Methods of hardfacing tools include bonding PCD particles to surfaces of the tools using a metal matrix material. The PCD particles comprise a plurality of inter-bonded diamond grains. Material compositions and structures used to apply a hardfacing material to an earth-boring tool (e.g., welding rods) include PCD particles. Earth-boring tools include hardfacing material comprising PCD particles embedded within a matrix material on at least a portion of a surface of a body of the tools. Methods of forming a hardfacing material include subjecting diamond grains to elevated temperatures and pressures to form diamond-to-diamond bonds between the diamond grains and form a PCD material. The PCD material is broken down to form PCD particles that include a plurality of inter-bonded diamond grains. Methods of hardfacing tools include bonding PCD particles to surfaces of the tools using a metal matrix material.
PRIORITY CLAIM

This application claims the benefit of the filing date of United States Patent Application Serial No. 12,497,420, filed July 2, 2009, for "Hardfacing Materials Including PCD Particles, Welding Rods and Earth-Boring Tools Including Such Materials, and Methods of Forming and Using Same."

TECHNICAL FIELD

Embodiments of the present invention relate to materials that may be used to increase the wear-resistance of earth-boring tools and components of earth-boring tools used in the formation of wellbores, and to methods of forming and using such materials, tools, and components.

BACKGROUND

Wellbores are formed in subterranean formations for various purposes including, for example, extraction of oil and gas from subterranean formations and extraction of geothermal heat from subterranean formations. A wellbore may be formed in a subterranean formation using an earth-boring rotary drill bit. Different types of earth-boring rotary drill bits are known in the art including, for example, fixed-cutter drill bits (which are often referred to in the art as "drag" bits), roller cone drill bits (which are often referred to in the art as "rock" bits), diamond-impregnated bits, and hybrid bits (which may include, for example, both fixed cutters and roller cone cutters). The drill bit is rotated under an applied axial force, termed "weight-on-bit" (WOB) in the art, and advanced into the subterranean formation. As the drill bit rotates, the cutters or abrasive structures thereof cut, crush, shear, and/or abrade away the formation material to form the wellbore.

The drill bit is coupled, either directly or indirectly, to an end of what is referred to in the art as a "drill string," which comprises a series of elongated tubular segments connected end-to-end that extends into the wellbore from the surface of the
formation. Various tools and components, including the drill bit, may be coupled together at the distal end of the drill string at the bottom of the wellbore being drilled. This assembly of tools and components is referred to in the art as a "bottom hole assembly" (BHA).

The drill bit may be rotated within the wellbore by rotating the drill string from the surface of the formation, or the drill bit may be rotated by coupling the drill bit to a downhole motor, which is also coupled to the drill string and disposed proximate the bottom of the wellbore. The downhole motor may comprise, for example, a hydraulic Moineau-type motor having a shaft, to which the drill bit is coupled. The shaft of the motor is rotated by pumping fluid (e.g., drilling mud or fluid) from the surface of the formation down through the center of the drill string, through the hydraulic motor, out from nozzles in the drill bit, and back up to the surface of the formation through the annular space between the outer surface of the drill string and the exposed surface of the formation within the wellbore.

The materials of earth-boring tools need to be relatively hard and wear-resistant to efficiently remove formation material within a wellbore without undergoing excessive wear. Due to the extreme forces and stresses to which drill bits and other earth-boring tools are subjected during drilling and reaming operations, the materials of earth-boring tools must simultaneously exhibit relatively high fracture toughness. Materials that exhibit extremely high hardness, however, tend to be relatively brittle and do not exhibit high fracture toughness, while materials that exhibit high fracture toughness tend to be relatively soft and do not exhibit high hardness. As a result, a compromise must be made between hardness and fracture toughness when selecting materials for use in drill bits.

In an effort to simultaneously improve both the hardness and fracture toughness of earth-boring drill bits, composite materials have been applied to the surfaces of drill bits that are subjected to abrasion, erosion, or to both abrasion and erosion. These composite materials are often referred to as "hardfacing" materials. Hardfacing materials typically include at least one phase that exhibits relatively high hardness and another phase that exhibits relatively high fracture toughness.

For example, hardfacing materials often include tungsten carbide particles dispersed throughout a metal or metal alloy matrix material. The tungsten carbide
particles are relatively hard compared to the matrix material, and the matrix material is relatively tough compared to the tungsten carbide particles.

Tungsten carbide particles used in hardfacing materials may comprise one or more of cast tungsten carbide particles, sintered tungsten carbide particles, and macrocrystalline tungsten carbide particles. The tungsten carbide system includes two stoichiometric compounds, WC and W₂C, with a continuous range of compositions therebetween. Cast tungsten carbide generally includes a eutectic mixture of the WC and W₂C compounds. Sintered tungsten carbide particles include relatively smaller particles of WC bonded together by a matrix material. Cobalt and cobalt alloys are often used as matrix materials in sintered tungsten carbide particles. Sintered tungsten carbide particles can be formed by mixing together a first powder that includes the relatively smaller tungsten carbide particles and a second powder that includes cobalt particles. The powder mixture is formed in a "green" state. The green powder mixture then is sintered at a temperature near the melting temperature of the cobalt particles to form a matrix of cobalt material surrounding the tungsten carbide particles to form particles of sintered tungsten carbide. Finally, macrocrystalline tungsten carbide particles generally consist of single crystals of WC.

