiltrant 108-1. The contents 104-1, 106-1, 108-1 of the mold 102-1 may then be heated to an infiltration temperature. In some embodiments, the infiltration temperature is below the solidus temperature of the metallic starting material 106-1 and greater than or equal to the melting temperature of the infiltrant 108-1. The contents of the mold 102-1 may then cool. Upon solidification, the contents of the mold 102-1 form an infiltrated mill cutting structure having at least one cutting element (e.g., pre-formed hard material body 104-1) supported by a metal matrix composite support (e.g., metallic starting material 106-1 infiltrated by infiltrant 108-1). According to some embodiments, selecting features such as the heating technique and profile (e.g., maximum temperature, how quickly to heat to the maximum temperature, how long to stay at the maximum temperature, etc.), the cooling technique and profile (e.g., air cooling or quenching, how quickly to cool, etc.), post heating treatments (e.g., tempering, etc.), and the like, the pre-formed hard material bodies 104-1 and the support region 112-1 can affected and desired properties can be obtained.

The infiltrant 108-1 may be provided adjacent to the metallic starting material 106-1 in an amount sufficient to infiltrate the entire layer of metallic starting material 106-1 without any layer of infiltrant 108-1 remaining on or above the metallic starting material 106-1, or with merely a thin layer of infiltrant 108-1 remaining over the metallic starting material 106-1. In embodiments having a thin layer of infiltrant 108-1 remaining over the metallic support (formed of the layer of metallic starting material 106-1 after infiltration), the remaining layer of infiltrant 108-1 may form less than 35%, less

than 25%, less than 20%, less than 15%, less than 10%, less than 5%, less than 2%, less than 1%, or less than 0.5% of the volume, weight, or height of the support region 112-1. In some embodiments, a remaining layer of infiltrant 108-1 may be machined off.

The metallic starting material 106-1 may include any number of different types of metallic starting materials. For instance, the metallic starting material 106-1 may include different material compositions, different particle sizes, different size distributions such as mono-modal and bi-modal, different shapes, other variations, or combinations of the foregoing. In some embodiments, different starting materials 106-1 (e.g., powders) may be located in different regions of the mold to provide different material properties to the different regions of the mold 102-1. For example, a first starting material may be a first type of starting material (e.g., steel particles) having a selected particle size, size distribution, and shape (e.g., spherical, ellipsoidal, irregular, etc.). A second starting material may be of the same or different type of starting material, and may have the same or a different particle size, size distribution, or shape. Each different starting material may have one or more differences in material properties (e.g., hardness, toughness, erosion resistance, melting or solidus temperature, etc.).

In at least some embodiments, two or more different starting materials (e.g., two or more powdered metallic starting materials) may be mixed together and placed or otherwise loaded into the mold 102-1. In yet other embodiments, two or more different starting materials may be integrated together using additive manufacturing techniques, as discussed in more detail herein. When the contents of the mold 102-1 are heated to the flow or infiltration temperature of the infiltrant 108-1, the melted infiltrant 108-1 flows through and infiltrates the starting materials 106-1 within the mold 102-1 and bonds particles of the starting material 106-1 to each other and to any other components (e.g., pre-formed hard material body 104-1) to form a solid mill cutting structure. In other words, each region of starting material 106-1 within the mold (e.g., one region of a metallic starting material, two or more regions of different metallic starting materials, etc.) may be bonded together by the same infiltration material (or combination of materials). In some embodiments, the infiltrant 108-1 flows through the starting material 106-1 relatively homogenously. For instance, where multiple starting materials are used, the ratio of the infiltrant 108-1 to a first starting material and the ratio of the infiltrant 108-1 to a second starting material may be substantially the same within corresponding regions. Thus, in embodiments having two or more regions of different starting materials, the starting material 106-1 may be infiltrated with an infiltrant 108-1 during the infiltration process, such that the different regions are integrally formed together. Likewise, embodiments having a single starting material 106-1 may have an infiltrant 108-1 substantially uniformly distributed throughout the starting material 106-1.

Further, in embodiments having two or more different starting materials, the infiltration temperature may be lower than the solidus temperature of each starting material and greater than or equal to the melting temperature of the infiltrant 108-1. 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 starting material, depending on the composition of the starting materials, and greater than or equal to the melting temperature of the infiltrant 108-1.

In at least some embodiments, the infiltrant 108-1 may flow through and infiltrate the starting material 106-1 to bond the starting material 106-1 to the pre-formed hard material body 104-1. In such embodiments, the infiltrant 108-1 may not infiltrate the pre-formed hard material body 104-1, may not significantly infiltrate the pre-formed hard material body 104-1, or may not infiltrate the pre-formed hard material body 104-1 in a manner that is homogenous with the infiltration of the starting material 106-1. Regardless of the extent of infiltration of the pre-formed hard material body 104-1, the infiltration process may bond the pre-formed hard material body 104-1 to the support region 112 formed of the infiltrated starting material 106-1. In some embodiments, rather than the material 104-1 being a pre-formed hard material body of a specified shape and size, the material 104-1 may be a powder or have another form, and may be located at regions in the mold 102-1 which correspond to cutting element or cutting locations of a mill cutting structure. Optionally, the material 104-1 may have different properties than the starting material 106-1. Infiltration using the infiltrant 108-1 may then be used to infiltrate both the starting material 106-1 and the material 104-1. The infiltrant 108-1 may be heated to a temperature equal to or above the melting temperature of the infiltrant 108-1, but below the solidus temperature of one or both of the starting material 106-1 or the material 104-1. Upon cooling, the particles of the starting material 106-1 may be bonded together, the particles of the material 104-1 may be bonded together, and the starting material 106-1 and the material 104-1 may be integrally bonded together.

FIG. 1-2 is a cross-sectional view of another example embodiment of a mold assembly 100-2 for use in an infiltration process. The mold assembly 100-2 may be generally similar to the mold assembly 100-1 of FIG. 1-1, and may include a mold 102-2 having the general negative shape of a mill cutting structure. Contents of the mold 102-2 may include pre-formed hard material bodies 104-2, starting material 106-2, and infiltrant 108-2. Rather than layering each of the materials 104-2, 106-2, 108-2 (see FIG. 1-1), one or more of the materials 104-2, 106-2, 108-2 may overlap in the mold 102-2. For instance, the one or more pre-formed hard material bodies 104-2 may be partially embedded in the starting material 106-2. Optionally, the infiltrant 108-2 may be fully or partially within the starting material 106-2. Infiltration may then occur as discussed herein to form a cutting region 110-2 and a support region 112-2. In the orientation shown in FIG. 1-2, the support region 112-2 may extend past the upper surface of the pre-formed hard material bodies 104-2 to support (and be bonded to) upper and side surfaces of the pre-formed hard material bodies 104-2. While FIG. 1-2 illustrates the infiltrant 108-2 as masses of material within the starting material 106-2, this embodiment is illustrative. In other embodiments, for instance, the infiltrant 108-2 may be layered on the starting material 106-2. In still other embodiments, particles of the starting material 106-2 may be coated with the infiltrant 108-2.

Although shown somewhat schematically in FIGS. 1-1 and 1-2, a mold 102-1, 102-2 may have a negative shape that may vary depending on the mill cutting structure being formed. The mold may be made of graphite or other materials, and in some embodiments, at least a portion of the inner walls of a mold may be coated. A coating such as a refractory metal or boron nitride may be used, for instance, to reduce carbon additions from the graphite mold during infiltration. In other embodiments, the inner walls of a mold may remain uncoated.

While FIGS. 1-1 and 1-2 relate to the use of a mold to form a mill cutting structure, according to some embodiments of the present disclosure, metallic starting material may be built into a structure using other manufacturing processes. FIGS. 2-1 to 2-3, for instance, illustrate an example additive manufacturing process, which may be representative of 3D printing, simultaneous casting, binder jetting, laser metal deposition, electron beam melting, direct metal laser sintering, selective laser sintering, fused deposition modeling, or the like. In at least some embodiments, an additive manufacturing process may be automated or fully or partially manually performed. In some embodiments, the additive manufacturing process may occur prior to infiltrating the starting material. For example, an additive manufacturing assembly 200 may include a deposition device 214 used to form a mill cutting structure by depositing sequential volumes or layers of selected starting material 206 in designated regions on a support structure 216. The additive manufacturing assembly 200 may include a support 216 on which the mill cutting structure may be formed. A supply system 218 may provide access to starting materials in a powder or other form, and a guide system 220 may be used to guide the deposition device 214 when positioning layers of the starting material 206. The guide system 220 may include physical supports, microprocessors, memory devices, user interfaces, or any other components that may be used to guide or control movement of the deposition device 214.

When layering the starting material 206, a binder or adhesive may be used to bind the multiple sequential layers together. For example, the binder may be mixed with the starting material prior to being deposited by the deposition device 214, the binder may be applied through a separate nozzle of the deposition device 214 and simultaneously applied with the starting material 206, or a layer of the binder may be deposited between layers of the starting material 206. 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.

According to some embodiments, a metallic starting material structure may be built upon one or more pre-formed hard material bodies 204. As shown in FIGS. 2-1, for instance, the one or more pre-formed hard material bodies 204 may be positioned on the support structure 216, which optionally may include cavities, tabs, or other features that facilitate placement of the pre-formed hard material bodies 204. The deposition device 214 may then be used to sequentially build layers of starting material 206 (see FIGS. 2-2 and 2-3), and the starting material 206 and the one or more pre-formed hard material bodies 204 may have a combined shape substantially corresponding with the final shape

of the mill cutting structure to be formed upon completion of the formation and infiltration process. In other embodiments, the starting material 206 and the one or more pre-formed hard material bodies 204 may have a combined shape substantially corresponding with a final shape of a portion of a mill cutting structure, to allow attachment, bonding, or other coupling with one or more additional features of a mill cutting structure. For example, a starting material 204 and one or more pre-formed hard material bodies 204 may have a combined shape substantially corresponding with a final shape of a mill cutting structure support having cutting elements arranged thereon, where the infiltrated mill cutting structure support with cutting elements may be attached to a blade or other portion of a downhole cutting tool.

