608
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FIGURE 6

(54) Title: A ROCK REMOVAL BODY

(57) Abstract: A rock removal body comprises a PCD material (601) bonded to a substrate (602) along an interface. The body is of right circular cylindrical shape and the PCD material has a thickness (607) from the circumferential edge axially along the surface of the barrel portion of around 3mm or greater, and a functional working volume (606) having a maximum extent such that the final wear surface does not intersect the interface of the PCD material volume and the substrate. The PCD material volume comprises a diamond network and a metallic component forming a metallic network, the substrate comprises a cementing metal, the metallic component and the cementing metal being independent of one another, independently derived, have not interacted during the high pressure high temperature manufacturing process, are measurably distinguishable and are pre-selected to be different with respect to their alloy composition. The PCD material encompasses the functional working volume and is homogeneous.

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A ROCK REMOVAL BODY

Field
This disclosure relates to a rock removal body for a drag bit rock drilling application and a rock removal body for a roller cone bit rock drilling application.

Background
Polycrystalline diamond materials (PCD) typically comprise an intergrown network of diamond grains with an interpenetrating metallic network. The network of diamond grains is formed by sintering of diamond powders facilitated by molten metal catalyst/solvent for carbon at elevated pressures and temperatures. The diamond powders may have a monomodal size distribution whereby there is a single maximum in the particle number or mass size distribution, which leads to a monomodal grain size distribution in the diamond network. Alternatively, the diamond powders may have a multimodal size distribution where there are two or more maxima in the particle number or mass size distribution, which leads to a multimodal grain size distribution in the diamond network. Typical pressures used in this process are in the range of around 4 to 7 GPa but higher pressures up to 10 GPa or more are also practically accessible and may be used. The temperatures employed are above the melting point at such pressures of the metals. The metallic network is the result of the molten metal freezing on return to normal room conditions and will inevitably be a high carbon content alloy. In principle, any molten metal solvent for carbon which can enable diamond crystallization at such conditions may be employed. The transition metals of the periodic table and their alloys may be included in such metals.

Conventionally, the predominant custom and practice is to use the binder metal of hard metal substrates caused to infiltrate into a mass of diamond powder, after melting of such binders at the elevated temperature and pressure. This is infiltration of molten metal at the macroscopic scale of the conventional PCD construction, i.e., infiltrating at the scale of millimetres. By far the commonest conventional situation is the use of tungsten carbide, with cobalt metal binders, as the sintered hard metal substrate. This inevitably results in the sintered hard metal substrate being bonded in-situ to the resultant PCD. Successful commercial exploitation of PCD materials to date has been very heavily dominated by such custom and practice.

For the purposes of this disclosure, PCD constructs which use sintered hard metal substrates as a source of the molten metal sintering agent via directional infiltration and the bonding in-situ to that substrate, are referred to as "conventional PCD" constructions or bodies.

Historically, conventional PCD structures comprising PCD material bonded and attached to carbide hard metal substrates are used for material removal elements attached and arranged in housing bodies. General applications where the material to be removed is rock include drill bits for oil well and mining purposes and the like. PCD structures may also find application in, for example, as road planing and building construction where the material to be removed may be considered as synthetic or re-constituted rock-like materials such as asphalt, rock chipping containing asphalt, concrete, brick
and the like, including combinations of such. Henceforth, as used herein the term "rock" will be considered to refer to both natural geological rocks and synthetic or re-constituted rock-like materials.

Very important applications such as oil well drilling use two main streams of drilling technology, either in competition with or complementing each other. These are drag bit and roller cone technologies. Both of these technologies exploit conventional PCD structures.¹

Figure 1 is a schematic diagram of a typical conventional drag bit, 101, and housing body, 102. The diagram shows conventional PCD rock removal elements 103, 104, and 105 in different radial positions in the housing body, consisting of right circular cylinders comprising relatively thin layers of PCD material bonded and attached to much larger carbide hard metal cylindrical substrates. On rotation of the drill bit, such elements are caused to continuously bear on the rock and operate by a predominantly shearing action, where the rock is progressively fractured and fragmented. Figure 2 schematically shows one edge of a conventional PCD rock cutting element, 201, continuously shearing rock, 202.

Such drag drill bit designs have been extensively optimized over many years such that the dominant and convenient custom and practice is to exploit right cylindrical rock removal elements which are brazed into cylindrical recessed pockets such that, on rotation of the drill bit, overlapping of the sweep of the cutters or rock removal elements provides for rock removal across the full face of the drill bit. These highly established and optimized drill bit designs with the attendant brazing technologies for attachment of the cylindrical cutting elements are not lightly or conveniently altered. Thus, desired and improved rock removal elements or cutters are still conveniently restricted to overall right cylindrical shapes and geometries. Moreover, the establishment of the barrel of rock removal elements or cutters being made of hard and wear resistant hard metals, providing appropriate mechanical wear and brazability properties is a generally desired and not a lightly changed aspect of the present drilling paradigm.

Figure 3 is a schematic diagram of a typical roller cone drill bit, 301, consisting of a housing body, 302, and three roller cone structures, 303, which are able to freely rotate on bearings. Each roller cone, 303, rotates around the surface of the rock as the overall drill bit housing body, 302, is rotated. The rock removal elements or bodies, 304, are inserted and attached to the surface of each of the three cone structures. As the cone structures turn, they bring the rock removing elements sequentially to bear on the rock surface. The roller cone structures are attached to the housing body via shaft and bearing structures which are in turn protected by gage pad surfaces, 305, with abrasion resistant gage elements, 306. Water cooling and crushed rock removal is facilitated by nozzles, 307. In this case the rock removing elements, 304, have typically rounded ends such as general chisel shapes, or domed and/or conical surfaces which bear upon the rock surface. These rock removal elements typically have a relatively thin PCD material layer bonded with the shaped hard metal substrate, and remove rock by a predominantly crushing action. This is illustrated in Figure 4 which schematically shows a cross-section of a dome shaped conventional PCD rock crushing element, 401, consisting of
a thin layer of PCD material, 402, forming a shell bonded to a dome shaped hard metal body, 403, bearing and crushing rock, 404.

Similarly to drag bit designs, roller cone designs are highly optimized and established. These too, therefore, are not lightly and conveniently altered. Thus, it would be advantageous for improved rock removal or rock crushing elements intended for roller cone bits to have shapes and geometries with a right cylindrical barrel made from easily brazable hard metal materials, whereby one end of the generally cylindrical shape forms a convex surface such as a dome, a rounded cone or a chisel shape involving edges.

Conventional PCD rock removal elements, be they intended for drag bit or roller cone bits, have been restricted to relatively thin layers of PCD material (typically from 1 to about 2.5mm and rarely up to about 4mm) formed attached to typically one side of large, substantially cylindrical hard metal substrates in the same high pressure high temperature processes. The required metal for the partial re-crystallisation and sintering of the diamond particles leading to the inter-grown polycrystalline diamond grains is predominantly derived from and infiltrated from the hard metal substrates. The long range infiltration of the required metal necessary for PCD layers between 2.5 and 4mm progressively contributes to difficulties of producing well sintered diamond grains.

The dominant life limiting mechanism for conventional PCD rock removal elements or bodies involves crack propagation in the PCD body which extends to the free surfaces of the PCD material resulting in extremely damaging chipping and spalling behaviour. It is believed that a governing aspect for such crack propagation is the residual stress distribution in the PCD rock removal element or body which results from the differential thermal contraction of the PCD layer compared to the hard metal substrate material during the return-to-room pressure and temperature of the manufacturing process. Due to the conventional rock removal element or body designs involving the PCD layers being attached to one side of the hard metal substrates, the return-to-room pressure and temperature in the manufacturing process causes bending distortion to occur in the PCD layers, necessarily resulting in the residual stress distribution spanning the PCD layers involving substantial and significant tensile stress components. These tensile stress components govern the direction of crack propagation. Their particular magnitude, gradients and directional residual stress distributions for specific designs and arrangements for PCD layers and substrates distinguishes the poorest and the best designs.