Various techniques known in the art may be used to apply a hardfacing material to a surface of an earth-boring tool. For example, automated and manual welding processes may be used to apply hardfacing material to an earth-boring tool. In some manual processes, a welding rod that comprises the hardfacing material is provided, and a torch (e.g., an oxyacetylene torch or an arc-welding torch) is used to heat an end of the rod and, optionally, the surface of the tool to which the hardfacing is to be applied. The end of the rod is heated until at least the matrix material begins to melt. As the matrix material at the end of the rod begins to melt, the melting hardfacing material is applied to the surface of the tool. The hard particles dispersed within the matrix material are also applied to the surface with the molten matrix material. After application, the molten matrix material is allowed to cool and solidify.

Such welding rods may comprise a substantially solid, cast rod of the hardfacing material, or they may comprise a hollow, cylindrical tube formed from
the matrix material of the hardfacing material and filled with hard particles (e.g., tungsten carbide particles). In welding rods of the tubular configuration, at least one end of the hollow, cylindrical tube may be sealed. The sealed end of the tube then may be melted or welded onto the desired surface on the earth-boring tool. As the tube melts, the tungsten carbide particles within the hollow, cylindrical tube mix with the molten matrix material as it is deposited onto the surface of the tool. An alternative technique involves forming a cast rod of the hardfacing material.

Flame spray processes are also used to apply hardfacing materials to earth-boring tools. In a flame spray process, a powder comprising the hard particles and particles of the matrix material is carried by a pressurized fluid (e.g., a pressurized gas) to a nozzle. The powder mixture is sprayed out from the nozzle and through a flame toward the surface of the tool to which the hardfacing is to be applied. The flame causes the particles of matrix material to at least partially melt. As the material is sprayed onto the tool, the molten matrix material cools and solidifies, and the hard particles become embedded in the matrix material to form the hardfacing on the surface of the tool.

Various types of arc welding processes are known in the art and may be used to apply hardfacing to a surface of an earth-boring tool. For example, metal-inert gas (MIG) welding processes, tungsten-inert gas (TIG) welding processes, and plasma-transferred arc (PTA) welding processes may be used to apply hardfacing to a surface of an earth-boring tool.

There remains a need in the art for abrasive, wear-resistant hardfacing materials that exhibit improved resistance to abrasion, erosion, or both abrasion and erosion.

DISCLOSURE

In some embodiments, the present invention includes hardfacing materials comprising particles of polycrystalline diamond material embedded within a matrix material. The particles of polycrystalline diamond material comprise a plurality of inter-bonded diamond grains.

In additional embodiments, the present invention includes material compositions and structures, such as welding rods, that may be used to apply a
hardfacing material to a surface of an earth-boring tool. The material compositions and structures include particles of polycrystalline diamond material comprising a plurality of inter-bonded diamond grains. For example, a welding rod may comprise an elongated, generally cylindrical body comprising a metal matrix material, and particles of polycrystalline diamond material carried by the elongated, generally cylindrical body.

In additional embodiments, the present invention includes earth-boring tools that include a body, at least one cutting element on the body, and a hardfacing material on at least a portion of a surface of the body. The hardfacing material includes particles of polycrystalline diamond material embedded within a matrix material. The particles of polycrystalline diamond material include a plurality of inter-bonded diamond grains.

In further embodiments, the present invention includes methods of forming a hardfacing material in which diamond grains are subjected to a temperature greater than about 1500°C and a pressure greater than about 5.0 gigapascals (GPa) to form diamond-to-diamond bonds between the diamond grains and form a polycrystalline diamond material. The polycrystalline diamond material is broken down to form particles of polycrystalline diamond material that include a plurality of inter-bonded diamond grains.

Yet further embodiments of the present invention include methods of hardfacing an earth-boring tool in which particles of polycrystalline diamond material that include a plurality of inter-bonded diamond grains are bonded to a surface of an earth-boring tool using a metal matrix material.

BRIEF DESCRIPTION OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming that which is regarded as the present invention, various features and advantages of embodiments of the invention may be more readily ascertained from the following description of some embodiments invention when read in conjunction with the accompanying drawings, in which:

FIG. 1 is a simplified drawing of an embodiment of a hardfacing material of the present invention;
FIG. 2A is a simplified drawing of a hard particle of the hardfacing material of FIG. 1 that includes polycrystalline diamond material;

FIG. 2B is a cross-sectional view of the hard particle shown in FIG. 2A taken along section line 2B-2B therein;

FIG. 2C is a simplified sketch showing how the hard particle of FIGS. 2A and 2B may appear under magnification, and illustrates a plurality of inter-bonded diamond grains;

FIG. 3 is a partially cut-away view of a cutting element that includes a layer of polycrystalline diamond material that may be used to form hard particles like that shown in FIGS. 2A-2C;

FIG. 4 is a partially cut-away view of the layer of polycrystalline diamond material shown in FIG. 3 removed from a substrate on which the layer was previously disposed;

FIG. 5 is a perspective view of an embodiment of a welding rod of the present invention that includes hard particles like that shown in FIGS. 2A-2C;

FIG. 6A is a perspective view of another embodiment of a welding rod of the present invention that includes hard particles like that shown in FIGS. 2A-2C;

FIG. 6B is a longitudinal cross-sectional view of the welding rod shown in FIG. 6A;

FIG. 7 is a side view of an embodiment of a roller cone earth-boring rotary drill bit of the present invention that includes a hardfacing material like that shown in FIG. 1; and

FIG. 8 is a perspective view of an embodiment of a fixed-cutter earth-boring rotary drill bit of the present invention that includes a hardfacing material like that shown in FIG. 1.

MODE(S) FOR CARRYING OUT THE INVENTION

The illustrations presented herein are not actual views of any particular drilling system, drilling tool assembly, or component of such an assembly, but are merely idealized representations which are employed to describe the present invention.