Upon forming a structure of starting material 206 (see FIG. 2-3) using additive manufacturing, the starting material 206 may be infiltrated, as described herein. For example, a structure of starting material 206 having at least one region formed with a metallic starting material may be infiltrated with an infiltrant by applying an infiltrant to the starting material 206, heating the infiltrant to an infiltration temperature lower than the solidus temperature of the starting material 206 and greater than or equal to the melting temperature of the infiltrant, such that the infiltrant infiltrates through the starting material 206. Optionally, the infiltrant may be applied during the additive manufacturing process (e.g., by the deposition device 214) as layers of the starting material 206 are formed. In other embodiments, the infiltrant may be applied to the structure formed by the starting material 206 after formation of the structure. In some embodiments, the starting material 206 may be infiltrated in the presence of a carbon source, such as graphite. Forming starting material 206 into a suitable shape and configuration using additive manufacturing may form one or more regions of a mill cutting structure, for example, an entire support of a mill cutting structure.

The additive manufacturing assembly 200 may be any suitable device capable of fabricating a structure from the starting material 206, or for forming a mold (e.g., molds 102-1, 102-2 of FIGS. 1-1 and 1-2) in which starting material is infiltrated. The additive manufacturing assembly 200 may use a CAD or other model as a template/guide. Suitable commercially available additive manufacturing assemblies capable of assembling starting material structures or molds include S-MAX, S-PRINT, M-PRINT, M-FLEX, and X1-LAB, marketed by The ExOne Company, of North Huntingdon, PA.

FIG. 3 shows a mill cutting structure 322 that may be formed using infiltration method according to embodiments of the present disclosure. The mill cutting structure 322 may include, for example, a mill blade or knife formed by providing metallic materials, including a metallic infiltrant and a metallic starting material to be infiltrated, adjacent to a plurality of pre-formed hard material bodies. The metallic materials and pre-formed hard material bodies may be part of an assembly or structure that is heated to an infiltration temperature, and the assembly may subsequently be cooled. Heating may melt the infiltrant and cooling may allow the infiltrant to solidify. Upon solidification, the assembly may form the mill cutting structure 322 having a plurality of cutting elements 304 arranged on a metal matrix composite body or support 312 (the metallic starting material infiltrated with the infiltrant).

In the embodiment shown, the mill cutting structure 322 includes a longitudinally extending blade 324, the upper end portion of which has an opening 326 acting as a pivot point. A pin or shaft (not shown) may be positioned in opening 326 and may couple the mill cutting structure 322 to a downhole milling tool (see FIG. 7). In the illustrated embodiment, the opening 326 is situated in a necked portion of the blade 324, which broadens out to a main or cutting portion 328 of the blade 324, where a radially inner side portion 330 may link to a rib 332. In some embodiments, the rib 332 may have a generally triangular cross-sectional shape. The rib 332 and/or the radially inner side portion 330 may in some embodiments define a cam surface which can be used to pivot the blade 324 about the opening 326 to selectively expand or retract the mill cutting structure 322.

A lower part of the blade 324 may be configured to engage and mill casing, cement, or some other structure. In some embodiments, the blade 324 includes an L-shaped cutout at the lower surface. This cutout may define a lower edge portion 334, which may be the portion or region of the blade 324 that initially contacts or cuts the structure being milled. The lower edge portion 334 may be adjacent a cutting portion 336 which assists in the milling process. In particular, the cutting portion 336 may include multiple cutting elements 304 arranged on the support 312. The cutting elements 304 may be located along a leading or front surface of the blade 324, i.e. facing forwardly in the direction of rotation of the mill cutting structure 322, and forming at least a portion of the cutting portion 336 of the mill cutting structure 322. The cutting elements 304 may be bonded to the support 312 by an infiltration process such as those disclosed herein. For instance, the support 312 may be a metal matrix composite with a metal infiltrant material that partially forms the metal matrix composite.

In the embodiment shown, the cutting elements 304 are positioned in multiple radially extending rows, with rows being positioned axially one above the other. The rows may be adjacent each other, and the cutting elements 304 of adjacent rows (or adjacent cutting elements 304 within a same row) may contact each other, or may be separated some distance from adjacent cutting elements 304. Optionally, the rows of cutting elements 304 may be staggered with respect to adjacent rows. For instance, odd numbered rows starting from the lower edge 334 and extending upwardly in the longitudinal direction may include cutting elements 304 which generally align with one another, while the even numbered rows may include cutting elements 304 which generally align with one another. The cutting elements 304 of the odd numbered rows may be offset from the cutting elements 304 of the even numbered rows by about half the radial length of a cutting element, thereby forming a "brickwork" pattern. In other embodiments, however, cutting elements may be positioned in other arrangements, including, for example, non-linear arrangements and spaced apart arrangements. Further, while the illustrated cutting elements 304 are shown as being generally rectangular, in other embodiments the cutting elements may have other shapes, including cylindrical, triangular, tooth-shaped, other regular or irregular shapes, or combinations of the foregoing.

According to some embodiments, at least the support 312 portion of the blade 324 may be formed of a metal matrix composite material (i.e., a metallic starting material infiltrated with an infiltrant) according to infiltration methods disclosed herein. For example, in some embodiments, an entire blade (e.g., support 312, cutting portion 328, rib 332, the neck portion, etc.) may be formed of a metal matrix composite material. Further, in some embodiments, one or more regions of a mill cutting structure 322 may be formed with different infiltrated or metal matrix composite materials. For example, the mill cutting structure 322 may include the plurality of cutting elements 304 on the support 312 of the blade 324, and the support 312 may be formed of a first metal matrix composite, and a remaining region (e.g., cutting portion 328, rib 332, neck portion, etc.) of the blade 324 may be formed of a different metal matrix composite or other material. In some embodiments, infiltrated or metal matrix composite materials may be coupled to other materials (e.g., steel), such that a portion of the blade 324 may be formed of an infiltrated or metal matrix composite material (e.g., support 312), while another portion may be formed of a non-infiltrated or non-metal matrix composite material (e.g., rib 332).

"Metal matrix composite" regions forming mill cutting structures according to embodiments of the present disclosure may include at least some amounts of non-metallic materials. For instance, small amounts of non-metallic materials may be introduced as impurities due to manufacturing conditions, interstitial alloying constituents, carbon diffusion from a mold during infiltration, other conditions, or combinations of the foregoing. As non-metallic material may enter during infiltration, formation, or other processes, an infiltrated metallic region may have a greater weight percent 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 the "metal matrix composite" region formed from infiltrating the metallic starting material may have at least 97% by weight of the material composition formed of one or more metal components. In other embodiments, the metallic starting material may be at least 90% by weight metal components, and the metal matrix composite region may be at least 88% by weight metal components. In still another embodiment, the metallic starting material may be at least 95% by weight metal components, and the metal matrix composite region may be at least 92% or at least 94% by weight metal components. The difference in percentage by weight between the metal matrix composite region and the metallic starting material may be less than 0.5% in some embodiments. For instance, in some embodiments, one or more metal matrix composite regions forming a mill cutting structure may be made by infiltrating a steel starting material with a metal alloy infiltrant. The steel may have a carbon interstitial alloying constituent of less than 1% by weight, and less than 1% by weight carbon may diffuse into the one or more metallic regions during infiltration, and the one or more metallic regions may have less than 0.5% by weight of non-metal impurities.

In some embodiments, low temperature infiltration may be conducted in a carbon rich environment, such as in a graphite mold, in a mold made with carbon containing material, or using a

carbon source such as graphite provided with the infiltrant, 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 mill cutting structure with an integrally formed outer shell having a hardness greater than a portion of the mill cutting structure not within the CAZ. The outer shell may also maintain toughness and ductility from the infiltrated metallic composition (from the infiltration temperature being low enough to avoid formation or precipitation of carbides.

According to embodiments of the present disclosure, a CAZ may have up to 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 an infiltration process according to embodiments 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%, 6.7 wt%, 7 wt%, or 10 wt%, where any limit may be used in combination with any other limit. For instance, a CAZ may have 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%. A ratio of 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 be within a range having lower and/or upper limits that include any of 1:1.5, 1:5, 1:10, 1:15, 1:20, 1:25, 1:30, 1:40, or 1:50. 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 3.0 wt%, an increase of 15 times (or a starting to ending weight percent ratio of 1:15). In another 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 1.5 times (or a starting to ending weight percent ratio of 1:1.5). In other embodiments, the starting to ending weight percent ratio may be less than 1:1.5 or greater than 1:50. Further, according to embodiments of the present disclosure a CAZ may be formed along one or more outer regions of a generally metallic mill cutting structure support (or tool body), 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 1 wt% carbon, the one or more CAZs may form less than 10 vol% of the infiltrated metallic mill cutting structure support.