Conventional PCD bodies comprising a thin layer of PCD material attached during manufacturing processes to substantial hard metal substrates also are restricted in both PCD layer thickness and composition of the PCD material itself. PCD layer thicknesses made conventionally are typically less than 2.5mm, though exceptionally up to 4mm. These thicker PCD layers are very difficult to make and progressively suffer from inferior structure and properties arising from poor diamond-to-diamond bonding as a consequence of impurity segregation and general difficulties of long range infiltration of the catalyst/solvent metals for sintering of the diamond particles. The compositional restrictions of the conventional PCD layers concern a dependence of the overall metal content of the PCD material to the diamond grain size distribution. This is illustrated in Figure 5 where the cobalt content of
conventional PCD material is plotted against the average grain size of well-established conventional PCD materials. It can be seen from this graph that the cobalt content is limited to a band, 501, of approximate thickness 4 volume per cent, where for fine grain PCD material, e.g. of average grain size 1 micro meter, the metal content is about 12 volume per cent, decreasing for coarse PCD material, e.g., of average grain size 20 micro meters to about 6 volume per cent. Metal contents outside this band are not typical and are very difficult to make. Moreover, the metallurgy of conventional PCD materials is restricted to the metallurgies which are suitable for diamond particle recrystallization and sintering, and of viable hard metal materials, if such materials are exploited as substrate materials. Typically and commercially, the dominant metal in this regard is cobalt with, to a far lesser extent, certain nickel and/or iron alloy variations of cobalt.

Thus there is a need for improved rock removal or rock crushing elements which ameliorate or substantially overcome one or more of the abovementioned problems or disadvantages.

**Summary**

Viewed from a first aspect there is provided a rock removal body for a drag bit rock drilling application comprising a polycrystalline diamond (PCD) material volume bonded to a cemented hard metal substrate along an interface; wherein:

a. the body has an overall body volume, and is of a right circular cylindrical shape having a circumferential edge, and a barrel portion, the PCD material volume being axially asymmetrically disposed at one end of the body;

b. the PCD material volume has a thickness from the circumferential edge axially along the surface of the barrel portion of around 3mm or greater and a functional working volume, the functional working volume being the volume of PCD material progressively worn away in use during useful life of the rock removal body to a form a final wear surface, the functional working volume having a maximum extent such that the final wear surface does not intersect the interface of the PCD material volume and the substrate;

c. the interface bonding the polycrystalline diamond material volume to the cemented hard metal substrate comprising a layer of a third material derived from a refractory material, the third material being a metal diffusion blocking barrier material to molten bonding material of the substrate and molten catalyst solvent sintering aid of the PCD material volume during formation of the rock removal body;

d. the PCD material volume comprising a plurality of inter-bonded diamond grains having an average diamond grain size forming a diamond network and a metallic component forming a metallic network, and the substrate comprising a cementing metal, the metallic component and the cementing metal being independent of one another, independently derived, have not interacted during the high pressure high temperature manufacturing process, are measurably distinguishable and are pre-selected to be different with respect to their alloy composition;

e. the PCD material at least encompasses the functional working volume and is homogeneous in that the PCD material is spatially constant and invariant with respect to diamond network to
metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten times the average diamond grain size, the maximum diamond grain size in the diamond network being less than three times the average diamond grain size.

Viewed from a second aspect there is provided a rock removal body for a roller cone bit rock drilling application comprising a polycrystalline diamond (PCD) material volume bonded to a cemented hard metal substrate along an interface; wherein:

a. the body comprises a right circular cylinder portion having an associated radius, one end of the cylinder portion forming a generally convex curved surface or surfaces with an apex, or one end forming a general chisel shape where two or more flat surfaces meet to form an apex, the PCD material volume being axially asymmetrically disposed extending from and abutting the apex, the cemented hard metal substrate being disposed at the opposite end of the cylinder;

b. the PCD material volume has a thickness from the apex in the axial direction of the cylinder portion of the body to the interface with the substrate equal to or greater than the radius of the cylinder portion of the body, the PCD material volume further comprising a functional working volume, the functional working volume being the volume of PCD material progressively worn away in use during useful life of the rock removal body to a form a final wear surface, the functional working volume having a maximum extent such that the maximum extent of the functional working volume is less than the thickness of the PCD material volume thickness; the functional working volume extending from the apex in the axial direction;

c. the interface bonding the PCD material volume to the substrate comprising a thin layer of a third material derived from a refractory material, the third material being a metal diffusion blocking barrier material to molten bonding material of the substrate and molten catalyst solvent sintering aid of the PCD material volume during formation of the rock removal body;

d. the PCD material volume comprising a plurality of inter-bonded diamond grains having an average diamond grain size forming a diamond network and a metallic component forming a metallic network, and the substrate comprising a cementing metal, the metallic component and the cementing metal being independent of one another, independently derived, have not interacted during the high pressure high temperature manufacturing process, are measurably distinguishable and are pre-selected to be different with respect to their alloy composition;

e. the PCD material at least encompasses the functional working volume and is homogeneous in that the PCD material is spatially constant and invariant with respect to diamond network to metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten times the average diamond grain size, the maximum diamond grain size in the diamond network being less than three times the average diamond grain size.

**Brief Description of the Drawings**

Examples will now be described with reference to the accompanying drawings in which:
Figure 1 is a schematic diagram of a conventional drag bit and housing body;

Figure 2 is a schematic side view of one edge of a conventional PCD rock cutting element continuously shearing rock;

Figure 3 is a schematic diagram of a typical roller cone drill bit consisting of a housing body and three roller cone structures;

Figure 4 is a cross-section of a dome shaped conventional PCD rock crushing element consisting of a thin layer of PCD material bearing on and crushing rock;

Figure 5 is a graph of the cobalt content of conventional PCD material plotted against the average grain size of well-established conventional PCD materials;

Figure 6 is a schematic cross-section of a right cylindrical rock removal body intended for use in drag bit rock drilling wherein the dotted line indicates the final position of a wear scar formed during rock drilling application at end of life of the rock removal element or body;

Figures 7a, 7b and 7c are half cross-sectional schematic diagrams of examples giving the main characteristics of the residual stress distribution in a PCD material volume thickness of 2, 5 and 8mm, respectively;

Figures 8a, 8b and 8c are schematic cross-sectional diagrams which illustrate a generally convex curved surface or surfaces which can take a hemispheroidal form, either a prolate hemispheroidal, oblate hemispheroidal or a hemispherical form, respectively;

Figure 9a is a schematic cross-sectional diagram of an example curved surface which takes the form of a cone with a rounded apex, and Figure 9b shows an example of a general chisel shape which forms an apex;

Figures 10a, 10b, 10c and 10d are axial cross-sections of an example rock removal body for use in a conventional roller cone bit design, showing the zones of principal residual stress distinguished by grey shading where the thickness of the PCD material layer are 2, 8, 10 and 16mm, respectively;

Figures 11a and 11b indicate the positions of the dominant principal tensile residual stress maxima in the PCD material volume and the cemented hard metal substrate where Figure 11a represents examples for drag bit applications and Figure 11b represents the examples for roller cone bit applications;

Figure 12 shows an example of a PCD rock removal body intended for drag bit applications, where the PCD material volume comprises two or more layers of differing PCD material and a half cross-section of the body is shown where the principal residual stress distribution is presented by a series of grey shaded volumes which are delineated by contour lines of equal stress;

Figure 13 is a set of examples comprising one homogeneous PCD material and the cemented hard metal substrate comprising two layers of differing material and illustrates the residual stress benefits of employing discrete layers of differing cemented hard metal carbide materials; and
Figure 14 shows the residual stress benefits when the two layered arrangement of differing PCD materials of Figure 12 are combined with the two layer arrangement of differing tungsten carbide cobalt hard metal of Figure 13.

**Detailed Description**

As shown in Figure 6, the rock removal bodies of examples described herein may comprise a right circular cylindrical overall shape with a PCD material volume 601 axially asymmetrically disposed at one end of the cylindrical body, with a right cylindrical cemented hard metal carbide substrate 602 disposed at the opposite end. The cemented hard metal substrate 602 ensures that the standard custom and practice of braze technologies developed for drag bit manufacture may be applied in substantively unaltered form. Moreover, there should be sufficient cemented hard metal substrate free surface area to provide adequate bond strength to the braze layer or engagement, this consideration implies a chosen minimum size of substrate for each design of the examples described herein.