As used herein, the term "polycrystalline diamond material" means and includes a volume of material that includes two or more grains (also referred to in the
art as "crystals") bonded directly to one another at least partially by diamond-to-diamond bonds. In other words, polycrystalline diamond material is a material that includes two or more inter-bonded diamond grains.

As used herein, the term "inter-bonded diamond grains" means grains that are directly bonded to one another at least partially by diamond-to-diamond bonds.

FIG. 1 is a simplified drawing illustrating an embodiment of a hardfacing material 10 of the present invention. The hardfacing material 10 comprises a composite material that includes a discontinuous or "dispersed" phase 12 embedded within and dispersed throughout a continuous matrix phase 14. The discontinuous phase 12 exhibits a hardness higher than a hardness exhibited by the matrix phase 14, and the matrix phase 14 exhibits a fracture toughness higher than a fracture toughness exhibited by the discontinuous phase 12.

The matrix phase 14 of the hardfacing material 10 may comprise a metal or metal alloy. By way of example and not limitation, the matrix phase 14 may comprise cobalt-based, iron-based, nickel-based, iron and nickel-based, cobalt and nickel-based, iron and cobalt-based, copper-based, and titanium-based alloys. The matrix phase 14 may also be selected from commercially pure elements such as cobalt, iron, nickel, copper, and titanium. In some embodiments, the matrix phase 14 may comprise a matrix or "binder" material having a melting point below about 1350°C, as disclosed in U.S. Patent Application Publication No. 2005/0247491 Al, filed April 28, 2008 and entitled "Earth-Boring Bits."

The discontinuous phase 12 may comprise finite spatial volumes of polycrystalline diamond material that are dispersed throughout and embedded within the matrix phase 14. In some embodiments, the finite spatial volumes of the discontinuous phase 12 may be formed from and comprise particles of polycrystalline diamond (PCD) material, which are hereinafter referred to as PCD particles.

The hardfacing material 10 optionally may also comprise an additional discontinuous phase 13 that includes at least one of a carbide material (e.g., tungsten carbide, titanium carbide, tantalum carbide, silicon carbide, etc.), a boride material (e.g., titanium boride), a nitride material (e.g., silicon nitride), and non-polycrystalline diamond grit.
The hardfacing material 10 may be applied to surfaces of earth-boring tools using various methods. For example, automated and manual welding processes may be used to apply hardfacing material 10 to a surface of an earth-boring tool. Various types of arc welding processes may be used to apply hardfacing material 10 to a surface of an earth-boring tool. For example, metal-inert gas (MIG) welding processes, tungsten-inert gas (TIG) welding processes, and plasma-transferred arc (PTA) welding processes may be used to apply hardfacing material 10 to a surface of an earth-boring tool. Flame spray processes also may be used to apply hardfacing material 10 to surfaces of earth-boring tools.

FIGS. 2A-2C illustrate an example of a PCD particle 16 that may be used in accordance with embodiments of the present invention to form the discontinuous phase 12 of the hardfacing material 10 of FIG. 1.

Referring to FIG. 2A, the PCD particles 16 used to form the hardfacing material 10 (FIG. 1) may have irregular rough and jagged shapes in some embodiments of the present invention. In other words, the PCD particles 16 may comprise relatively sharp edges and corners. In additional embodiments of the present invention, the PCD particles 16 may be relatively smooth and rounded. Relatively rough and jagged PCD particles 16 may be processed to form relatively smooth and rounded PCD particles using processes known in the art, such as, for example, tumbling processes, jet blending processes, and etching processes. Depending on the particular application for which the hardfacing material 10 (FIG. 1) is to be used, either relatively rough and jagged PCD particles 16, as shown in FIG. 2A, or relatively smooth and rounded PCD particles may exhibit more desirable physical characteristics and performance.

FIG. 2B is a cross-sectional view of the PCD particle 16 of FIG. 2A taken along section line 2B-2B therein. As shown in FIG. 2B, in some embodiments of the present invention, the PCD particles 16 used to form the discontinuous phase 12 of the hardfacing material 10 (FIG. 1) may be at least substantially planar. In other embodiments, however, the PCD particles 16 may not be planar, and may be generally spherical, cubical, etc.

In embodiments in which the PCD particles 16 are at least substantially planar as shown in FIGS. 2A and 2B, the PCD particles 16 may have an average particle diameter D of, for example, between about 0.25 millimeter and about 7.0 millimeters,
and an average thickness T of, for example, between about 0.1 millimeter and about
5.0 millimeters.

As shown in FIG. 2B, in some embodiments, the PCD particles 16 may be at least partially encapsulated with a coating 17 prior to forming a hardfacing material 10 using the PCD particles 16. The coating 17 may be used to protect the polycrystalline diamond material within the PCD particles 16 against thermal degradation (e.g., graphitization) that might occur during formation of a hardfacing material 10 using the PCD particles 16. By way of example and not limitation, the coating 17 may comprise a powder material comprising particles of a metal or metal alloy material that does not serve as a catalyst material for catalyzing the formation of diamond-to-diamond bonds at elevated temperatures and pressures, as described in further detail below. Such catalyst materials may, conversely, contribute to the thermal degradation of diamond material when the diamond material and the catalyst are heated to relatively lower temperatures and pressures. For example, the coating 17 may comprise particles of tungsten metal or a tungsten metal alloy. The coating 17 also may comprise particles of at least one of a carbide material (e.g., tungsten carbide, titanium carbide, tantalum carbide, silicon carbide, etc.), a boride material (e.g., titanium boride), a nitride material (e.g., silicon nitride), and non-polycrystalline diamond grit. Such a powder coating 17 optionally may be subjected to a sintering process to at least partially sinter particles within the powder coating 17. By way of non-limiting example, the PCD particles 16 may be coated using methods such as those disclosed in U.S. Patent No. 7,350,599, which issued April 1, 2008 to Lockwood et al.