Carburization from a carbon source (e.g., a carbon containing mold material or other carbon source) to a mill cutting structure assembly ready for infiltration 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, the amount of carbon in the carbon source and material composition of the mill cutting structure assembly may be controlled. An 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 carbon source (e.g., mold material in embodiments having a mill cutting structure assembly infiltrated in a mold) and heating time may affect how much carbon is transported. According to some embodiments of the present disclosure, parameters of infiltrating a generally metallic mill cutting structure support, including starting material composition (e.g., amount of carbon initially present in the starting material), carbon source composition (e.g., amount and/or structure of carbon in a mold or other carbon source), infiltration temperature (including any intermediate temperatures the mill cutting structure assembly is heated to for carbon diffusion), and time the mill cutting structure 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 mill cutting structure) 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 inch (1.3 mm) from an outer surface of a mill cutting structure. In some embodiments, the CAZ region may extend a depth from an outer surface of a mill cutting structure that is within a range including lower and/or upper limits including any of 0.01 inch (0.3 mm), 0.03 inch (0.8 mm), 0.05 inch (1.3 mm), 0.1 inch (2.5 mm), 0.5 inch (12.7 mm), 0.6 inch (15.2 mm), 0.75 inch (19.1 mm), 1 inch (25.4 mm), or any depth therebetween. For instance, the CAZ depth may be between 0.03 inch (0.8 mm) to 1 inch (25.4 mm) or between 0.05 inch (1.3 mm) and 0.75 inch (19.1 mm). In other embodiments, the depth of the CAZ region may be less than 0.01 inch (0.3 mm) or greater than 1 inch (25.4 mm).

In some embodiments, carburization may be controlled so that the CAZ includes composite metallic particles with a gradient hardness from the center toward the outer boundary of each composite metallic particle. For example, a metallic starting material may be selected where upon diffusion of carbon from a carbon source, 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. The gradient

hardness may increase or decrease from the center toward the outer boundary, depending on the embodiment.

According to some embodiments of the present disclosure, a mill cutting structure (e.g., mill cutting structure 322) may be formed by infiltrating metallic starting material (e.g., having at least 98% by weight of at least one metal and/or metal alloy) with an infiltrant at an infiltration temperature less than the solidus temperature of the metallic starting material and greater than or equal to the melting temperature of the infiltrant. The metallic starting material may be loaded into at least one region of a graphite mold of the mill cutting structure and optionally over and/or around at least one pre-formed hard material body. The at least one region of metallic starting material may form, in some embodiments, at least 80% by volume of the infiltrating space of the mold (e.g., the space or volume of the mold excluding the volume filled with pre-formed hard material bodies). The metallic starting material may be positioned adjacent at least a portion of an inner wall of a mold. During infiltration, carbon from the carbon source (e.g., graphite mold) may diffuse into the metallic starting material adjacent 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. In other embodiments, the portion of the infiltrating space in the mold filled by the at least one region of metallic starting material may be within a range including lower and/or upper limits including any of 40%, 50%, 60%, 70%, 80%, 90%, 100%, or any value therebetween. 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 herein and surrounded with a carbon source, such as a graphite powder.

The size and hardness of the composite metallic particles in the CAZ may at least partially be a function of infiltration temperature and time. In some embodiments, the hardness of the composite metallic particles in the CAZ may be between 110% and 300% (between 1.1 and 3.0 times greater than) the hardness of the material in an interior region of an infiltrated metallic body on the HRC scale. For example, in some embodiments, the hardness in the CAZ may be between HRC 30.5 and 40.0 (306 and 392 HV), where HRC refers to the hardness on the C scale of the Rockwell hardness test, and HV refers to the hardness on the Vickers hardness scale. Optionally, the hardness in the interior region may be between HRC 19.5 and 20.0 (234 and 238 HV), and the CAZ may thus have a hardness that is between 150% and 205% the hardness of the interior region of the infiltrated metallic body, on the HRC scale (or between 130% and 170% on the HV scale). In other embodiments, the hardness in the CAZ may be between HRC 29.0 and 30.0 (294 and 302 HV) and the hardness in the interior region may be between HRC 24.5 and 25.5 (263 and 269 HV). As a result, the hardness of the CAZ may be between 115% and 125% the hardness of the interior region on the HRC scale (or between 110% and 115% on the HV scale). According to some embodiments of the present disclosure, the hardness in a CAZ may be within a range including upper and/or lower limits including any of HRC 15, 17.5, 20,

22.5, 25, 27.5, 30, 32.5, 35, 37.5, 40, 42.5, 45 (213, 228, 238, 251, 266, 283, 302, 323, 345, 368, 392, 418, 446 HV), or values therebetween. For instance, the hardness in the CAZ may be between HRC 15 and 45 (213 and 446 HV), between HRC 20 and 40 (238 and 392 HV), or between HRC 25 and 35 (266 and 345 HV). In still other embodiments, the hardness in the CAZ may be less than HRC 15 (213 HV) or greater than HRC 45 (446 HV), or the hardness of the composite metallic materials in the CAZ may be less than 110% or greater than 300% the hardness of the interior region on the HRC scale. The difference between the hardness of the CAZ and the interior region may also vary as will be appreciated in view of the differences in hardness as described herein.

In some embodiments of the present disclosure, a metallic starting material (and non-carburized infiltrated metallic particles) may have a hardness within a range including lower and/or upper limits including any of 50, 80, 100, 200, 300, 400, 600, 800 HV (HRC <0, <0, <0, 11, 29.7, 40.8, 55.3, 64), or any values therebetween, where HRC 0 is about equal to 160 HV. After carburization from infiltration, composite metallic particles may have a hardness within a range including lower and/or upper limits including any of 100, 200, 300, 400, 500, 750, 900, 1000 HV (HRC <0, 11, 29.7, 40.8, 49.1, 62.2, 67, 68.6), or any values therebetween. For example, after carburization, composite metallic particles may have a hardness between 100 and 1000 HV (up to HRC 68.6) or between 100 and 750 HV (up to HRC 62.2). 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 includes lower and/or upper limits including any of 1:1, 2:1, 3:1, 4:1, 5:1, 8:1, 10:1, or any values therebetween. For instance, such a hardness ratio may be between 1:1 and 10:1, between 2:1 and 10:1, between 2:1 and 8:1, or between 3:1 and 5:1. In still other embodiments, the described hardness ratio of the exterior of a particle compared to the center may be less than 1:1 (i.e., the center may be harder), or greater than 10:1.

According to embodiments of the present disclosure, composite metallic particles may have a particle hardness gradient, where a center hardness is within a range having lower and/or upper limits including any of 50, 80, 100, 200, 300, 400, 600, 800 HV (HRC <0, <0, <0, 11, 29.7, 40.8, 55.3, 64), or any values therebetween, and an exterior hardness is within a range having lower and/or upper limits including any of 100, 200, 300, 400, 500, 750, 900, 1000 HV (HRC <0, 11, 29.7, 40.8, 49.1, 62.2, 67, 68.6), or any values therebetween. As discussed herein, a hardness may decrease from the exterior of the particle toward the center of the particle. For example, composite metallic particles may have a particle hardness gradient with a center hardness within a range between 80 and 200 HV (HRC <0 and 11) and an exterior hardness within a range between 500 and 1000 HV (HRC 49.1 and 68.6), and a decreasing hardness from the exterior toward the center.

In some embodiments, at least one region of a cutting structure support or an entire cutting structure support 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, and other materials having greater than 10% by weight formed 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. "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 instead of cermet starting material, to form the non-metallic regions. Regions of a cutting structure support that are not formed 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.

Carbide starting materials may include a powder or other form 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 including vanadium carbide, chromium carbide, titanium carbide, tantalum carbide, niobium carbide, silicon carbide, aluminum carbide, other transition metal carbides, or combinations of the foregoing, may be used. In yet other embodiments, one or more of a carbide, oxide, or 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 with a carbide, cermet, or ceramic material.

Some embodiments may have two or more different starting materials forming different regions of the cutting structure support. In at least some such embodiments, 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 (e.g., tungsten carbide or another transition metal carbide). Additionally, in some embodiments having at least one metallic starting material and a cermet starting material, at least one starting material may be a transition starting material. The transition starting material may include a mixture of metallic starting material and cermet starting material, and may be located between the metallic starting material and the cermet starting material. In some embodiments, an entire mill cutting structure support may be formed of one or more non-metallic regions, where one or more regions of a non-metallic starting material, such as tungsten carbide or other transition metal carbide, is infiltrated adjacent to (and potentially forming an interface with) at least one pre-formed hard material body.

By using infiltration methods of the present disclosure to form mill cutting structures, material properties of the starting material and infiltrant may be designed and selected for different regions of the cutting structure and/or according to the volume and type of pre-formed hard material bodies used to form cutting elements. For example, the material properties of one or more metal matrix composite regions of a mill cutting structure may be designed by selecting the starting material composition (e.g., starting materials having a selected initial amount of carbon), the type of carbon source (if any), provided during infiltration (e.g., infiltrating in a mold made with carbon containing material such as graphite or graphite and sand, or in 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 mill cutting structure assembly during infiltration at selected temperatures.

As discussed herein, in some embodiments, one or more pre-formed hard material bodies may be positioned with the metallic or non-metallic or non-metallic starting materials and heated during infiltration of the starting materials. A pre-formed hard material body (or cutting element or gauge protection element) may be distinguished from the starting materials in various manners. For instance, a pre-formed hard material body may have a higher hardness than the starting materials before or after an infiltration process. By way of illustration, a starting materials or a support formed by infiltrating the starting materials may have a hardness between HRC 11 and 53 (200 and 560 HV, and the pre-formed hard material bodies may have a hardness between HRC 56 and 70 (613 and 1076 HV). In still further example embodiments, the pre-formed hard material bodies may have a larger size than particles of the starting materials. For instance, as discussed herein, the particles may have a mesh size, which in some embodiments may result in the starting material particle size to be between 0.0015 in. (38 μm or 400 mesh) and 0.079 in. (2000 μm or 10 mesh). In some embodiments, the average width, length, or thickness of a pre-formed hard material body may be at least 300% the maximum size of the starting material particles, and in some embodiments up to or greater than 2000% the maximum size of the starting material particles. For instance, a pre-formed hard material body may have a width of 0.5 in. (12.7 mm), which may be 630% the maximum size of a 10 mesh particle. In other embodiments, the ratio of the size of a pre-formed hard material body to a maximum size of the starting material particles may be within a range having lower and/or upper limits including any of 300%, 500%, 750%, 1000%, 1500%, 2000%, or values therebetween. In some embodiments, however, such a ratio may be less than 300% or greater than 2000%.