Figure 6 is a schematic cross section of a right cylindrical rock removal body intended for use in drag bit rock drilling. A layer of PCD material 601 is separated from a cemented hard metal substrate, 602, by a thin layer of material, 603, which is extant from the use of a barrier layer material used to separate the PCD material volume and the cemented hard metal substrate during manufacture. The dotted line 604 indicates the final position of a wear scar formed during rock drilling application at end of life of the rock removal element or body. A part of the circumferential edge, 605, indicates the part of the composite rock removal body which first is made to bear on the rock strata. The volume of material 606 between the circumferential edge 605 and the dotted line 604 is the volume of PCD material which is progressively worn away during use and will subsequently be referred to as the functional working volume. The remainder of the volume of the composite body outside 606 will subsequently be referred to as the functional support volume. The functional support volume is extant at end of life of the body and comprises the part of PCD material volume 601 left after end of life together with the barrier layer 603 and hard metal substrate 602. The thicknesses of the PCD material layer, 601, and the barrier layer material, 603, and the length of hard metal substrate, 602, are designated by 607, 608 and 609, respectively. The interfacial thin layer of material 603 separating and bonding the PCD material volume 601 and the substrate 602 may form a planar interface or a non-planar curved surface. Planar in this context means that the interface between the PCD bonding boundary layer and the cemented hard metal substrate is substantially flat and substantially parallel to the base of the cylindrical rock removal body, that being the cemented hard metal substrate. The interfacial layer 603 alternatively may not be flat but may be made up of a curved surface or surfaces usually arcuate in regard to the flat end of the cylindrical body. This will be referred to as non-planar interfaces. In some examples, the outer free surface of the cemented hard metal substrate 602 is in the form of a right circular cylinder. The layer of PCD material 601 will be a cylindrical layer when the interfacial thin layer of material 601 is planar.

The presence of a cemented hard metal substrate 602 bonded in an axially asymmetric manner to the PCD material volume 601 during the high pressure high temperature manufacture of the PCD
material volume causes residual stress distributions in both the PCD and cemented hard metal material volumes. The residual stress distributions are due to bending effects caused by differential expansion and contraction of the PCD and cemented hard metal material volumes during the return-to-room temperature and pressure at the end of the high pressure high temperature manufacturing process. These differential dilations are a result of the elastic modulus and thermal expansion properties of the PCD and cemented hard metal carbides being significantly different. In the experience of the inventors of the current application, the residual stress distribution in PCD, hard metal composite rock removal elements, in particular the tensile residual components in the PCD material volume, are the dominant aspects which may determine the useful life of such rock removal bodies. This is understood to be due to the fact that, typically, crack related failures such as chipping and spalling are the dominant life limiting considerations.

In conventional PCD cutters where the required metal for the liquid phase sintering of the PCD particulate network of the PCD material volumes is derived from long range infiltration of molten cementing metals of the carbide substrate, the residual stress distribution in the PCD material volume is of particular highly significance in this regard. The long range infiltration of the required metal into the PCD volume results in the restriction of the general thickness of the PCD material volume to typically less than 3mm.

Some examples described herein provide for means whereby there is no such molten metal infiltration related limitation on PCD material volume dimensions and thicknesses. In order to provide a relatively unrestricted scale to the PCD material volume dimensions, the metal required for the PCD material may be independently derived and isolated from the cementing metal of the hard metal substrate. PCD material volumes of any general simple shape, up to dimensions limited by the high pressure high temperature apparatus available, may be made by providing the necessary metal for the PCD material from a starting mass of particulate diamond intimately and homogeneously combined with metallic particles. Thus, the metallic component of the PCD material volume and the cementing metal of the hard metal substrate are independent of one another, independently derived and have not interacted during the high pressure high temperature process. Moreover, in the rock removal elements of the examples described herein, the metal components of the PCD material volume and the hard metal substrate are measurably different and pre-selected to be different in their elemental composition.

The molten binder metal of the hard metal substrate may be precluded from infiltrating into the polycrystalline diamond volume of the composite and an example of a means of achieving this separation and isolation of the metallurgy of the PCD volume and the hard metal substrate volume is to provide a barrier layer 603 between the said volumes which is capable of preventing significant cross contamination of the molten metals of the substrate and PCD material volumes. Barrier layers which may operate in this way may comprise materials which have significantly higher melting points than the catalyst/solvent metals for the PCD material and also the binder metal of the hard metal substrate. In addition, such metals may alloy and react slowly with the molten catalyst/solvent metals
for the PCD materials and the molten binder metal for the hard metal substrate. This latter point may assist in providing for sufficient barrier behaviour and also bonding behaviour with both the PCD material and the substrate material. Examples of metals which may satisfy these behaviours may comprise the refractory metals including tantalum, vanadium, niobium, molybdenum, zirconium and their alloys.

Certain ceramic materials such as nitrides, borides and carbides may also fulfil the required criteria. Some examples of such ceramics are tantalum nitride, titanium nitride, aluminium nitride, silicon nitride and mixed nitrides. In some examples, a 50 to 500 micro meter thick continuous zirconium metal barrier layer or bonding layer may be used. In some examples, the barrier layer may comprise a 50 micro meter thick tantalum metal or zirconium metal layer. Also, in some embodiments, a thin layer of nitrides/borides and/or carbides of the elements of groups IVa, Va and/or Via of the periodic table and B, Si and Al, including, for example, TaN, TiB2, ZrB2, AlN, Si3N4, AlB2 and ZrN, refractory metals, solids solutions, e.g., (Ti, Al)N and mixtures of these, may be used and may be applied using physical vapour deposition (PVD) or chemical vapour deposition (CVD) techniques. In some examples, the barrier layer between the PCD volume and hard metal substrate may comprise a continuous titanium nitride (TiN) layer, greater than around 3 micro meters in thickness. These thin barrier layers may have particular utility when the interface geometry between the PCD layer and substrate has a non-planar geometry.

Thus, examples may comprise an interface bonding the polycrystalline material volume to the cemented hard metal substrate, which is comprised of a thin layer of a third material derived from a refractory material which acts as a metal diffusion blocking barrier material to the molten cementing material of the hard metal substrate and the molten catalyst sintering aid of the polycrystalline diamond material during the high pressure high temperature process.

The metallic component of the PCD material volume and the cementing metal of the hard metal substrate are independent of one another as a result of being prevented from interacting with one another during the high pressure high temperature process due to the presence of the barrier material layer.

This independence of the metallurgy of the PCD material volume and the cementing metal of the hard metal substrate may assist in allowing each of these metallic components to be independently pre-selected in regard to particular desired composition and properties for each of the PCD material volume and hard metal substrate. This is in contrast to much of the conventional prior art PCD where the metal of the PCD material volume is wholly or in part derived from the cementing metal of the hard metal substrate. For example, it may be desired to exploit a corrosion resistant grade of tungsten carbide hard metal based upon the cementing metal. This corrosion resistance is often and typically achieved by alloying the cobalt cementing metal with elements such as nickel and chromium, or completely replacing it with a more corrosion resistant alloy. These alloying agents may well not be ideal or desired components of the metal of the PCD material volume. In this regard, elements such as chromium and other stable carbide forming metals will always and necessarily form precipitated
carbides in metal network of the PCD material volume. Such precipitated carbides may well undesirably alter the properties of the PCD material volume.

By contrast, some examples described herein may allow for the exploitation of a greatly expanded range of substrate materials without suffering from such potentially undesired metallurgies of the PCD material volume. A further example may well be the use of titanium carbide cemented with nickel hard metal material for the substrates while exploiting well established simple cobalt PCD material volume metallurgy. Thus, greatly expanded material design capabilities may be achievable in comparison with the conventional prior art where the metallurgies of the PCD material volume and the cemented hard metal substrate are co-dependent.

Thus, in some examples, the metallic component of the PCD material volume and the cementing metal of the hard metal substrate are independent of one another, are independently derived, have not interacted during the high pressure high temperature process, are measurably distinguishable and are pre-selected to be different with respect to the alloy composition. Since a role of the metal of the PCD material volume is to act as a molten catalyst/solvent for diamond recrystallization from solution, the metallic component of the PCD material volume may be a high carbon content alloy of transition metals which may be able to act as catalyst/solvent for diamond recrystallization from solution. These include, for example, transition metals such as cobalt, nickel, iron, manganese and their alloys. High carbon content cobalt may be a catalyst/solvent for the formation of the PCD network. In contrast, the cementing metal of the hard metal substrate will have acted as a liquid phase for the sintering of the carbide hard material. Such cementing metals will therefore tend to be alloys containing the hard metal carbide and the metallic element or elements of the carbide in solid solution. Typical of such cementing metals is, for example, cobalt with tungsten in solid solution for tungsten carbide cobalt based hard metal or nickel with titanium in solid solution for titanium carbide nickel based hard metal. Even if both the metal component of the PCD material volume and the cementing metal of the hard metal substrate are dominated and substantially the same metallic element, such as cobalt, they will be measurably distinguishable in such examples. The former will be a high carbon cobalt alloy as compared to a cobalt tungsten alloy for the latter. The metallic component of the PCD material volume and the cementing metal of the hard metal substrate of some examples may be preselected to be different with respect to their alloy composition. The metal component of the PCD material volume may be shown to be different in alloy composition using standard analytical techniques known in the art. These techniques include Energy Dispersive Analysis (EDS) on a Scanning Electron Microscope, X-Ray Diffraction and Wet Chemical Analysis.