In additional embodiments, the coating 17 may comprise a layer of one or more of the above-mentioned coating materials deposited by, for example, using a physical vapor deposition (PVD) process or a chemical vapor deposition (CVD) process.

As previously mentioned, the PCD particles 16 may comprise a plurality of inter-bonded diamond grains. FIG. 2C is a simplified drawing illustrating how the microstructure of the PCD particles 16 may appear at a magnification of between about 500 times and about 1,500 times.

FIG. 2C illustrates a plurality of inter-bonded diamond grains 18, 18’. The diamond grains 18, 18’ may have an average particle size within a range extending from about five microns (5.0 µm) to about thirty microns (30.0 µm). In some
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embodiments, the diamond grains 18, 18' may have a multi-modal grain size
distribution. In other words, the diamond grains 18, 18' may comprise a mixture of
two, three, or even more different sizes of grains. For example, in the embodiment of
FIG. 2C, the inter-bonded diamond grains 18, 18' include both larger diamond
grains 18 and smaller diamond grains 18'. The larger and smaller diamond grains 18,
18' are bonded together by diamond-to-diamond bonds at grain boundaries between the
diamond grains 18, 18' (the grain boundaries being represented in FIG. 2C by dashed
lines) to form the polycrystalline diamond material of the PCD particles 16. In some
embodiments, interstitial spaces 20 (shaded black in FIG. 2C) between the
inter-bonded diamond grains 18, 18' may be filled with a catalyst material used to
catalyze formation of the diamond-to-diamond bonds between the diamond grains 18,
18'. In other embodiments, however, catalyst material may be removed from the
interstitial spaces 20 between the inter-bonded diamond grains 18, 18' such that the
interstitial spaces 20 comprise voids, as discussed in further detail herein below. In
such embodiments, the polycrystalline diamond material of the PCD particles 16 may
be porous, and a majority of the pores within the PCD particles 16 may form a
continuous open pore network within the polycrystalline diamond material.

In some embodiments of the present invention, PCD particles 16 used in the
hardfacing material 10 (FIG. 1) may be formed by breaking down (e.g., crushing,
milling, grinding, etc.) a relatively larger volume of polycrystalline diamond material.
By way of example and not limitation, the PCD particles 16 may be formed by
breaking down a layer of polycrystalline diamond material of a cutting element, which
previously may have been disposed on a substrate. Thus, the PCD particles 16 may
comprise fragments of a layer of polycrystalline diamond material. In some
embodiments, such fragments may be at least substantially planar.

FIG. 3 illustrates a cutting element 30 like those often used on drill bits and
reamers used to form wellbores in subterranean formations. The cutting element 30
shown in FIG. 3 includes a volume of polycrystalline diamond material 32 bonded to a
substrate 34. The volume of polycrystalline diamond material 32 is often referred to in
the art as a "diamond table." The volume of polycrystalline diamond material 32 may
be formed on the substrate 34, or the volume of polycrystalline diamond material 32
may be formed separately from the substrate 34 and subsequently attached to the
substrate 34. As known in the art, polycrystalline diamond material may be formed by subjecting diamond grains to elevated temperatures and pressures to form diamond-to-diamond bonds between the diamond grains. For example, polycrystalline diamond material may be formed by subjecting diamond grains to temperatures greater than about 1500°C and pressures greater than about 5.0 GPa in the presence of a catalyst material such as, for example, cobalt for a time of between about ten seconds and several minutes. The catalyst is used to catalyze formation of the diamond-to-diamond bonds between the diamond grains. Other suitable catalysts are also known in the art. If the temperatures and pressures are sufficiently high (e.g., at a temperature greater than about 3,000°C and a pressure greater than about 13.0 GPa), diamond-to-diamond bonds may form even in the absence of a catalyst.

Referring to FIG. 4, the volume of polycrystalline diamond material 32 may be removed from the substrate 34 of the cutting element 30. The volume of polycrystalline diamond material 32 may be removed from the substrate 34 using, for example, a wire Electrical Discharge Machining (EDM) process. Other processes, such as grinding processes, etching processes, or fracturing processes, also may be used to separate the volume of polycrystalline diamond material 32 and the substrate 34. After removing the volume of polycrystalline diamond material 32 from the substrate 34, the volume of polycrystalline diamond material 32 may be broken down to form a plurality of PCD particles 16 (FIGS. 2A-2C) therefrom.