According to at least some embodiments, the pre-formed hard material bodies may further be distinguished from particles of the starting materials in the manner in which they interact with the infiltrant or binder. For instance, during infiltration, the infiltrant may infiltrate the starting materials

to bond the starting materials to each other. In contrast, in at least some embodiments, the infiltrant may not bond the pre-formed hard material bodies to each other, but instead to the starting materials or support structure.

Referring now to FIG. 4-1, a cross-sectional view of another example of a mill cutting structure 422-1 is shown according to embodiments of the present disclosure. The mill cutting structure 422-1 may include a matrix composite support 412-1 (formed by infiltrating starting metal, ceramic, or cermet material with an infiltrant according to infiltration methods disclosed herein) and a plurality of cutting elements 404-1 arranged on the matrix composite support 412-1. Each cutting element 404-1 may, in this embodiment, include a flank face 438, a trailing face 440, a front face 442 extending from the flank face 438 to the trailing face 440, and a plurality of teeth 444 (or ridges) formed in the front face 440. The cutting elements 404-1 may be bonded to the matrix composite support 412-1 at a planar interface 446-1 during infiltration of the matrix composite support 412-1. In other embodiments, however, one or more cutting elements may be bonded to a matrix composite support non-planar, interlocking, or other types of interfaces, or along multiple planar or non-planar surfaces.

FIG. 4-2, for instance, is a cross-sectional view of another mill cutting structure 422-2 according to embodiments of the present disclosure. The mill cutting structure 422-2 may include a support (e.g., matrix composite support 412-2 formed by infiltrating starting material with an infiltrant) and a plurality of cutting elements 404-2 arranged on the matrix composite support 412-2. Each cutting element 404-2 may have a flank face 438, a trailing face 440, a front face 442 extending from the flank face 438 to the trailing face 440, and a plurality of teeth 444 (or ridges) formed in the front face 442. The cutting elements 404-2 may be positioned adjacent each other such that the flank face 438 of a cutting element 404-2 is in full or partial contact with the trailing face 440 of an adjacent cutting element 404-2.

As further shown in FIG. 4-2, the cutting elements 404-2 may be bonded to the matrix composite support 412-2 at a non-planar interface 446-2 (e.g., during infiltration of the matrix composite support 412-2). In the embodiment shown, the non-planar interface 446-2 includes a dovetail-type interlocking geometry. In particular, the dovetail geometry may increase in width moving away from the front face 442, and the matrix composite support 412-2 may have a corresponding recess to receive the dovetail geometry. Such geometry may make it difficult to delaminate or remove the cutting elements 404-2 as the dovetail geometry restricts and potentially prevents not only longitudinal movement (e.g., left-to-right or right-to-left in FIG. 4-2), but also movement away from the matrix composite support (e.g., upward movement in FIG. 4-2).

A dovetail is one type of interlocking geometry, but interfaces having interlocking geometries may be formed in various other manners. Regardless of the particular structure of the interlocking or non-planar interface 446-2, the non-planar interface 446-2 may be formed, for example, by positioning starting material adjacent to the non-planar geometry of the cutting elements 404-2 (e.g., by pouring

or otherwise placing powdered starting material around the interlocking geometry while in mold, by depositing starting material around the interlocking geometry during an additive manufacturing process). The starting material may then be infiltrated with an infiltrant to form the matrix composite support 412-2 (e.g., metal matrix composite support infiltrated with a metal infiltrant) and to bond the pre-formed hard material bodies (e.g., cutting elements 404-2) to the matrix composite support 412-2 at the non-planar interface 446-2. Other non-planar interfaces (e.g., curved, undulating, protrusions, depressions in the geometry) and other interlocking geometries are within the scope of this disclosure.

For example, FIG. 4-3 shows another example of a mill cutting structure 422-3 having a plurality of cutting elements 404-3 bonded or otherwise coupled to a matrix composite support 412-3. In the illustrated embodiment, each cutting element 404-3 has a front face 448 opposite a non-planar interface 446-3 between the cutting element 404-3 and the matrix composite support 412-3. One or more side surfaces 450 may the periphery of the cutting element 404-3 and extend fully or partially from the front face 448 to the non-planar interface 446-3. In the embodiment shown, the non-planar interfaces 446-3 is shown as having one or more curved features; however, in other embodiments, non-planar interfaces may have other curved or defined profiles, e.g., a convex or concave profile.

FIG. 4-3 further illustrates an example embodiment in which the cutting elements 404-3 may be at least partially embedded in the matrix composite support 412-3. In particular, at least a portion of the side surfaces 450 may be bonded to the matrix composite support 412-3 in some embodiments. The side surfaces 450 may be planar or non-planar. For instance, the cutting elements 404-3 may have a generally cylindrical shape similar to shear cutters which are configured to use an edge between the front face 448 and the cylindrical side surface 450 cut or otherwise degrade casing, formation, cement, or other materials during a milling or drilling process. Whether planar, cylindrical, or having some other construction, the side surface 450 may include other features. For instance, one or more depressions 452 or protrusions 453 (shown in dotted lines) may be formed in the side surface 450. Where the side surface 450 is cylindrical, the depression 452 or protrusion 453 may extend partially around the circumference of the cutting element 404-2, or it may extend fully around the circumference and have an annular shape. The side surface 450 may also include multiple depressions 452 or protrusions 453 at different heights above the interface 446-3. Further, although depressions and protrusions are shown in FIG. 4-3, in other embodiments additional or other features may include curved surfaces, detents, or other features which may be planar, non-planar, interlocking, have other characteristics, or any combination of the foregoing.

While the cutting elements 404-2 may be shear cutting elements, cutting elements of embodiments of the present disclosure may have other configurations. For instance, cutting elements may have: a generally cylindrical shape and/or a circular cutting edge; conical or other pointed face surfaces; frusto-conical face surfaces; semi-round face surfaces; domed face-surfaces; toothed or ridged face surfaces; other shaped face surfaces; or combinations of the foregoing. In the same or other

embodiments, a cutting element may be used or designed to cut by shearing, gouging, face milling, turning, or combinations of the foregoing.

FIG. 4-4 shows another example of a mill cutting structure 422-4 having a plurality of cutting elements 404-4, 404-5 bonded or otherwise coupled to a matrix composite support 412-4. In the illustrated embodiment, each cutting element 404-4, 404-5 has a front face 448, 449, respectively, opposite a non-planar interface 446-4 between the respective cutting element 404-4, 404-5 and the matrix composite support 412-4. In the embodiment shown, the non-planar interfaces 446-4 is shown as having a concavely curved profile; however, in other embodiments, non-planar interfaces may have other curved profiles, e.g., a convex profile, multiple concave and/or convex profiles, sinusoidal wave profiles, curved and linear profiles, or combinations of the foregoing.

In the example embodiment of FIG. 4-4, the cutting elements 404-4, 404-5 may be embedded in the matrix composite support 412-4. In particular, the front surfaces 448, 449 may be about even with, or offset radially within, the top or other surface of the matrix composite support 412-4. A full portion of the side surfaces of the cutting elements 404-4, 404-5 may be bonded to the matrix composite support 412-4 in some embodiments. In other embodiments, however, the front surfaces 448, 449 may be radially offset outward from the top, front, or other surface of the matrix composite support 412 and partially embedded therein. Optionally, the front surfaces 448, 449 may be substantially flush with the top or other surface of the matrix composite support 412-4 during manufacture, but such configuration may change during use. For instance, a portion 413 of the matrix composite support 412-4 may wear away to expose a portion of a side surface of the cutting element 404-5.

In the illustrated embodiment, the cutting elements bonded to the matrix composite support 412-4 may include multiple different profiles. In particular, one or more cutting elements 404-4 may have a first profile, and one or more cutting elements 404-5 may have a second profile. One or more other cutting elements may also have third, fourth, or other profiles. In some embodiments, the cutting elements 404-4, 404-5 may be pre-formed with their respective, differing profiles when bonded to the matrix composite support 412-4. In other embodiments, however, the cutting elements having the second profile 404-5 may be pre-formed to have the first profile, but then may be modified or subsequently processed after bonding to the matrix composite support 412-4. For instance, the illustrated cutting element 404-5 may have had the same profile as the cutting elements 404-4, but the front surface 448 may have been cut or otherwise modified to form the front surface 449. For instance, laser etching, laser cutting, electric discharge machining (EDM), or other techniques may be used to cut or otherwise modify the front surfaces 448, 449. In some embodiments, each cutting element 404-4 may be modified to form a cutting element 404-5, although in other embodiments a subset of cutting elements 404-4 may be modified. According to at least some embodiments, heating the cutting elements 404-4, 404-5 during bonding to the matrix composite support 412-4 (or cooling after heating) may degrade or otherwise have undesired effects on surfaces of the cutting elements 404-4, 404-5. In

some embodiments, modifying the surface of the cutting elements 404-4, 404-5 after bonding to the matrix can reduce or even remove heat affected zones, the impacts of thermal shock, and the like.

As should be appreciated by a person having ordinary skill in the art upon review of the disclosure herein, use of infiltration methods of the present disclosure to form mill cutting structures may allow a relatively more complicated interface geometry to be formed between a cutting element and matrix composite support when compared with interfaces formed using conventional brazing techniques of attaching a cutting element to a support. For example, interfaces formed between a cutting element and a matrix composite using methods disclosed herein may have a combination of one or more planar, curved or non-planar geometries forming a non-planar geometry (e.g., interlocking geometry) that may not otherwise be formed using conventional brazing techniques of attaching a cutting element to a support. Although more complicated interface geometries may be formed in some embodiments using infiltration methods of the present disclosure, some embodiments may have other interface geometries (e.g., planar, curved or other non-planar geometries) formed using infiltration methods of the present disclosure, and which are similar to interface geometries used in conventional brazing.