It has been observed in general drag bit subterranean rock drilling that when the life of cylindrical rock removing elements such as those schematically depicted in Figure 6 is not determined by premature chipping and spalling, the typical size of the functional working volume at end of life is such that the remaining wear scar extends down the barrel of the cylindrical surface by about 3mm. This is indicated in Figure 6 by the intersection of the dotted line 604 with the barrel of the cylindrical body. In such circumstances, the life of the rock removal body has been determined by normal wear behaviour
and not by macroscopic fracture. This is a desirable situation as macroscopic fracture such as in chipping and spalling is a variable uncontrolled premature failure. However, it must be emphasized that in the inventors’ experience, the conventional prior art rock removal element designs have their lives primarily determined by chipping and spalling macroscopic crack related phenomena. Examples described herein may assist in providing a means by which the desirable normal wear dominated behaviour may be approached. In this regard, the residual stress distribution of any given example will be of primary consideration. More specifically, some examples are created which are characterised by lowering tensile stress maxima, displacing these maxima from the environs of the functional working volume and the reduction of tensile stress gradients in and close to the functional working volume. In this way the probability of macroscopic crack propagation in use may be reduced.

The commonest conventional rock removal elements, commonly known as cutters, are all generally right circular cylinders with the PCD material volume dimension at the barrel being typically around 2.5mm and rarely and exceptionally around 3 to 4mm. The diameter and length are usually selected according to the specifications given in the Table 1 below.

<table>
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<th>Configuration</th>
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<tr>
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</tbody>
</table>

**TABLE 1**

The examples described may be directed at any of the standard configurations. The 1616 configuration will be used to exemplify various features, which may be applied to all of the configurations in Table 1.

The PCD material volume may be made to any predetermined dimensions. In the context of the 1616 example, where also a flat planar interfacial boundary is specified, the PCD material volume therefore may be chosen to be of any thickness within the constraints of the overall length. Figures 7a, 7b and 7c are half cross-sectional schematic diagrams giving the main characteristics of the residual stress distribution for a 1616 configuration and comparing a PCD material volume thickness of 2, 5 and 8mm, respectively. The stress distribution provided gives information of the principle residual stress and thus no information is provided at any given position of the direction of the stress. The residual stress distribution information was generated using an ABACUS Finite Element Analysis (FEA)
computer package well known in the art and general engineering practice. The properties of the PCD material and the cemented hard metal material used for the analysis were as follows. The elastic modulus of the PCD material and the cemented hard metal material used in the analysis were 1020 GPa and 550 GPa, respectively. The linear coefficients of thermal expansion of the PCD material and the cemented carbide material used in the analysis were 4.01 ppm°K⁻¹ and 5.5 ppm°K⁻¹, respectively. The line 701 represents the planar interfacial boundary thin layer of third material derived from the refractory barrier material. For the purposes of this analysis no detail is included with regard to this thin boundary bonding layer, as the general semi-quantitative and qualitative character of the residual stress distribution in both the PCD material and the cemented hard metal substrate is not significantly altered by such detailed information. This thin boundary bonding layer may however operate to locally graduate the stresses across the boundary. The dotted line 702 represents the position of the final wear scar surface, i.e., the final extent of the functional working volume at end of life. Thus, the material progressively worn away during use extends from the line 702 to a position on the circumferential edge of the PCD material volume, 703, which indicates the point of first contact of the rock removal element or cutter at commencement of use.

As already stated, in the experience of the inventors, the dimension of the functional working volume at end of life is chosen to be around 3mm vertically down the barrel of the cylindrical surface.

The angle 704 the final wear scar 702 makes with respect to the vertical of the cylindrical barrel is dependent upon the chosen rake angle in relation to the rock surface. This angle is chosen to be 20° for the purpose of this analysis and is typical of what is used in practice. This means that the extent of the functional working volume at end of life radially from 703, along the top flat surface, will be about 1.1mm.

The lines labelled 705 represent principle tensile iso-stress contour lines in the cemented carbide substrate. Between this line and the base and barrel free surfaces of the substrate, the volume is occupied by a principle tensile stress field of very low magnitude. Between 705 and the line representing the barrier layer 701, in the direction of the barrier 701, there is a principal tensile stress field increasing in magnitude with an increase in stress gradient becoming more and more intense as the barrier layer is approached. The line 706 represents an intermediate principal iso-stress contour line.

The dotted line 707 indicates the position of the maximum principal tensile stress in the substrate material immediately below the barrier layer 701. Note that at all positions in the cemented hard metal carbide the principal stresses are tensile. The line 708 in the PCD material volume represents the zero stress contour line which separates the hatched volume of PCD material which is in compression from a general tensile field occupying the remainder of the PCD material volume. Two positions of principal tensile stress maxima are indicated by 709 and 710, respectively. The principal stress tensile maximum 709 occupies a position at the circumferential barrel surface of the PCD material volume slightly above the barrier layer 701. This principal stress tensile maximum 709 is dominated by an axial tensile stress. The principal stress tensile maximum 710 occupies a position on the flat top free
surface of the PCD material volume. This principal stress tensile maximum, 710, is dominated by a radial tensile stress.

In Figure 7a where the PCD material volume is 2mm thick, it should be noted that the line dotted line 702, representing the final wear scar at end of life intersects the boundary layer 701 and extends into a highly tensile region of the cemented hard metal substrate. Moreover, the volume of material between the dotted lines 702 and 703, namely the functional working volume, encompasses the tensile maximum stress 709. So, during the progressive wearing away of the functional working volume during application, the wear scar moving parallel towards line 702 will interact with the axial tensile maximum 709, and followed by interacting with the highly tensile location below the barrier layer 701 in the cemented hard metal substrate, 707.

It has been observed by the inventors that, when a wear scar interacts with such tensile stress maxima and high tensile stress gradients, macroscopic cracks propagate behind the wear scar in the PCD material volume guided by the general residual stress fields and gradients. Such cracks may lead to chipping and spalling and premature end to the useful life of such rock removing elements or cutters. The PCD construction depicted in Figure 7a may therefore be undesirable in some applications because of the final wear scar position 702 crossing the boundary 701 and extending into the cemented hard metal substrate.

In comparison, Figure 7b illustrates an example where the PCD material volume thickness is 5mm. Note that the functional working volume is invariant with respect to position and scale. In this example, the final wear scar position 702 does not cross the boundary 701 and thus does not extend into the cemented hard metal substrate. Moreover, the functional working volume in example of Figure 7b does not encompass the tensile stress maximum 710 and occupies a volume therefore of greatly reduced residual stresses and gradients. Such examples may be more favourable in that the probability of macroscopic crack propagation to free surfaces leading to chipping and spalling may now be significantly reduced.

A distinguishing factor between the example of Figure 7b and the PCD construction of Figure 7a is the crossing and interaction of the final wear scar 702 with the barrier boundary layer 701. In general, examples where the final wear scar position 702 does not cross and interact with the boundary layer 701 may be favoured. The functional working volume is considered to be invariant in the use of these drag bit examples, such that the extension of the final wear scar 702 down the circumferential barrel surface of the cylindrical cutter is about 3mm, so examples where the thickness of the PCD material volume from its circumferential edge axially along the curved barrel of the cylinder is 3mm or greater are a feature of some of the examples described herein.

The example depicted in Figure 7c where the PCD material volume thickness is 8mm and the cemented hard metal substrate is also 8mm indicates a further improvement over the embodiment of Figure 7b, when considering the residual stress distribution character in the PCD material volume, in that both the tensile maxima 709 and 710 are further displaced from the position of the functional working volume. Moreover, the tensile stress gradients in the functional working volume are
progressively reduced as the thickness of the PCD material volume is increased. This may be further illustrated by considering the arrows 711 and 712 which represent the direction of the tensile stress gradients in the axial and radial directions, respectively, in the functional working volume.

Table 2 gives the estimated values of the average principal tensile stress gradients, 711 and 712. It may be seen that these estimates indicate that, as the PCD material volume thickness increases from 2 to 8mm, the tensile stress gradient 711 is progressively reduced by an order of magnitude and that the tensile stress gradient 712 is progressively reduced by about a factor of 4. This analysis, therefore, indicates that a less damaging tensile residual stress distribution in the functional working volume may progressively develop as the PCD material volume thickness increases from around 3mm.