Thus, some embodiments of methods of the present invention include forming a plurality of PCD particles 16 from a volume of polycrystalline diamond material 32 that was previously part of a cutting element 30. As a result, in accordance with some embodiments of the present invention, cutting elements 30 (which may or may not have been previously used in drilling or reaming a wellbore) that would otherwise be discarded may be salvaged and recycled by using the cutting elements 30 to form PCD particles 16 (FIGS. 2A-2C) for use in a hardfacing material 10 (FIG. 1). In additional embodiments of methods of the present invention, a volume of polycrystalline diamond material 32 may be formed with the intention of subsequently breaking down the volume of polycrystalline diamond material 32 to form PCD particles 16 (FIGS. 2A-2C) for use in a hardfacing material 10 (FIG. 1).
After forming the PCD particles 16, the PCD particles 16 may optionally be subjected to a leaching process to remove catalyst material from interstitial spaces 20 between the inter-bonded diamond grains 18. By way of example and not limitation, the PCD particles 16 may be leached using a leaching agent and process such as those described more fully in, for example, U.S. Patent No. 5,127,923 to Bunting et al. (issued July 7, 1992), and U.S. Patent No. 4,224,380 to Bovenkerk et al. (issued September 23, 1980). Specifically, *aqua regia* (a mixture of concentrated nitric acid (HNO₃) and concentrated hydrochloric acid (HCl)) may be used to at least substantially remove catalyst material from the interstitial spaces 20 between the inter-bonded diamond grains 18 in the PCD particles 16. It is also known to use boiling hydrochloric acid (HCl) and boiling hydrofluoric acid (HF) as leaching agents. One particularly suitable leaching agent is hydrochloric acid (HCl) at a temperature of above 110°C, which may be provided in contact with the PCD particles 16 for a period of about two hours to about 60 hours, depending upon the size of the PCD particles 16.

After leaching the PCD particles 16, the interstitial spaces 20 between the plurality of inter-bonded diamond grains 18 within the PCD particles 16 may be at least substantially free of catalyst material used to catalyze formation of diamond-to-diamond bonds between the plurality of inter-bonded diamond grains 18.

Additional embodiments of the present invention include material compositions and structures that may be used to form a hardfacing material 10 on an earth-boring tool. Such material compositions and structures also include PCD particles (such as the PCD particles 16 as previously described with reference to FIGS. 2A-2C), and may include a matrix material used to form a matrix phase 14 of hardfacing material 10. By way of example and not limitation, the PCD particles 16 may be incorporated into a welding rod, and the welding rod may be used to deposit hardfacing material 10 on a surface of an earth-boring tool.

FIG. 5 is a simplified perspective view of an embodiment of a solid welding rod 40 of the present invention. The solid welding rod 40 shown in FIG. 5 may comprise an at least substantially solid cylinder that includes PCD particles 16 embedded within a matrix material that will ultimately form the matrix phase 14 of the hardfacing material 10 (FIG. 1). Thus, the solid welding rod 40 includes an elongated, generally cylindrical body comprising the matrix material, and the PCD particles 16 are
carried by the body. As the matrix material of the welding rod 40 will ultimately form
the matrix phase 14 of the hard-facing material 10, the matrix material of the welding
rod 40 may have a material composition as previously described for the matrix phase
14 of the hard-facing material 10 of FIG. 1. The solid welding rod 40 may further
comprise additional hard particles that include at least one of a carbide material (e.g.,
tungsten carbide, titanium carbide, tantalum carbide, silicon carbide, etc.), a boride
material (e.g., titanium boride), a nitride material (e.g., silicon nitride), and
non-polycrystalline diamond grit. The solid welding rod 40 of FIG. 5 may be formed
using, for example, a forging process, a casting process, or an extrusion process.

FIG. 6A is a simplified perspective view of another embodiment of a tubular
welding rod 50 of the present invention. The tubular welding rod 50 shown in FIG. 6A
may comprise a generally hollow, cylindrical tube 52 that is at least substantially
comprised by a metal or metal alloy that will be used to form the matrix phase 14 of the
hard-facing material 10 (FIG. 1). Thus, the matrix material of the welding rod 50 may
have a material composition as previously described for the matrix phase 14 of the
hard-facing material 10 of FIG. 1. FIG. 6B is a longitudinal cross-sectional view of the
tubular welding rod 50 of FIG. 6A. As shown in FIG. 6B, the interior space within the
hollow, cylindrical tube 52 may be filled with PCD particles 16. The tube 52 may also
contain additional hard particles that include at least one of a carbide material (e.g.,
tungsten carbide, titanium carbide, tantalum carbide, silicon carbide, etc.), a boride
material (e.g., titanium boride), a nitride material (e.g., silicon nitride), and
non-polycrystalline diamond grit. One or both ends of the tube 52 may be capped,
crimped, or otherwise sealed to prevent the PCD particles 16 (and any other hard
particles therein) from falling out from the tube 52. Thus, the tubular welding rod 50
also includes an elongated, generally cylindrical tubular body comprising a matrix
material (i.e., tube 52), and the PCD particles 16 are carried by the body. The hollow,
cylindrical tube 52 of the welding rod 50 of FIGS. 6A and 6B may be formed using, for
example, a forging process, a casting process, or an extrusion process.

Embodiments of welding rods of the present invention (e.g., the solid
welding rod 40 of FIG. 5 and the tubular welding rod 50 of FIGS. 6A and 6B) may
be used to apply hard-facing material 10 to a surface of an earth-boring tool using a
torch such as, for example, an oxyacetylene torch or an arc-welding torch. The torch
is used to heat an end of the welding rod and, optionally, the surface of the earth-boring tool to which the hardfacing material is to be applied. An end of the welding rod is heated until at least the matrix material in the welding rod begins to melt. As the matrix material at the end of the welding rod begins to melt, the melting matrix material, and PCD particles 16 from the welding rod that become entrained within the melting matrix material, are applied to the surface of the earth-boring tool. After application, the molten matrix material is allowed to cool and solidify on the surface of the earth-boring tool, the PCD particles 16 become embedded within the solidified matrix material. The resulting hardfacing material 10 (FIG. 1) includes a continuous matrix phase 14, which is formed by the matrix material of the welding rod, and a discontinuous phase 12 comprising polycrystalline diamond material that is formed by the PCD particles 16 of the welding rod.