Further, using infiltration methods of the present disclosure to form a mill cutting structure may provide improved bonding or other coupling between a cutting element and a support when compared with conventional brazing techniques used to attach cutting elements to supports. For example, FIG. 5 shows a micrograph of a cutting element 504 brazed to a support 512. In between the cutting element 504 and the support 512 is a braze material 508, which couples the cutting element 504 to the support 512. As shown, porosity 554 may occur within the braze material 508 due, for example, to the type of braze material, the brazing process used, the amount of braze used, the care/attention by a person performing the braze process, the braze temperature, and the like. Porosity 554 may weaken the attachment between the cutting element 504 and the support 512. In contrast, FIG. 6 shows a micrograph of a cutting element 604 bonded and coupled directly to a support 612 using an infiltration process in accordance with embodiments of the present disclosure. The support 612 is formed of a matrix composite having a plurality of particles 606 (e.g., metallic particles) bonded together (and potentially within) an infiltration binder 608 (e.g., a metallic binder). The support 612 was formed by infiltrating starting material (forming metallic particles 606) with an infiltrant (forming infiltration binder 608) according to infiltration methods described herein. Upon infiltrating and forming the support 612 adjacent the cutting element 604, the infiltration binder 608 bonds the support 612 to the cutting element 604, resulting in a stronger attachment compared to conventional brazing methods.

In some embodiments, material properties and/or attachment of the cutting elements to a support can be facilitated through additional or other techniques. For instance, a cutting element (e.g., cutting element 604) may have a coating applied thereto. The coating may be used to improve bonding strength and/or protect the cutting element in some manner. For instance, where the coating may protect surfaces of the cutting element from damage or other effects of cooling, heating, thermal shock,

and the like. Any suitable coating may be applied. For instance, in some embodiments, a nickel coating on a carbide cutting element may protect carbide surfaces. In some embodiments, the grade of materials used for the cutting element (e.g., carbide grades) may affect how heating, cooling, or other processes affect the cutting element.

Infiltrating a starting material with an infiltrant having a lower melting temperature to form a mill cutting structure according to embodiments of the present disclosure may also suppress self-sintering of the starting material and potentially preserve the particle size of the starting material. When self-sintering occurs, starting particles sinter together and the infiltrant may not infiltrate around individual particles of the starting material. Thus, rather than forming an infiltrated material microstructure (particles of starting material within a matrix of infiltration binder) according to some embodiments of the present disclosure, a non-uniform microstructure including partially sintered together particles of the starting material may be formed using other methods. Nevertheless, in some embodiments of the present disclosure, the infiltrant may have a melting temperature above, or near, the solidus temperature of the starting material, or at least some self-sintering may occur during infiltration.

An infiltrated support formed according to methods disclosed herein may have improved material properties over a conventionally formed support. For example, in some embodiments, a mill cutting structure may include at least one cutting element bonded or otherwise coupled to a support made of a plurality of metallic particles interspersed with an infiltration binder. The support may, in some embodiments, have material properties including a yield strength between 40 ksi (275 MPa) and 70 ksi (480 MPa), an ultimate tensile strength between 60 ksi (415 MPa) and 100 ksi (690 MPa), elongation between 5% and 16%, and hardness between HRC 18 (230 HV) and HRC 35 (345 HV). Regions of a generally metallic support may be designed to have selected material compositions such that desired material properties are provided to different regions of the support. For example, a first metallic starting material having a greater hardness than a second metallic starting material may be loaded into a first region of a mold of the support, while the second metallic starting material may be loaded into a second region of the mold.

	Conventionally formed steel before brazing (one sample)	Conventionally formed steel before brazing (multiple samples)	Infiltrated steel support
Yield strength (ksi)	75	64 – 77	40 – 70
Ultimate tensile strength (ksi)	95	85 – 90	60 – 100
Elongation (%)	20	16 – 22	5 – 16
Maximum Hardness	22 HRC / 248 HV	7.5 – 10 HRC (12 if quenched and tempered)	18 – 35 HRC

Table 1

Table 1 shows examples of material properties for conventionally formed supports (before and after brazing one or more cutting elements thereto) and infiltrated metallic supports formed according

to some infiltration methods disclosed herein. In the samples of conventionally formed mill cutting structures having one or more cutting elements brazed to a steel support, the lower values of yield strength and hardness presented in Table 1 correspond with the regions of the support that are close to the brazing area.

Mill cutting structures according to embodiments of the present disclosure may be used in downhole cutting tools such as a shown in FIG. 7. A cross-sectional view of a downhole cutting tool 760 is shown having mill cutting structures 704 in accordance with embodiments disclosed herein. The downhole cutting tool 760 may have a body 762 extending in a longitudinal direction from an upper end 764 to a lower end 766. Optionally, the body 674 may be generally tubular and/or may have a generally circular cross-sectional shape.

The downhole cutting tool 760 may include an axial passage 768 extending fully or partially therethrough for the circulation of fluid. The upper end 764 of the body 762 may be internally threaded to define a female or box connection for connecting the body 762 to a drill string or other component of a BHA. The lower end 766 of the body 762 may also be internally threaded to define a female or box connection for connecting the body 672 to further drill string or BHA components. For instance, a stabilizer, lead mill, drill collar, bull nose, or the like may be coupled to the lower end 766. In still other embodiments, the upper and/or lower ends 764, 766 may instead have externally threaded male or pin connections, may have other connections, or may have no connections at all (e.g., the lower end 766 may not be coupled to further BHA or drill string components).

In some embodiments, the body 762 may have one or more mill cutting structures 722 (e.g., milling blades or knives) coupled thereto. For example, the downhole cutting tool 760 may have between 3 and 8 equi-azimuthally spaced mill cutting structures 722, although fewer than 3 mill cutting structures 722 or more than 8 mill cutting structures 722 may be used, or the mill cutting structures 722 may not be equally spaced about tool 760. The mill cutting structures 722 may include a support 712 bonded or otherwise coupled to one or more cutting elements 704. The cutting elements 704 may face forwardly in the direction of rotation of the downhole cutting tool 760. The downhole cutting tool 760 shown in FIG. 7 has cutting elements 704 arranged axially and radially along each support 712. Each mill cutting structure 722 is shown as radially expanded relative to the body 762. The mill cutting structures 722 may be selectively expandable in some embodiments. For instance, the mill cutting structures 722 may selectively expand or retract in response to hydraulic flow rates, hydraulic pressure, downlinking, electronic activation signals, wireless signals, other signals, or any combination of the foregoing.

As a mill blade or other mill cutting structure 722 meets a casing wall or other material, the mill cutting structure 722 can encounters severe vibrations and impacts that may lead to cracks in the cutting elements 704. Such cracks may lead to failure of the cutting elements 704, or loss of the cutting elements 704 (e.g., by delamination when attached by a brazing process). Such failure can reduce the

life of the downhole cutting tool 760 and, in some tools, may limit or prevent the tool from being used to mill a window of a desired length, to drill through a sidetracked, secondary borehole (through the earth formation) after a window is milled, or the like. In at least some embodiments, mill cutting structures 722 formed according to embodiments of the present disclosure may reduce the damage to the cutting elements, reduce the propagation of cracks, reduce loss of cutting elements, have other effects, or some combination of the foregoing.

Mill cutting structures 722 formed according to embodiments of the present disclosure may be used on other downhole tools, and the downhole cutting tool 760 is merely illustrative of example tools in which embodiments of the present disclosure may be used. Embodiments of the present disclosure further extend to use with casing mills, reamers, junk mills, window mills, drill bits, stabilizers, pipe cutter knives, hole openers, other tools (e.g., other tools used with cutting elements, gauge protection elements, or the like), or any combination of the foregoing. Further, while various examples of mill cutting structure types and shapes are described herein, the disclosure is not limited thereto. Rather, the examples should be considered as a guide for providing clarity in explaining some example mill cutting structures and methods for forming mill cutting structures according to embodiments of the present disclosure. Thus, other shapes and types of mill cutting structures may be formed using the infiltration methods of the present disclosure, for example, depending on the type of tool with which the cutting structures are used.

According to some embodiments of the present disclosure, a method of making a cutting structure includes combining cutting structure assembly components, including at least an infiltrant, a non-metallic starting material, and at least one pre-formed hard material body. The cutting structure assembly components are heated to an infiltration temperature lower than a solidus temperature of the non-metallic starting material and greater than or equal to a melting temperature of the infiltrant. In the same or other embodiments, the pre-formed hard material body may be a milling cutting element. Further, in some embodiments, the non-metallic starting material may include at least one of a cermet, a carbide, or a ceramic starting material.

While embodiments of the present disclosure have been primarily described with reference to downhole milling operations, the tools, cutting elements, cutting structures, and the like described herein may be used in applications other than milling within a wellbore. In other embodiments, devices according to the present disclosure may be used outside a wellbore or other downhole environment used for the exploration or production of natural resources. For instance, devices of the present disclosure may be used in a wellbore used for placement of utility lines, or in connection with other systems, including within automotive, aquatic, aerospace, hydroelectric, manufacturing, other industries, or even in other downhole environments. Accordingly, the terms “wellbore,” “borehole” and the like should not be interpreted to limit tools, systems, assemblies, or methods of the present disclosure to any particular industry, field, or environment.

The articles "a," "an," and "the" are intended to mean that there are one or more of the elements in the preceding descriptions. It should be understood that any directions, orientations, or reference frames in the preceding description are merely relative directions or movements. For example, any references to "up" and "down," "right" and "left," "above" or "below," and the like are merely descriptive of the relative position or movement of the related elements as illustrated or as intended during use.