<table>
<thead>
<tr>
<th>Construction of Figure No.</th>
<th>PCD material volume thickness (mm)</th>
<th>Stress gradient, 711 (MPa/mm)</th>
<th>Stress gradient, 712 (MPa/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7a</td>
<td>2</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>7b</td>
<td>5</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>7c</td>
<td>8</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

**TABLE 2**

The trend of beneficial displacement of the tensile stress maxima, 709 and 710, at the free surface of the PCD material volumes, progressively becoming more and more remote from the functional working volume may continue as the PCD material volume thickness becomes larger and larger. However, as the PCD material volume thickness becomes larger, the principal tensile stresses in the cemented hard metal substrate may increase in magnitude and extent. This may be seen by comparing the maximum principal tensile stress 707 for Figures 7a, 7b and 7c as the PCD material volume thickness changes from 2 to 5 to 8mm, respectively. Note that the extent of this maximum principal tensile stress progressively expands and spreads along the boundary layer 701. This maximum principal tensile stress, 707, is dominated by primarily tensile stress in the hoop direction, i.e., along the circumferential direction. Cracks that form and extend into this region will then tend to split the hard metal substrate diametrically. This was indeed observed for situations where the PCD material layer was large in comparison with the cemented hard metal substrate.

Moreover, it may also be seen from the comparison of Figures 7a, 7b and 7c that, as the thickness or length of the hard metal substrate becomes reduced, the principal tensile stress gradient, extending from the base of the substrate towards the interfacial boundary 701, significantly increases. This is a
progressively unsatisfactory situation which further contributes to the probability of crack propagation in the cemented hard metal substrate leading to failure of the rock removal element.

Experientially, the inventors have found that the occurrence of diametrical splitting of the hard metal substrate may be greatly reduced when the volume of the PCD material is less than 50 per cent of the overall rock removal body volume, i.e., when the ratio of the PCD material volume thickness to the cemented hard metal substrate length or thickness measured from the circumferential edge of the body along the curved barrel surface of the cylinder is less than 1.0.

For a 16mm diameter and 16mm long right circular cylinder as illustrated Figures 7a 7b and 7c, this may be expressed such that the PCD material volume is a cylindrical layer with thickness 3mm or greater and the combined thickness of the boundary layer and the cemented hard metal substrate is 8mm or greater, the interfaces between the PCD material volume boundary and cemented hard metal substrate being flat, planar and parallel to the base of the PCD rock removal body. This means that the thickness of the PCD material volume layer is between 3mm and 8mm for these constructions.

More generally, for the configurations listed in Table 1, encompassed by the diameter of the cylindrical body being in the range 12 to 20mm and the overall length of the body 11 to 20mm, the PCD material volume is a cylindrical layer with thickness 3mm or greater and the combined thickness of the bonding boundary layer and the cemented hard metal substrate is 8mm or greater, the bonding interface between the PCD material volume and the cemented hard metal substrate being flat, planar and parallel to the base of the cylindrical rock removal body.

One of the advantages and benefits of the PCD of some of the examples, is that the resulting PCD material exhibits a very high degree of homogeneity in that the diamond network to metallic network volume ratio is spatially constant and invariant at and above a scale directly related to the diamond grain size. This may be achieved by generating a starting particulate mass of diamond particles homogeneously mixed with an accurately determined amount of metal particles such that the metal is always smaller than the diamond particle sizes. The methods may involve suspending the diamond particles in a liquid and nucleating and growing precursor compound(s) for the required metals on the surfaces of the diamond particles. The precursor compound(s) are then conveniently converted to pure metals attached to the diamond surfaces by heat treatment in reducing furnace environment. Specifically, the homogeneity obtainable in the resulting PCD material by such methods may be demonstrated and measured at a scale greater than ten times the average diamond grain size. A further constraint on the diamond grain size distribution in the context of such homogeneous materials is that the maximum grain size be less than three times the average diamond grain size. Such homogeneous PCD materials may have best utility if they at least encompass the functional working volume. Homogeneity in this regard may allow the avoidance of local stress inducing inhomogeneity-based defect structures to occur. In turn this may allow the full exploitation of the residual stress minimizing aspects.

Thus, the PCD material in some of the examples that at least encompasses the functional working volume is homogeneous in that it is spatially constant and invariant with respect to diamond network
and metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten times the average grain size, the maximum diamond grain size being less than three times the average diamond grain size.

The residual stress related criteria applied to the examples may allow the probability of macroscopic crack related behaviour, such as chipping and spalling, to be so reduced that they become of secondary consideration. The primary consideration for the performance of such examples intended for drag bit applications may now be considered to be normal wear behaviour during the rock removal application. PCD material compositions and structures which exhibit improved wear resistance may then be favourably exploited.

It is generally known in the art that high wear resistance is associated with finer diamond grain sizes, and also with high diamond concentration, i.e., low metal content. In the conventional prior art where the required metal for the sintering of the PCD material is derived from long range infiltration from a cemented hard metal substrate, finer diamond grain sizes are invariably associated with high metal content. The diamond grain size and metal content are not independently pre-selectable. For example, in the conventional prior art, when the average grain size is chosen in the range ten to one micro meters, the typical metal contents progressively increase from about nine volume per cent to about twelve volume per cent. Experientially, in such conventional prior art, metal contents as low as five volume per cent are not obtainable for PCD materials with average diamond grain sizes less than ten microns.

By contrast, in some examples, the diamond grain size distribution and the metal content are independently pre-selected. Fine grained PCD material less than ten micro meters average grain size with a metal content between five and nine volume per cent may be utilized to assist in exploiting high wear resistant behaviour of the PCD material in the functional working volume.

To enable the examples to be used in largely unaltered roller cone bit designs and custom and practice, the rock removal bodies of the examples intended for roller cone bit applications may comprise a body comprising a right circular cylinder body with one end extending to an apex, with the PCD material volume being axially asymmetrically disposed extending from or abutting the apex, the cemented hard metal substrate being disposed at the opposite cylindrical end. The apex may be formed by a generally convex curved surface or surfaces. Alternatively, the apex may be formed by a general chisel shape where two or more flat surfaces meet to form the apex.

The generally convex curved surface or surfaces may take a hemispherical form, for example, either a prolate hemispherical, oblate hemispherical or a hemispherical form, respectively. Figures 8a, 8b, 8c are schematic cross-sectional diagrams which illustrate such examples, respectively. The PCD material volumes, cemented hard metal substrates with a thin layer of bonding material are labelled 801, 802 and 803, respectively. The PCD material volume 801 extends from and abuts the apex 804. Note that in these examples, the interfacial bonding material layer 803 separating the PCD material 801 and the cemented hard metal substrate intersects the free surface of the body in the cylindrical barrel surface below the shoulder 805, this being defined as the line of departure of the barrel.
cylindrical surface extending into the generally convex curved surface. The generally curved surface or surfaces may take the form of a cone with a rounded apex where the radius of the rounded apex is about a quarter to a half of the radius of the cylindrical part of the body. This is illustrated in the schematic cross-sectional diagram Figure 9a where the PCD material volume, cemented hard metal substrate with a thin layer of bonding material are labelled 901, 902 and 903, respectively. The PCD material volume, 901, extends from the rounded apex 904.

Yet another example is illustrated in Figure 9b, which shows an example having a general chisel shape which forms an apex. The PCD material volume and cemented hard metal substrate with a thin layer of bonding material are labelled 901, 902 and 903, respectively. The illustrated chisel shape comprises a conical surface, 905, with a rounded apex, 904, modified by two symmetrical flat inclined surfaces, 906, which meet at an apex, 904. The interfacial bonding material layer, 903, separating the PCD material volume, 901, and the cemented hard metal substrate, 902, intersects the free surface of the body in the barrel below the shoulder, 907, this being defined as the line of departure of the barrel cylindrical surface extending into the conical curved surface.

In Figures 8a to c and 9a and 9b, the interfacial bonding material layer, 803 and 903, is a thin layer of material which is extant from the use of a barrier layer material used to separate the PCD material volume, 801 and 901, and the cemented hard metal substrate, 802 and 902, during manufacture. The barrier layer material assists in isolating the molten cementing metal of the hard metal substrate from the molten catalyst/solvent metal of the PCD material volume during the high pressure high temperature manufacturing process.