Additional embodiments of the present invention include powder feedstock mixtures for use in flame spray processes that include PCD particles 16. For example, a powder feedstock mixture for a flame spray process may comprise a mixture of PCD particles 16, as well as particles of a metal or metal alloy matrix material having a composition as previously described in relation to the matrix phase 14 of the hardfacing material 10 (FIG. 1). The mixture may also comprise additional hard particles that include at least one of a carbide material (e.g., tungsten carbide, titanium carbide, tantalum carbide, silicon carbide, etc.), a boride material (e.g., titanium boride), a nitride material (e.g., silicon nitride), and non-polycrystalline diamond grit. In a flame spray process, such a powder feedstock mixture may be entrained within and carried by a pressurized fluid (e.g., a pressurized gas) to a flame spray nozzle. The pressurized fluid and the powder mixture may be sprayed out from the nozzle and through a flame toward the surface of the earth-boring tool to which the hardfacing material 10 is to be applied. The flame causes the particles of matrix material to at least partially melt. As the powder mixture is sprayed onto the tool, the molten matrix material cools and solidifies, and the PCD particles 16 become embedded within the solidified matrix material. The resulting hardfacing material 10 (FIG. 1) includes a continuous matrix phase 14, which is formed by the particles of matrix material in the powder feedstock mixture,
and a discontinuous phase 12 comprising polycrystalline diamond material that is formed by the PCD particles 16 in the powder feedstock mixture.

Additional embodiments of the present invention include earth-boring tools having a hardfacing material 10 (as previously described herein in relation to FIG. 1 and including a discontinuous phase 12 comprising finite spatial volumes of polycrystalline diamond material dispersed within a matrix phase 14) on at least a portion of a surface of a body of the tools. The tools may also include at least one cutting element. By way of example and not limitation, earth-boring tools such as, for example, fixed-cutter rotary drill bits, roller cone rotary drill bits, diamond impregnated rotary drill bits, reamer tools, mills, and coring bits may include hardfacing material 10 and may embody the present invention.

FIG. 7 illustrates an embodiment of a roller cone drill bit 60 of the present invention. The roller cone drill bit 60 includes a bit body 62 having threads 64 at its proximal longitudinal end for connection to a drill string (not shown). The bit body 62 may comprise a plurality (e.g., three) of head sections 66 (which are separated by the dotted lines in FIG. 7) that are welded together concentrically about a longitudinal axis 67 of the drill bit 60. The threads 64 may be machined in the conical shank region of the bit body 62 after welding together the head sections 66. Two of the head sections 66 are visible from the perspective of FIG. 7.

Each head section 66 comprises a head section body or proximal section 68 nearest the threads 64 and a bit leg 70 depending distally therefrom. Each upper section 68 of the drill bit 60 may include a lubricant fluid pressure compensator 72, as known in the art. At least one nozzle 74 may be provided in the bit body 62 for controlling the direction and velocity of pressurized drilling fluid flowing through the bit body 62 and out from the nozzle 74 during drilling operations. A roller cone cutter 76 is rotatably secured to a bearing shaft (not shown) of each respective bit leg 70 of bit body 62. By way of example, the drill bit 60 has three roller cone cutters 76, one of which is obscured from view from the perspective of FIG. 7. Each roller cone cutter 76 has rows of cutting elements 78. The cutting elements 78 may comprise cutting teeth, which may be machined in exterior surfaces of the bodies of the roller cone cutters 76. Alternatively, the cutting elements 78 may comprise separately formed inserts, which may be formed from a wear resistant material such as cemented...
tungsten carbide and pressed into recesses drilled or otherwise formed in exterior surfaces of the bodies of the roller cone cutters 76.

The roller cone drill bit 60 of FIG. 7 may include hardfacing material 10 on one or more surfaces of the drill bit 60. By way of example and not limitation, the outer surfaces of the head sections 66, including exterior surfaces of both the proximal sections 68 of the head sections 66 and the bit legs 70 of the head sections 66 may comprise hardfacing material 10 thereon. Furthermore, hardfacing material 10 may be provided on various surfaces of the roller cone cutters 76. For example, hardfacing material 10 may be provided on gage surfaces 80 of the roller cone cutters 76, on the cutting elements 78 (e.g., on cutting teeth), or on both the gage surfaces 80 and on the cutting elements 78. Hardfacing material 10 also may be applied to surfaces of the drill bit 60 within the fluid passageways (not shown) extending through the drill bit 60, as well as to surfaces of the drill bit 60 proximate the nozzles 74, and other surfaces that might be susceptible to fluid erosion during drilling operations.

FIG. 8 illustrates an embodiment of a fixed-cutter drill bit 90 of the present invention. The fixed-cutter drill bit 90 includes a bit body 92 having threads 94 at its proximal longitudinal end for connection to a drill string (not shown). The bit body 92 may comprise a crown 96, which may be formed from a particle-matrix composite material (e.g., a cemented tungsten carbide material) or a metal alloy (e.g., steel). The crown 96 may be attached to a shank 97, and the threads 94 may be machined in the shank 97.

The crown 96 of the drill bit 90 may comprise a plurality of blades 98 that are separated from one another by fluid passageways 100. The blades 98 may extend over the face of the crown 96 from a central cone region of the crown 96 to a gage region of the crown 96. Radially outer surfaces of the blades 98 in the gage region of the crown 96 comprise gage surfaces 102 of the drill bit 90. These gage surfaces 102 define the diameter of any wellbore drilled by the drill bit 90. The portions of the fluid passageways 100 between the blades 98 in the gage region of the crown 96 are often referred to in the art as "junk slots."