Unless otherwise stated, all percentages of composition are weight percentages. Numbers, percentages, ratios, or other values stated herein are intended to include the stated value, and also other values that are "about" or "approximately" the stated value, as would be appreciated by one of ordinary skill in the art encompassed by embodiments of the present disclosure. A stated value should therefore be interpreted broadly enough to encompass values that are at least close enough to the stated value to perform a desired function or achieve a desired result. The stated values include at least the variation to be expected in a suitable manufacturing or production process, and may include values that are within 5%, within 1%, within 0.1%, or within 0.01% of a stated value. For any list of values or ranges included herein, any value may be used as an upper endpoint or limit (e.g., less than the upper limit), any value may be used as a lower endpoint or limit (e.g., at least the lower limit), or any two values may be used to define lower and upper endpoints or limits of the range.

A person having ordinary skill in the art should realize in view of the present disclosure that equivalent constructions do not depart from the spirit and scope of the present disclosure, and that various changes, substitutions, and alterations may be made to embodiments disclosed herein without departing from the spirit and scope of the present disclosure. Equivalent constructions, including functional "means-plus-function" clauses are intended to cover the structures described herein as performing the recited function, including both structural equivalents that operate in the same manner, and equivalent structures that provide the same function. It is the express intention of the applicant not to invoke means-plus-function or other functional claiming for any claim except for those in which the words 'means for' appear together with an associated function. Each addition, deletion, and modification to the embodiments that falls within the meaning and scope of the claims is to be embraced by the claims.

The present disclosure may be embodied in other specific forms without departing from its spirit or characteristics. The described embodiments are to be considered as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. Changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

CLAIMS

What is claimed is:

1. A method of making a cutting structure, comprising:

combining cutting structure assembly components, including at least:

an infiltrant;

a metallic starting material; and

at least one pre-formed hard material body; and

heating the cutting structure assembly components to an infiltration temperature lower than a solidus temperature of the metallic starting material and greater than or equal to a melting temperature of the infiltrant.

2. The method of claim 1, wherein combining cutting structure assembly components includes combining the infiltrant, metallic starting material, and at least one pre-formed hard material body within a mold, the at least one pre-formed hard material body being positioned in a region of the mold corresponding to a cutting portion.

3. The method of claim 2, wherein combining cutting structure assembly components includes positioning the metallic starting material in powdered form over the at least one pre-formed hard material body.

4. The method of any of claims 1–3, wherein combining cutting structure assembly components includes providing the metallic starting material as a support structure formed using additive manufacturing.

5. The method of any of claims 1–4, wherein the at least one pre-formed hard material body includes a hard material selected from the group consisting of carbide and diamond.

6. The method of any of claims 1–5, wherein heating the cutting structure assembly is conducted in a vacuum.

7. The method of any of claims 1–6, wherein heating the cutting structure includes bonding the at least one pre-formed hard material body to a support structure formed of the infiltrant and the metallic starting material, the method further comprising:

machining the at least one pre-formed hard material body after bonding to the support structure.

8. The method of any of claims 1–7, wherein the metallic starting material includes steel.

9. A mill cutting structure, comprising:

at least one cutting element; and

a support structure including a plurality of metallic particles interspersed with an infiltration binder, the infiltration binder coupling the at least one cutting element to the support structure without brazing.

10. The mill cutting structure of claim 9, at least 80% of a volume of the support structure including the plurality of metallic particles interspersed with the infiltration binder.

11. The mill cutting structure of claim 9 or claim 10, the support structure having a hardness gradient extending at least 0.5 inch (12.7 mm) from a portion of an outer surface of the support structure to an interior portion of the support structure, the hardness gradient having a decreasing amount of carbon from the outer surface toward the interior portion.

12. The mill cutting structure of any of claims 9–11, the plurality of metallic particles including composite metallic particles having a particle hardness gradient from a center toward an exterior of each composite metallic particle.

13. The mill cutting structure of any of claims 9–12, the infiltration binder coupling the at least one cutting element to the support structure at a non-planar interface.

14. The mill cutting structure of claim 13, the non-planar interface having an interlocking profile.

15. The mill cutting structure of any of claims 9–14, the at least one cutting element including a hard material selected from the group consisting of carbide and diamond.

16. The mill cutting structure of any of claims 9–15, the plurality of metallic particles including steel.

17. A mill cutting structure, comprising:

at least one cutting element; and

a support structure including a plurality of metallic particles interspersed with an infiltration binder, the support having material properties including:

a yield strength between 40 ksi and 70 ksi;

an ultimate tensile strength between 60 and 100 ksi;

elongation between 5% and 16%; and

hardness between HRC 18 and 35.

18. The mill cutting structure of claim 17, the at least one cutting element and the support structure having a non-planar interface therebetween.

19. The mill cutting structure of claim 17 or claim 18, the at least one cutting element being partially embedded in the support structure.

20. A method of making a mill cutting structure, comprising:

positioning one or more pre-formed hard material bodies within a manufacturing assembly;

layering a metallic starting material within the manufacturing assembly, including on an interface with the one or more pre-formed hard material bodies;

layering an infiltrant on the metallic starting material; and

heating the manufacturing assembly, including at least the metallic starting material and the infiltrant, to an infiltration temperature lower than a solidus temperature of the metallic starting material and greater than or equal to a melting temperature of the infiltrant.