The cemented hard metal substrate assists in enabling the standard custom and practice of braze technologies developed for roller cone bit manufacture to be applied in substantively unaltered form. Moreover, a chosen minimum size of substrate for each design of the examples may assist in enabling there to be sufficient cemented hard metal substrate free surface area to provide adequate bond strength to the braze layer for engagement.

Prior art rock removal elements utilizing PCD for roller cone bit applications conventionally exploit a thin layer of PCD material, typically 1.0 to 2.0 mm thick, forming a shell at a convexly curved surface or surfaces. This is illustrated in Figure 4. By contrast, the examples described herein are not restricted to thin layers of PCD material and may exploit PCD material volumes which may occupy large volumes adjacent to and abutting the apices of convexly curved surface or surfaces, conical surfaces or general chisel surfaces.

In Figures 8a to 9b, the dotted lines 806 and 908 indicate the final position of a wear scar formed during rock drilling application at end of life of the rock removal element or body. The apices, 804 and 904, of the PCD material volumes, 801 and 901, indicate the part of the rock removal body which is first made to bear on the rock strata. The volumes of PCD material 807 and 909 between 804 and 904 and the dotted lines 806 and 908, respectively, are the volumes of PCD material which are progressively worn away during use in the rock removal application. These volumes, 807 and 909, will subsequently be referred to as the functional working volumes. The remainder of the volume of the
composite bodies outside the volumes 807 and 909, respectively, will subsequently be referred to as the functional support volumes. The functional support volumes are extant at end of life of the body and comprise the part of PCD material volumes, 801 and 901, left after end of life together with the interfacial layers, 803 and 903, and the cemented hard metal substrates, 802 and 902.

For each of the examples illustrated in Figures 8a to 9b, the thicknesses of the PCD material volumes, 801 and 901, is defined as the distance from the apices 804 and 904 in the axial direction along the axis of the body to the interfacial bonding barrier layer, 803 and 903, respectively.

The thin interfacial bonding layers, 803 and 903, may be flat and parallel to the circular cylindrical end of the substrates as illustrated. Alternatively, the thin interfacial layers 803 and 903 may be generally arcuately curved in regard to the flat end free surface of the substrate. The arcuate nature may be convex in regard to this free surface of the substrate.

Thus some examples may comprise an interface bonding the PCD material volume to the cemented hard metal substrate comprising a layer of third material, for example a thin layer, derived from a refractory material which acts as a metal diffusion blocking barrier material to the molten bonding material of the hard metal substrate and the molten catalyst solvent sintering aid of the PCD material during the high pressure high temperature manufacturing process.

Rock removal elements in roller cone bit applications operate by predominantly a crushing action by indentation on the rock surface. In such applications, therefore, it is necessary that the rock removal elements bearing on the rock have high compressive strength. Typical roller cone bit designs employ conical rollers with protruding rock removal elements inserted into the surface of the rollers. During drilling, the conical rollers roll around the surface of the rock so that the apices of the rock removing elements are cyclically brought to the bear on the rock surface. This cyclical rotary action, therefore, always involves a degree of impact loading to which the rock removal elements are exposed close to and at the apices of these bodies. Cemented hard metal rock removal elements have been traditionally used in this application in that they have adequate strength and impact resistance properties for such crushing actions particularly for soft rock formations. Cemented hard metal rock removal elements however are somewhat inadequate in respect to their wear resistance properties in such applications and suffer from often unfortunate excessive wear which can limit their usefulness.

The systems of the prior art conventionally comprise a relatively thin PCD layer at the apices of cemented hard metal rock removal elements in an attempt to mitigate such wear resistance inadequacies by providing greatly improved wear resistance at the apices. However, these limited thicknesses of PCD material (up to about 1mm) do not provide significant improvements in strength of the rock removal elements and may suffer from easy chipping and spalling due to the inevitable high tensile residual stresses in the PCD layers. The present applicants have appreciated that such stresses are a consequence of bending effects resulting from the differential shrinkage of PCD layers or volumes bonded to cemented hard metal substrates during manufacture.

The thin PCD layers of the conventional structures usually involve functional grading to deal with local high interfacial stresses. This conventional prior art may thus be viewed as using PCD to provide an
enhanced wear resistance to the roller cone bullet which would still be dominated by the compressive properties of the carbide. In contrast, some examples described herein exploit the superior compressive strength of PCD over carbide by using large PCD material volumes and therefore may assist in enhancing the wear resistance of the PCD.

In some examples, the substantial volumes of PCD material may occupy at least the functional working volume. Thus the PCD material volume may provide the required strength and impact resistance for the crushing action of the rock removal element. The general bulk mechanical properties of homogeneous, well-sintered PCD materials may be far superior to general cemented hard metal materials for these purposes. Specifically, the hardness of PCD materials may be, in some examples, be two to five times greater than typical cobalt cemented tungsten carbide hard metals typically used in roller cone bit drilling applications. This means that the mechanical wear resistance of the PCD of some of the examples, may be greatly superior to such cemented hard metals, and the measured compressive strength of PCD material grades (greater than 6700 MPa) may be greater than those obtained for most cobalt cemented tungsten carbide hard metals (eg in the range 3500 to 5500 MPa). The fracture toughness of the PCD materials of some of the examples may be in the range 9 to 10.5 MPa.m\(^{0.5}\), which is high for such a hard material. Thus, where the examples exploit large bulk volumes of PCD material, they may exhibit, due to this combination of properties, very good behaviour in this application which may be far better than typical cemented hard metals.

To assist in enabling the bulk properties of PCD materials to be exploited, the PCD material volume in some examples must be sufficiently large, and avoid thin layers such as those exploited in the typical prior art PCD. Moreover, large pieces of PCD material which have an increase of cross-sectional area at right angles to the direction of the applied forces during the crushing action may benefit from the concept of massive support as taught by P W Bridgman\(^2\). Some of the examples described herein for roller cone drilling applications have this geometry as the PCD material volumes extend from an apex and have a general convex nature. These examples, may therefore enjoy the benefits of the high rigidity of PCD materials providing massive support to their apices when they are bearing upon and crushing the rock. The very high rigidity of such PCD materials may be superior to those exhibited by general cemented hard metals in these applications.

For roller cone drilling general applications, in some of the examples, the thickness of the PCD material volume from the apex in the axial direction of the cylindrical part of the body to the interface with the cemented hard metal substrate is equal to or greater than the radius of the right circular cylindrical body. The maximum extent of the functional working volume extending from the apex in the axial direction may be less than the PCD material volume thickness. This assists in achieving a minimum thickness of PCD material volume, and for a minimum volume of PCD material relative to the overall rock removal body volume.

The examples described may comprise a cemented hard metal substrate. To assist in enabling relatively large bulk pieces of PCD material to be made bonded to cemented hard metal substrates during manufacture, it may be advantageous for the molten cementing metal of the hard metal
substrate to be prevented from interacting with the molten catalyst/solvent metal/s necessary for the sintering of the PCD material volume. As previously explained in the context of examples for drag bit applications, refractory metal layers or certain ceramic layers may be used as metal diffusion blocking barriers during the manufacture of PCD material bonded to cemented hard metal substrates.

For roller cone bit applications, the interface bonding the PCD volume to the cemented hard metal substrate may comprise, for example, a thin layer of a third material derived from the refractory material which acted as a metal diffusion blocking barrier material to the molten bonding material of the hard metal substrate and the molten catalyst sintering aid of the PCD material during the high pressure high temperature manufacturing process. Thus, the metallic component of the PCD material volume and the cementing metal of the hard metal substrate may be independent of one another, may be independently derived, have not interacted during the high pressure high temperature process, may be measurably distinguishable and may be pre-selected to be different with respect to the alloy composition.

As discussed above, one of the potential advantages/benefits of the PCD of the examples, may be that the resulting PCD material exhibits a very high degree of homogeneity in that the diamond network to metallic network volume ratio is spatially constant and invariant at and above a scale directly related to the diamond grain size. To assist in achieving this, a starting particulate mass of diamond particles is generated which is homogeneously mixed with an accurately determined amount of metal particles such that the metal is always smaller than the diamond particle sizes. The methods may involve suspending the diamond particles in a liquid and nucleating and growing precursor compound(s) for the required metals on the surfaces of the diamond particles. The precursor compound(s) is/are then conveniently converted to pure metals attached to the diamond surfaces by heat treatment in reducing furnace environment. Details of this method are set out in the examples below. The homogeneity obtainable in the resulting PCD material by such methods may be demonstrated and measured at a scale greater than ten times the average diamond grain size. A further constraint on the diamond grain size distribution in the context of such homogeneous materials is that the maximum grain size is preferably less than around three times the average diamond grain size. Such homogeneous PCD materials may have improved utility if they at least encompass the functional working volume. Homogeneity in this regard may allow the avoidance of local stress inducing inhomogeneity-based defect structures to occur. In turn this may allow for the full exploitation of the residual stress minimizing aspects as described above. Thus, for roller cone bit applications, the PCD material of some examples material at least encompass the functional working volume, and is homogeneous in that it is spatially constant and invariant with respect to diamond network and metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten times the average grain size, the maximum diamond grain size being less than around three times the average diamond grain size.