A plurality of cutting elements 104 may be fixedly attached to each of the blades 98. The cutting elements 104 may comprise, for example, PDC cutting elements. Fluid passageways (not shown) also extend through the drill bit 90 to
nozzles 106 to allow drilling fluid to be pumped through the drill string (not shown) and the drill bit 90 and out the nozzles 106 during drilling operations.

The fixed-cutter drill bit 90 of FIG. 8 may include hardfacing material 10 on one or more surfaces of the drill bit 90. By way of example and not limitation, the gage surfaces 102 may comprise hardfacing material 10 thereon. Furthermore, hardfacing material 10 may be provided on various formation-engaging surfaces of the blades 98. Hardfacing material 10 also may be applied to surfaces of the drill bit 90 within the fluid passageways (not shown) extending through the drill bit 90, as well as to surfaces of the drill bit 90 proximate the nozzles 106, and other surfaces that might be susceptible to fluid erosion during drilling operations.

Thus, surfaces of earth-boring tools such as, for example, the roller cone drill bit 60 of FIG. 7 and the fixed-cutter drill bit 90 of FIG. 8, may be hardfaced by bonding particles of polycrystalline diamond material, such as the PCD particles 16 of FIGS. 2A-2C, to the surfaces using a matrix material, which may comprise a metal or metal alloy, as previously described herein.

PCD particles 16, as previously described herein, may also be used in other components of earth-boring tools other than hardfacing material to provide wear resistance to the earth-boring tools. As a non-limiting example, PCD particles 16 may be disposed within bit bodies of so-called "diamond-impregnated" rotary drill bits such as those disclosed in, for example, U.S. Patent No. 6,843,333, which issued January 18, 2005 to Richert et al.

Additional non-limiting example embodiments are described below.

Embodiment 1: A hardfacing material, comprising: a metal matrix material; and particles of polycrystalline diamond material embedded within the metal matrix material, the particles of polycrystalline diamond material comprising a plurality of inter-bonded diamond grains.

Embodiment 2: The hardfacing material of Embodiment 1, wherein the particles of polycrystalline diamond material comprise fragments of a layer of polycrystalline diamond material.

Embodiment 3: The hardfacing material of Embodiment 2, wherein the fragments of the layer of polycrystalline diamond material are at least substantially planar.
Embodiment 4: The hardfacing material of any one of Embodiments 1 through 3, wherein interstitial spaces between the plurality of inter-bonded diamond grains within the particles of polycrystalline diamond material are at least substantially free of catalyst material used to catalyze formation of diamond-to-diamond bonds between the plurality of inter-bonded diamond grains.

Embodiment 5: The hardfacing material of any one of Embodiments 1 through 4, wherein the particles of polycrystalline diamond material are encapsulated within a coating comprising a metal.

Embodiment 6: The hardfacing material of Embodiment 5, wherein the coating further comprises at least one of a carbide material, a boride material, a nitride material, and non-polycrystalline diamond grit.

Embodiment 7: The hardfacing material of any one of Embodiments 1 through 6, wherein interstitial spaces between the plurality of inter-bonded diamond grains within the particles of polycrystalline diamond material are at least substantially free of catalyst material used to catalyze formation of diamond-to-diamond bonds between the plurality of inter-bonded diamond grains, and wherein the particles of polycrystalline diamond material are encapsulated within a coating comprising a metal.

Embodiment 8: The hardfacing material of any one of Embodiments 1 through 7, wherein the particles of polycrystalline diamond material are at least substantially planar, have an average particle diameter between about 0.25 millimeter and about 7.0 millimeters, and have an average particle thickness between about 0.1 millimeter and about 5.0 millimeters.

Embodiment 9: A welding rod comprising a hardfacing material as recited in any one of claims 1 through 8.

Embodiment 10: An earth-boring tool comprising a hardfacing material as recited in any one of claims 1 through 8.

Embodiment 11: A welding rod for use in applying hardfacing to a surface of a tool, comprising: an elongated, generally cylindrical body comprising a metal matrix material; and particles of polycrystalline diamond material carried by the elongated, generally cylindrical body, the particles of polycrystalline diamond material comprising a plurality of inter-bonded diamond grains.
Embodiment 12: The welding rod of Embodiment 11, wherein the elongated, generally cylindrical body comprises a hollow tube, and wherein the particles of polycrystalline diamond material are disposed within the hollow tube.

Embodiment 13: An earth-boring tool, comprising: a body; at least one cutting element on the body; and hardfacing material on at least a portion of a surface of the body, the hardfacing material comprising: a metal matrix material; and particles of polycrystalline diamond material embedded within the metal matrix material, the particles of polycrystalline diamond material comprising a plurality of inter-bonded diamond grains.

Embodiment 14: The earth-boring tool of Embodiment 13, wherein the body comprises a bit body of a fixed-cutter rotary drill bit, and wherein the at least one cutting element comprises a polycrystalline diamond compact (PDC) cutting element fixedly attached to the bit body.

Embodiment 15: The earth-boring tool of Embodiment 13, wherein the body comprises a bit leg of a roller cone rotary drill bit, and wherein the at least one cutting element comprises a roller cone cutter.

Embodiment 16: The earth-boring tool of Embodiment 13, wherein the body comprises a roller cone cutter of a roller cone rotary drill bit, and wherein the at least one cutting element comprises a cutting insert or a cutting tooth on the roller cone cutter.

Embodiment 17: The earth-boring tool of any one of claims 13 through 16, wherein interstitial spaces between the plurality of inter-bonded diamond grains within the particles of polycrystalline diamond material are at least substantially free of catalyst material used to catalyze formation of diamond-to-diamond bonds between the plurality of inter-bonded diamond grains, and wherein the particles of polycrystalline diamond material are encapsulated within a coating comprising a metal.