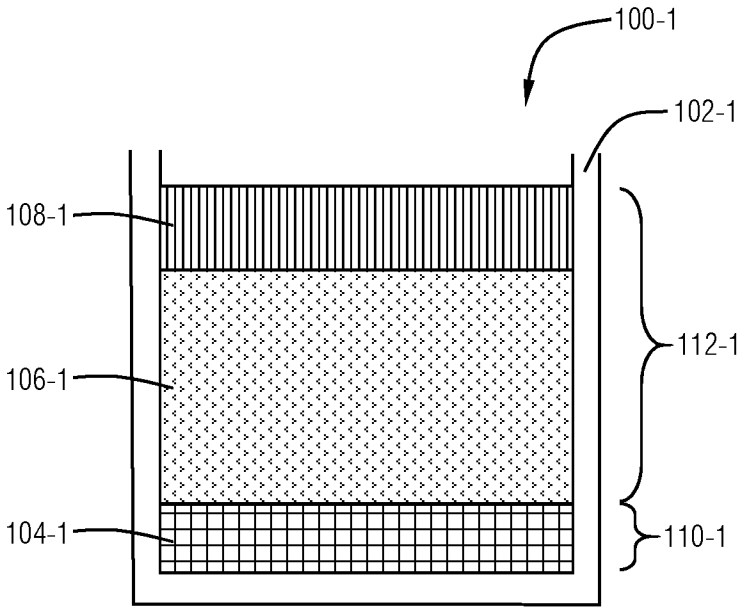

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Fig. 1-1

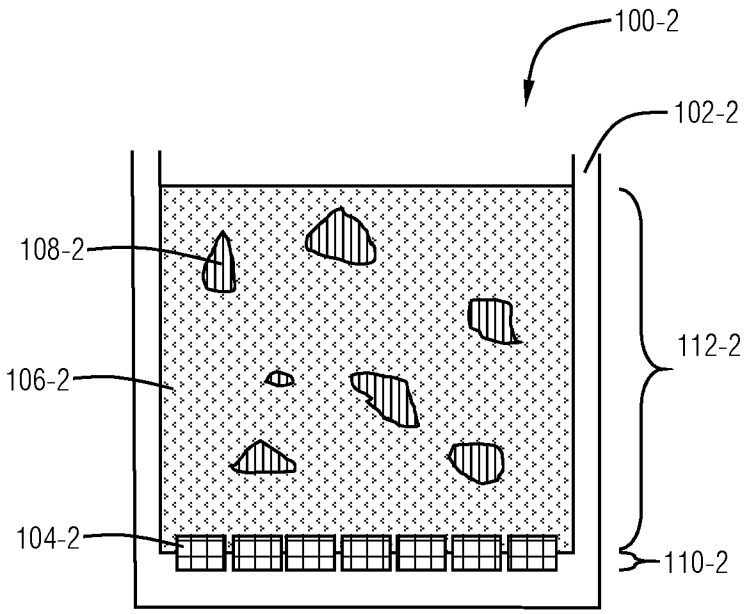

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Fig. 1-2

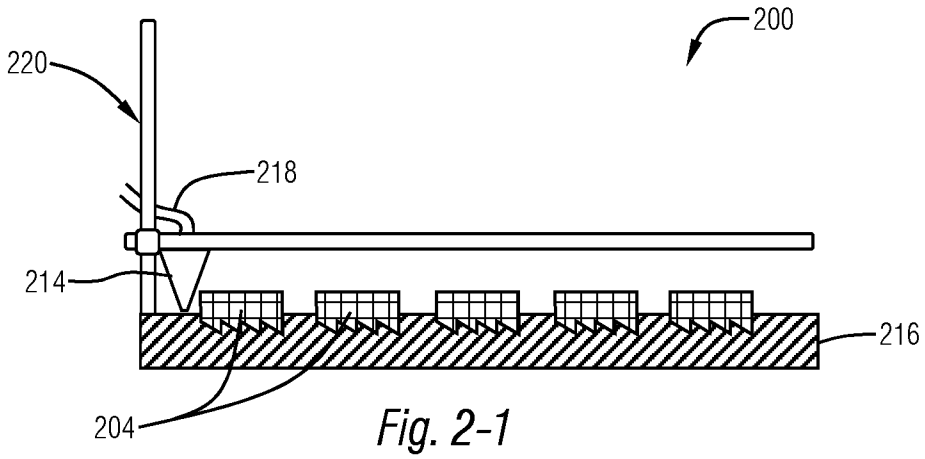


Fig. 2-1

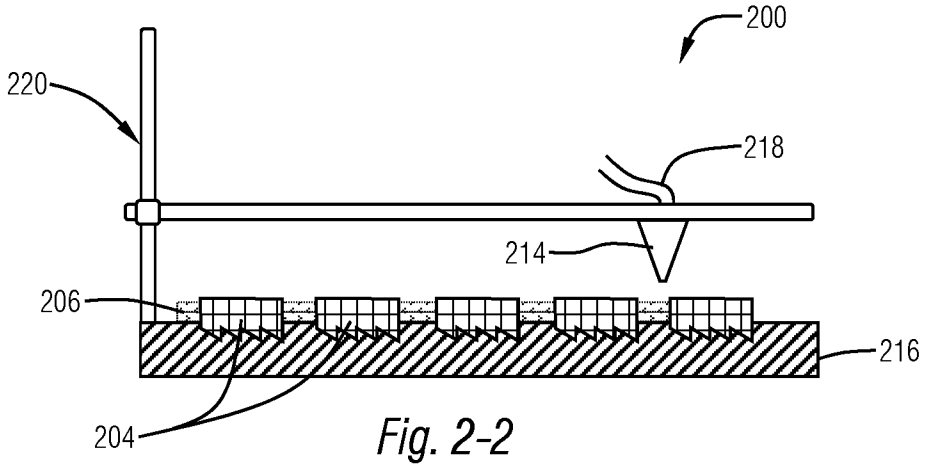


Fig. 2-2

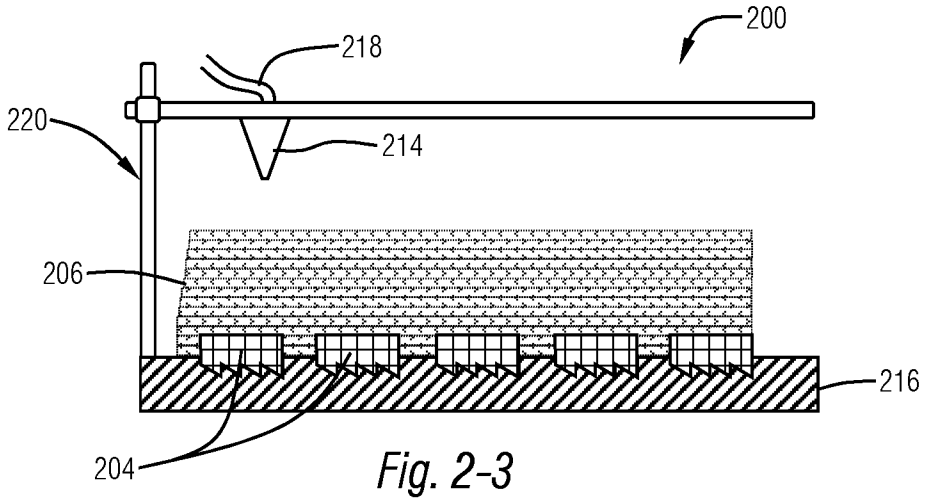


Fig. 2-3

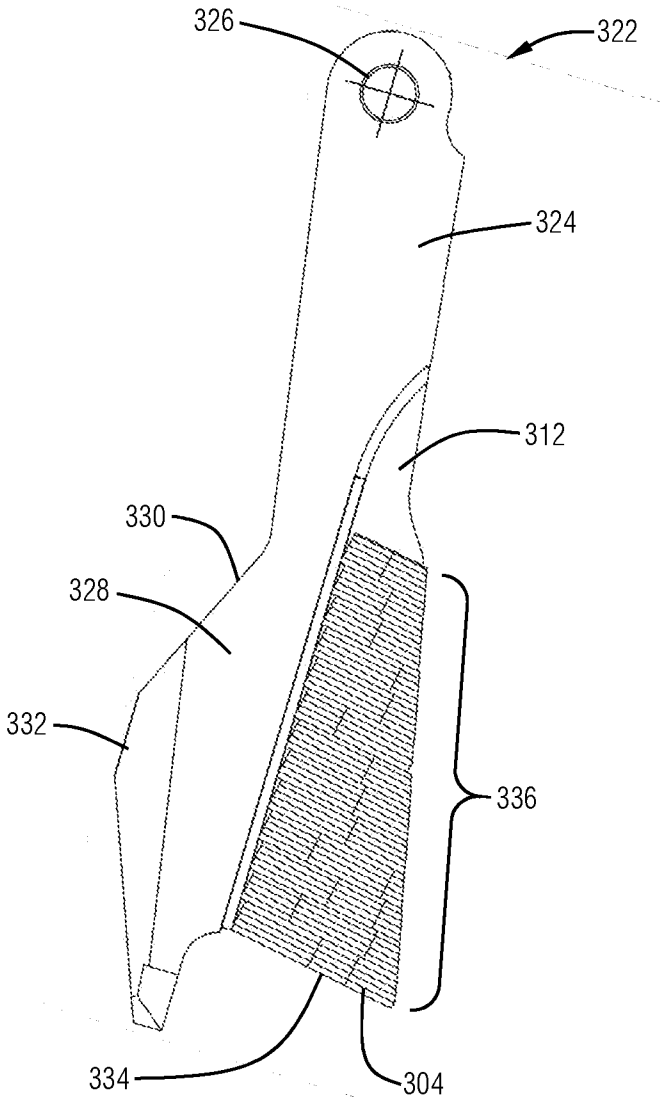

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Fig. 3

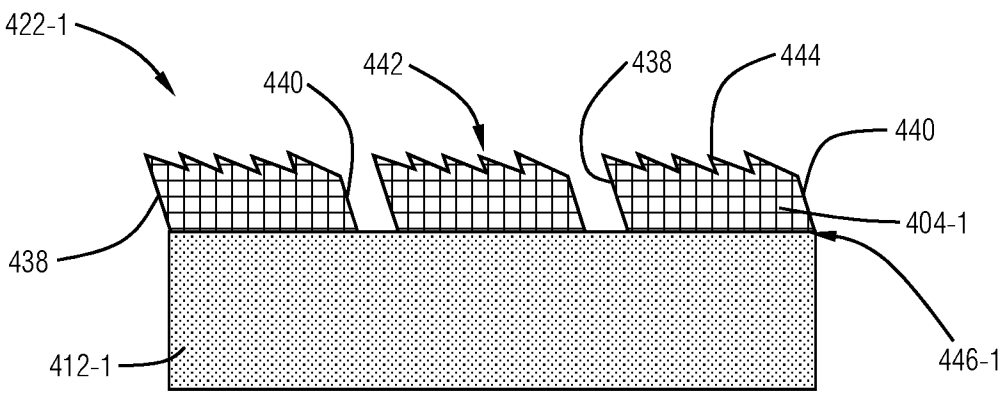

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Fig. 4-1

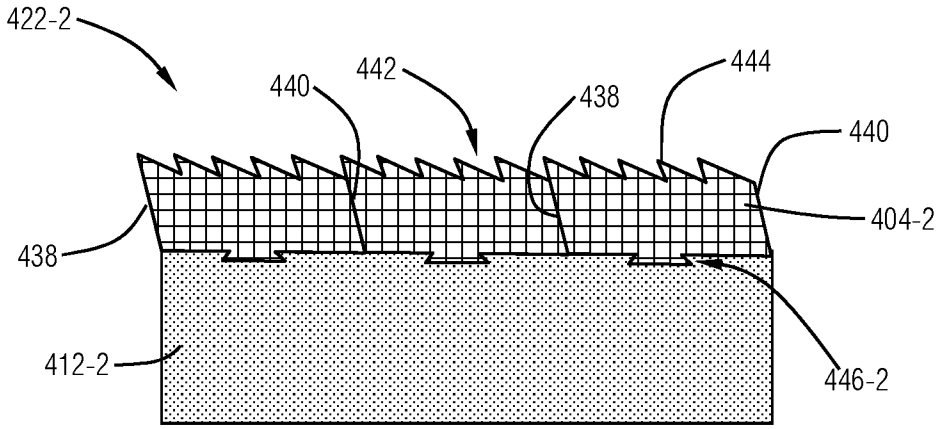


Fig. 4-2

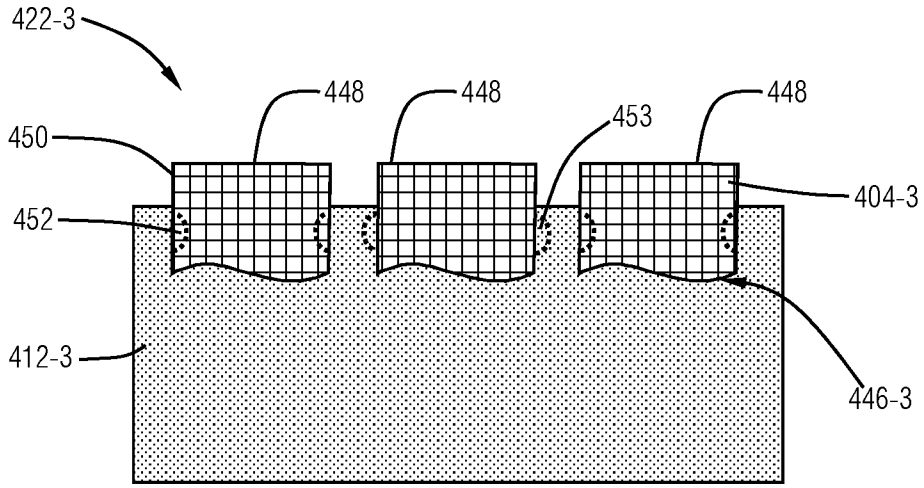


Fig. 4-3

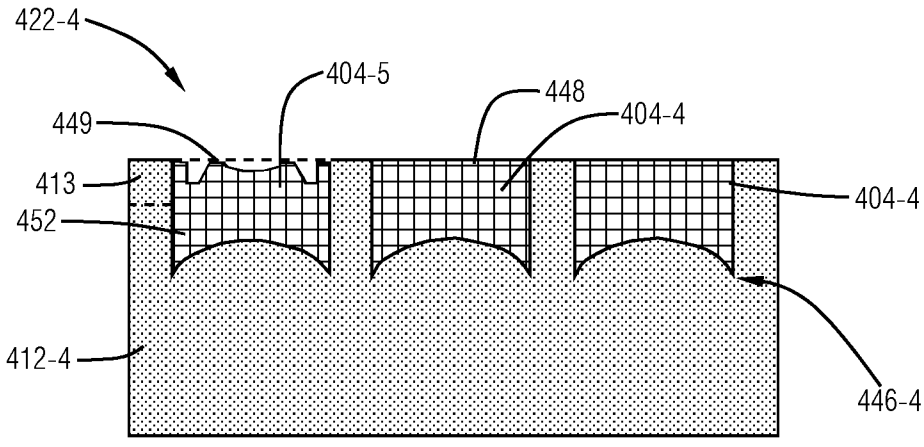


Fig. 4-4

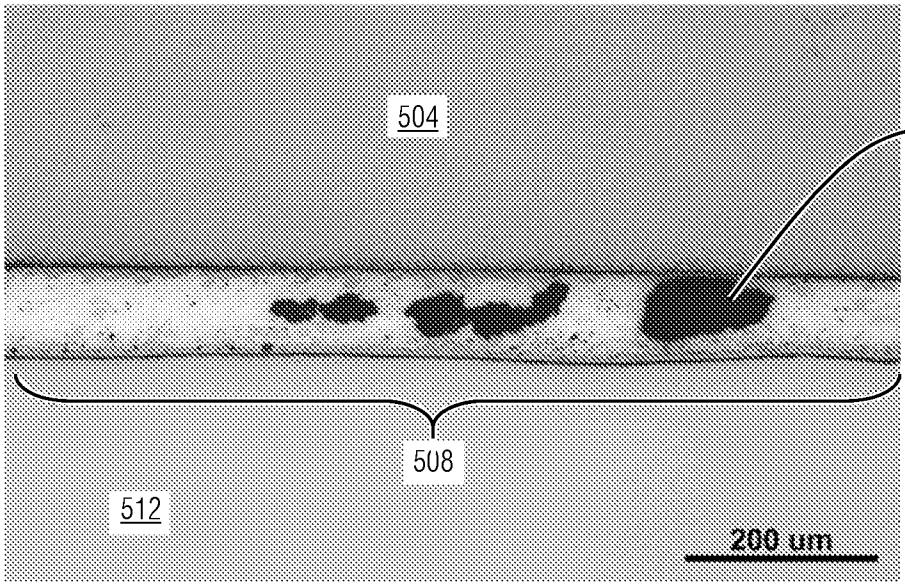


Fig. 5

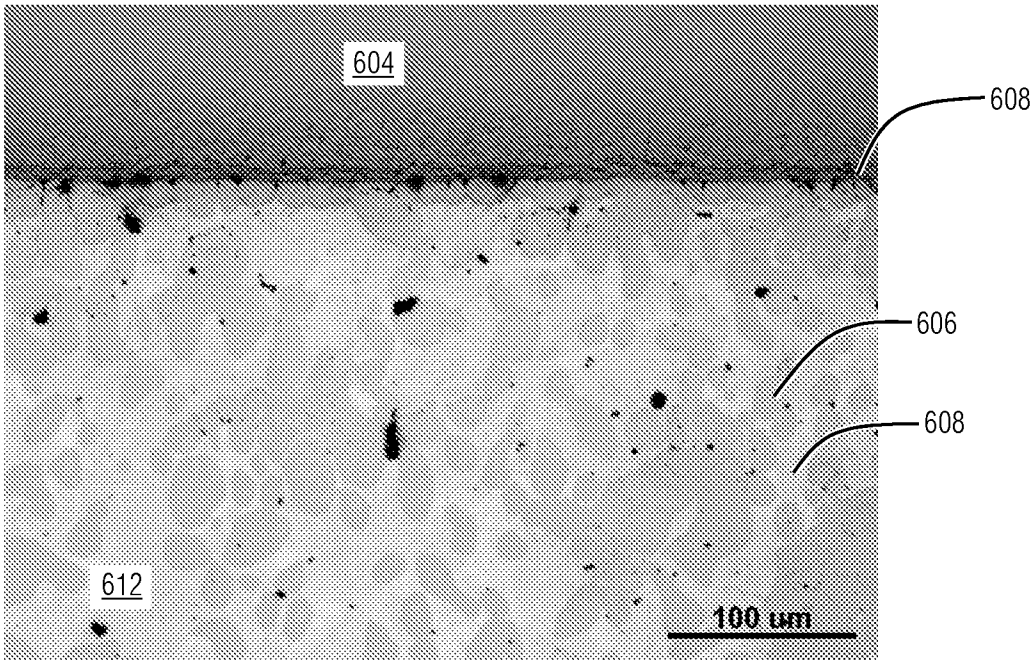


Fig. 6

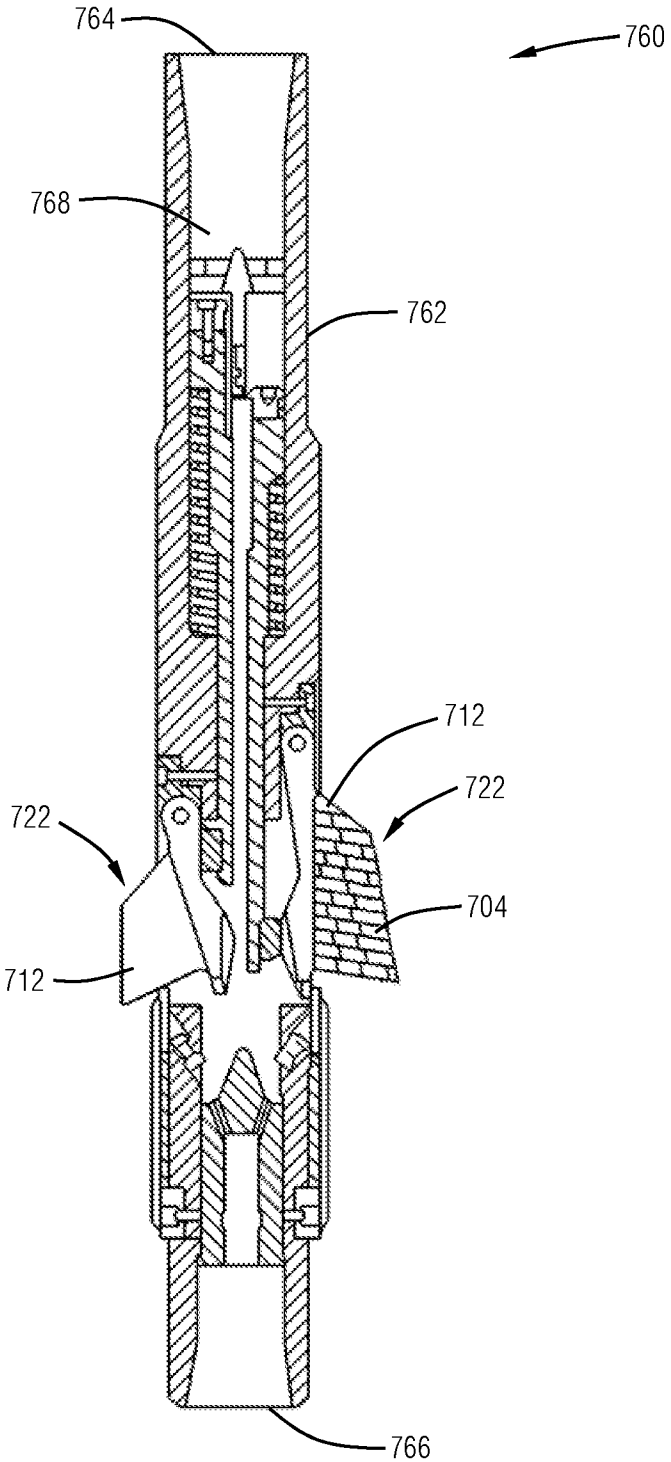


Fig. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/041810

A. CLASSIFICATION OF SUBJECT MATTER

B22F 5/00(2006.01)i, B22F 7/06(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)
B22F 5/00; B32B 9/00; E21B 10/00; C04B 35/56; E21B 10/61; B23B 27/14; B23K 31/02; B22F 7/06

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: mill, cutting, infiltrant, hard, heating, mold, support, structure,

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010-0288821 A1 (LADI et al.) 18 November 2010 See paragraphs [0040]-[0042], [0046], [0055], [0056], claim 10 and figures 1-3.	1-12,15-17,20
Y		13,14,18,19
Y	US 2010-0006345 A1 (STEVENS, JOHN H.) 14 January 2010 See paragraphs [0009], [0054] and figure 2.	13,14,18,19
A	US 2001-0000101 A1 (LOVATO et al.) 05 April 2001 See paragraph [0049] and claim 1.	1-20
A	US 2007-0092727 A1 (KOSTERS et al.) 26 April 2007 See paragraphs [0021]-[0023] and claim 1.	1-20
A	US 2014-0178139 A1 (KOREA INSTITUTE OF MACHINERY AND MATERIALS) 26 June 2014 See paragraphs [0032]-[0036] and claims 1, 13.	1-20

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

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"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
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"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
20 October 2016 (20.10.2016)	**20 October 2016 (20.10.2016)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
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