In general roller cone bit applications for subterranean rock drilling, the rock removal elements operate primarily by crushing rock as indicated in Figure 4. Figure 4 shows a generally example of a
rock removal element utilizing a conventional prior art thin layer (about 1 mm) of PCD material extending from an apex. Although in such prior art constructions a benefit can accrue from the very high wear resistance of PCD materials over cemented hard metals, serious potentially life limiting delamination, and chipping and spalling, of the PCD layer often occurs. The source of such macroscopic crack phenomena may be primarily associated with high magnitude tensile residual stress distributions in the PCD material thin layers and in the cemented hard metal substrate closely associated with the bonding interface between the PCD material and the cemented hard metal. In the language of the present disclosure, the residual stress distribution in the functional working volume extending from the apex of the rock removal element is of primary consideration and must be managed to mitigate macroscopic crack behaviour such as chipping and spalling. The methods of forming one or more examples which allow large volumes of PCD material to be made bonded to hard metal substrates may be of great benefit in this regard.

The example shown in Figure 8c is an illustration of this, whereby the generally convex curved surface of the PCD material volume is hemispherical.

Figures 10a to d are a series of examples based upon Figure 8c where the residual stress distribution in the PCD material volumes, and the cemented hard metal substrates are presented, resulting from a Finite Element Analysis (FEA). Such FEA techniques are well established in the art and provide semi-quantitative and qualitative information indicating compressive and tensile stress fields, the positions of stress maxima and meaningful comparisons of stress gradients in the stress fields. The examples of Figures 10a to d are for bodies with cylindrical diameter of 16mm and overall length from the apices along the axis to the base of 27mm. These dimensions were chosen as examples for use in conventional roller cone bit designs and custom and practice. The conclusions drawn from the FEA analysis for the examples of Figures 10a-d are believed to be applicable, for example, to the variations of dimensions and shape of the examples indicated in Figures 8a-c and 9a&b.

In particular, Figures 10a, 10b, 10c and 10d are axial cross-sections of rock removal body examples showing the zones of principal residual stress magnitude, distinguished by grey shading. The boundaries between the different shaded zones may be interpreted as equi-stress contour lines. The thickness of the PCD material layer expressed as the distance from the apices 1001 along the axes to the interface of the PCD material to the boundary layer on the axes 1002, are 2, 8, 10 and 16mm for Figures 10a, 10b, 10c and 10d, respectively. The line 1003 represents the thin interfacial bonding barrier material separating the PCD material volume above the line from the cemented hard metal substrate below the line. This interfacial bonding barrier material is represented by a single line, 1003, in these diagrams due to being very thin; the boundary layer material does not significantly alter the residual stress information presented. The zones or volumes of overall compression are indicated by cross-hatching. Outside these indicated compressive zones various levels of principal tensile stress are indicated by different shades of grey. In the cemented hard metal substrate in the direction along the axis towards the interfacial bonding barrier layer 1003, the tensile stress magnitude increases with
the tensile stress maximum being just below the interfacial line 1003 and indicated by the position 1004. The functional working volumes in these embodiments are considered to be invariant, of constant thickness, extending from the apices 1001 to the dotted line 1005.

In Figure 10a, the interfacial bonding barrier line 1003 and the boundary of the functional working volume, 1005, coincide. In this case, the functional working volume and the PCD material volume are one and the same. For the purposes of this example, the thickness of the functional working volume, from 1001 along the axis to the dotted line 1005, has been chosen to be 2mm. In the experience of the inventors, the most critical tensile residual stress aspects are the high tensile maxima at or close to the free surface of rock removal bodies. In the examples represented by Figures 10a-d, these are indicated by 1004 and 1006, respectively. 1006 represents a tensile maximum in the PCD material volume above the boundary line 1003 at or close to the free surface of the PCD material volume. The tensile stress maximum 1006 in the PCD material volume is dominated by an axial tensile stress. In the case of Figure 10a, the maximum stress 1006 has an axial and a radial component. The tensile stress maximum 1004 immediately below the interfacial boundary 1003 in the cemented hard metal substrate is dominated by a combination of hoop radial tensile stresses.

In Figures 10a, 10b, 10c and 10d, the position where the convex curved surface of the rock removal body joins with the cylindrical barrel surface is indicated by 1007, which may be described as the shoulder of the body. The shoulder may be further described and defined as being the line of departure of the barrel cylindrical surface extending into the generally convex curved surface.

In Figure 10b, the shoulder position 1007 coincides with the intersection of the interfacial boundary line 1003 with the free surface of the body. Note that, as Figures 10a, 10b, 10c and 10d are considered as a progression of increased thickness and volume of the PCD material volume, both the critical tensile stress positions 1004 and 1006 rapidly move away from the position of the invariant functional working volume. As these critical points move away from the functional working volume the probability of delamination, chipping and spalling progressively becomes reduced. In particular, when the critical stress position 1006 occurs below the shoulder 1007, both critical stress positions 1004 and 1006, may be considered to be sufficiently remote from the invariant functional working volume that the probability of delamination, chipping and spalling of the functional volume becomes insignificant.

In some examples with generally convex curved surfaces for the PCD material volume, where they take up hemispheroidal form, these examples have the interfacial bonding material separating the PCD material volume and the cemented hard metal substrate intersecting the free surface of the body in the cylindrical barrel surface below the shoulder, this being defined as the line of departure of the barrel cylindrical surface extending into the generally curve surface of the PCD material volume. The hemispheroidal form of the generally convex curved surface of the PCD material volume may be prolate hemispheroidal, oblate hemispheroidal or hemispherical, as depicted in Figures 8a, 8b and 8c, respectively.
Figures 10c and 10d show the principal residual stress distribution where the interfacial bonding material layer, 1003, intersects the free surface of the body at the cylindrical barrel surface below the shoulder, 1007. The PCD material thickness, from the apex, 1001, along the axis 1002, i.e., to the interfacial bonding line, 1003, increases from 10mm to 16mm for Figure 10c to Figure 10d, respectively. Note that the positions of the critical high tensile stress maxima 1004 and 1006, now progressively move to positions even further remote from the functional working volume, i.e., the volume of PCD between the dotted line 1005 and the apex 1001. This is considered to be progressively more and more advantageous. Moreover, note that the tensile residual stress in the functional working volume becomes progressively lower from Figure 10c to Figure 10d. Also note that at Figure 10d the tensile residual stress in the functional working volume approaches zero. In addition, the gradient of tensile stress across the functional working volume for this range of examples may be very low, for example less than around 10 MPa/mm, which may be considered to be negligible.

In applications where these examples will bear on the rock surface with applied load very close to the axial direction, these low tensile stresses in the functional working volume immediately adjacent to the apex may be largely cancelled out by the applied load. Clearly, in progressively moving from the example of Figure 10c to the example represented by Figure 10d, the volume of PCD material changes from being less than the volume of the hard metal substrate to being greater than the volume of the hard metal substrate. The examples represented by Figure 10d may have a more favourable general residual stress distribution for some applications, such as for rock removal bodies intended for roller cone bit applications, as the volume of the PCD material volume is greater than the cemented hard metal substrate. As stated previously, however, all the examples described preferably have sufficient surface area of hard metal substrate to enable sufficient engagement and bonding to the roller bit housing bodies or conical rollers. Creating the length of the cylindrical hard metal substrate to be greater than the radius of the cylindrical cemented hard metal substrate may assist in achieving this. In addition, where the PCD material volume is greater in volume than the cemented hard metal substrate, the increased volume of PCD material adds strength to the overall body by virtue of increased massive support to the apex bearing on the rock strata.