Embodiment 18: A method of forming a hardfacing material, comprising: subjecting diamond grains to a temperature greater than about 1500°C and a pressure greater than about 5.0 GPa to form diamond-to-diamond bonds between the diamond grains and form a polycrystalline diamond material; and breaking down the polycrystalline diamond material to form particles of polycrystalline diamond material,
the particles of polycrystalline diamond material comprising a plurality of inter-bonded
diamond grains.

Embodiment 19: The method of Embodiment 18, wherein breaking down the polycrystalline diamond material comprises crushing the polycrystalline diamond material.

Embodiment 20: The method of Embodiment 18 or Embodiment 19, further comprising catalyzing formation of the diamond-to-diamond bonds between the diamond grains using a catalyst material.

Embodiment 21: The method of Embodiment 20, further comprising removing the catalyst material from interstitial spaces between the inter-bonded diamond grains within the particles of polycrystalline diamond material.

Embodiment 22: The method of any one of Embodiments 18 through 21, further comprising encapsulating the particles of polycrystalline diamond material with an encapsulant material comprising a metal.


Embodiment 24: The method of Embodiment 23, wherein bonding particles of polycrystalline diamond material to a surface of an earth-boring tool comprises: using a welding torch to at least partially melt the metal matrix material; applying the at least partially molten metal matrix material and the particles of polycrystalline diamond material to the surface of the earth-boring tool; and allowing the at least partially molten metal matrix material to cool and solidify on the surface of the earth-boring tool.

The foregoing description is directed to particular embodiments for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiments set forth above are possible without departing from the scope of the embodiments disclosed herein as hereinafter claimed, including legal equivalents. It is intended that the following claims be interpreted to embrace all such modifications and changes.
What is claimed is:

1. An earth-boring tool, comprising:
   a body;
   at least one cutting element on the body; and
   hardfacing material on at least a portion of a surface of the body, the hardfacing
   material comprising:
   a metal matrix material; and
   particles of polycrystalline diamond material embedded within the metal matrix
   material, the particles of polycrystalline diamond material comprising a
   plurality of inter-bonded diamond grains.

2. The earth-boring tool of claim 1, wherein the body comprises a bit body
   of a fixed-cutter rotary drill bit, and wherein the at least one cutting element comprises
   a polycrystalline diamond compact (PDC) cutting element fixedly attached to the bit
   body.

3. The earth-boring tool of claim 1, wherein the body comprises a bit leg
   of a roller cone rotary drill bit, and wherein the at least one cutting element comprises a
   roller cone cutter.

4. The earth-boring tool of claim 1, wherein the body comprises a roller
   cone cutter of a roller cone rotary drill bit, and wherein the at least one cutting element
   comprises a cutting insert or a cutting tooth on the roller cone cutter.

5. The earth-boring tool of claim 1, wherein the particles of
   polycrystalline diamond material comprise at least substantially planar fragments of a
   layer of polycrystalline diamond material.
6. The earth-boring tool of claim 1, wherein the particles of polycrystalline diamond material are encapsulated within a coating comprising a metal, the metal comprising at least one of a carbide material, a boride material, a nitride material, and non-polycrystalline diamond grit.

7. The earth-boring tool of claim 1 or claim 6, wherein interstitial spaces between the plurality of inter-bonded diamond grains within the particles of polycrystalline diamond material are at least substantially free of catalyst material used to catalyze formation of diamond-to-diamond bonds between the plurality of inter-bonded diamond grains.

8. The earth-boring tool of claim 1, wherein the particles of polycrystalline diamond material are at least substantially planar, have an average particle diameter between about 0.25 millimeter and about 7.0 millimeters, and have an average particle thickness between about 0.1 millimeter and about 5.0 millimeters.

9. A method of hardfacing an earth-boring tool, comprising:
providing particles of polycrystalline diamond material including a plurality of inter-bonded diamond grains; and
bonding the particles of polycrystalline diamond material including a plurality of inter-bonded diamond grains to a surface of an earth-boring tool using a metal matrix material.

10. The method of claim 9, wherein bonding particles of polycrystalline diamond material to a surface of an earth-boring tool comprises:
using a welding torch to at least partially melt the metal matrix material;
applying the at least partially molten metal matrix material and the particles of polycrystalline diamond material to the surface of the earth-boring tool; and
allowing the at least partially molten metal matrix material to cool and solidify on the surface of the earth-boring tool.
11. The method of claim 9, wherein providing particles of polycrystalline diamond material including a plurality of inter-bonded diamond grains comprises: subjecting diamond grains to a temperature greater than about 1500°C and a pressure greater than about 5.0 GPa to form diamond-to-diamond bonds between the diamond grains and form a polycrystalline diamond material; and breaking down the polycrystalline diamond material to form particles of polycrystalline diamond material, the particles of polycrystalline diamond material comprising a plurality of inter-bonded diamond grains.

12. The method of claim 11, wherein breaking down the polycrystalline diamond material comprises crushing the polycrystalline diamond material.

13. The method of claim 11, further comprising catalyzing formation of the diamond-to-diamond bonds between the diamond grains using a catalyst material.

14. The method of claim 13, further comprising removing the catalyst material from interstitial spaces between the inter-bonded diamond grains within the particles of polycrystalline diamond material.

15. The method of claim 11, further comprising encapsulating the particles of polycrystalline diamond material with an encapsulant material comprising a metal.
FIG. 1