Such examples may be expected to have lowered probabilities of chipping, spalling and delamination. Moreover, since residual stress related premature failure phenomena in and close to the functional working volume are relegated to secondary considerations, such examples may allow the exploitation of the exceptional properties of PCD materials (with average diamond grain sizes in the range 1 to 30 micro meters) in regard to the loading situation typical of the roller cone bit applications, where the rock is predominantly removed by a crushing action. These properties are predominantly a combination of the high stiffness of PCD materials exhibited by property measurements such as modulus of elasticity at about a 1000 GPa, transverse rupture strength greater than 1200 MPa and adequate impact resistance exhibited by fracture toughness measurements \((K_Ic)\) at about 9.5 MPa.m\(^{0.5}\). Such measurements may be made with the techniques well established in the art and technical literature. The PCD material in the examples intended for roller cone bit applications thus
may have an average grain size in the range 1 to 30 micro meters, be homogeneous with well
intergrown diamond structure such the transverse rupture strength is greater than 1200 MPa as
measured in three point bend tests. In this broad range of PCD materials, in this particular application
PCD materials with the highest compressive strength may be favoured. This implies PCD material
types with higher diamond content, with good intergrowth. Typically, these would be materials with
larger average grain sizes, such as in the range 10 to 30 micro meters.

As described above, one or more of the examples, be they intended for drag bit or roller cone bit
applications, may have a refractory metal diffusion blocking barrier of material may assist in
preventing the molten cementing metal of the hard metal substrate and the molten catalyst/solvent
metal of the PCD material volume from interacting with one another during the manufacturing process
at high pressure high temperature. In addition, such materials may also provide bonding between the
PCD material volume and the cemented hard metal substrate. Typical materials which can serve such
purposes, may be, for example, thin (eg around 20 to around 100 micro meters thickness) refractory
metal layers chosen, for example, from any combination of one or more of tantalum, vanadium,
molybdenum, zirconium, tungsten and alloys thereof. During the high temperature high pressure
manufacturing process, these layers of refractory metals may be chosen such that they do not melt
but will be subject to exposure to high carbon content molten transition metals such as molten cobalt-
carbon alloy. Thus, these transition metals become partially carburised during the process.

Also, certain thin ceramic layers deposited using PVD or CVD techniques may also assist in providing
a barrier, bonding layer for one or more of the examples. The refractory bonding interfacial layer
separating the PCD material volume and the cemented hard metal substrate may be, for example, a
CVD or PVD deposited continuous ceramic layer of greater than, for example, around 3 micro meters
thickness, chosen for example, from any combination of nitrides of the elements of Group IVa, Va or
Via of the periodic table, such as titanium nitride, TiN.

Some of the examples, be they intended for drag bit or roller cone bit applications, may enjoy the
benefits of the tensile residual stress distribution in and around the functional working volume being
radically reduced in magnitude and intensity of gradient. Moreover, the principal tensile residual stress
maxima may be significantly removed from and remote from the functional working volume and its
environs. This may provide for a beneficial, significantly lowered possibility or probability of chipping
and spalling in and close to the functional working volume. The common feature which may assist in
providing this is if the PCD material volumes are large and are comparable in volume to the cemented
hard metal substrate or indeed are greater in volume than the cemented hard metal substrate. The
latter being the case for rock removal bodies intended for roller cone bit applications. For rock
removal bodies intended for drag bit applications, which may be restricted to an overall right
cylindrical shape, the desired size of the PCD material volume is expressed by stipulating that the
PCD material volume thickness is around 3mm or greater. The examples of Figures 7a-c and 10a-d
where the residual stress distributions are presented, are used to illustrate the reduction of tensile
stress in the functional working volume as the magnitude of the volume of the PCD material volume
increases. However, it may be observed in Figures 7a to 10d, that although tensile stress maxima may be made to be remote from the functional working volumes by appropriately large PCD material volume, they may remain as aspects of concern, in that these maxima may contribute to the possibility of impact related failure during application such as splitting and delamination of the cemented hard metal substrate. These tensile stress maxima are illustrated in Figures 7b and 7c for examples intended for drag bit applications. They are the axial tensile maximum in the PCD material volume positioned between the dotted line 709 and the cylindrical free surface, forming a ring of highly tensed material and the combined radial and hoop tensile maximum in the cemented hard metal substrate positioned between the dotted line 707 and the line representing the interfacial barrier, 701, which separate the PCD material volume and the cemented hard metal substrate.

Similarly, the tensile stress maxima are illustrated in Figures 10c and 10d for examples intended for roller cone bit applications. They are the axial tensile stress maxima in the PCD material volume 1006 and the combined hoop and radial tensile maxima, 1004, in the cemented hard metal substrate. It may be advantageous if the magnitude of these tensile stress maxima were to be reduced. A general way of doing this may be to minimize the difference between the average coefficient of thermal expansion of the PCD material volume and that of the cemented hard metal substrate. This may be done by choosing the PCD material to have a relatively high linear coefficient of thermal expansion in the typical range of PCD materials (around 3.7 to around 4.4 ppm.°K⁻¹) in conjunction choosing the cemented hard metal material to have a relatively low linear coefficient of thermal expansion in the range typical of cemented hard metal materials typically used in subterranean rock drilling applications (around 5.0 to around 6.1 ppm.°K⁻¹), for example.

In PCD materials made with cobalt as the catalyst solvent metal, the high linear coefficient of thermal expansion at the top of the range may restrict the PCD material to having a high metal cobalt content of at least above 9 volume per cent. The cemented hard metal grades typically used in subterranean rock drilling applications are cobalt cemented tungsten carbide grades chosen within the range of 6 to 14 weight per cent cobalt. Cemented hard metal carbide with low coefficient of thermal expansion may be restricted to grades with low cementing metal contents at most 10 weight per cent (16.3 volume per cent) cobalt.

Examples which exhibit lowered tensile stress maxima may be used where the metallic network of the PCD material is, for example, a cobalt-carbon alloy and the cementing metal of the hard metal substrate is, for example, a cobalt-tungsten-carbon alloy and the average metal content of the PCD material volume is, for example, greater than around 9 volume per cent (20 weight per cent) together with the average cobalt content of the hard metal substrate being less than around 16.3 volume per cent (10 weight per cent).

Some of the examples employ PCD material volumes where the composition and structure of the PCD material is macroscopically invariant and homogeneous across the dimensional extent of the PCD material volume. The composition and structure of the cemented hard metal substrates may also be invariant across the dimensional extent of the substrate, i.e., made of one grade of cemented hard
metal for these examples. Residual stress distributions extending across the macroscopic dimensions of high pressure high temperature PCD material bodies may be altered, manipulated and chosen by grading the composition of PCD material across the dimensions of the bodies. This may be done by graduating and changing the metal composition as a function of position in the PCD material volume such that the linear coefficient of thermal expansion is different as a function of position in the PCD material volume. The differential shrinkage of the PCD material from position to position during the cooling and pressure reduction phase of high pressure high temperature manufacturing process then induces residual stress from position to position. This method may be used by such positional choice of PCD material composition and structure to assist in reducing the intensity of tensile stress maxima and thus render them less likely to cause undesirable crack related fracture events such as chipping, spalling and delamination. This may be done by altering the composition and structure in a graduated way across the dimensions of the PCD material volume and/or by using discrete adjacent volumes of PCD materials differing appropriately in composition and linear coefficient of thermal expansion.

This approach to manipulation and control of the residual stress distribution may also be applied to the cemented hard metal substrate. Similarly, different grades of cemented hard metal materials with differing linear coefficients of thermal expansion may be employed in various positions in the substrate to advantageously lower tensile residual stress. These teachings may be applied to the examples so far disclosed herein. To illustrate this, Figures 11a and 11b are cross-sectional diagrams representing the arrived at examples for drag bit and roller cone bit applications, respectively. The PCD material volumes and cemented hard metal substrate are labelled 1101 and 1102, respectively. The interfacial barrier layer material is represented by the line 1103. In Figure 11a representing examples for drag bit applications, the functional working volume is the volume between a point on the circumferential edge, 1104, and the dotted line 1105. The point 1104 represents the initial part of the functional working volume to be made to bear on the rock during rock drilling applications. In Figure 11b representing the examples for roller cone bit applications the functional working volume is represented by the volume of PCD material between the apex 1106 and the dotted line 1105. The apex 1106 represents the initial part of the functional working volume to bear on the rock during drilling applications.

In both Figure 11a and 11b the central axial lines of the bodies intersect the free surface of the PCD material volume and the cemented hard metal substrate at 1106 and 1112, respectively. For Figure 11b, the apex 1106 is also the apex of the generally convex curved surface of the PCD material volume. In both Figures 11a and 11b, the position of the axial dominated principal tensile residual stress maximum in the PCD material volume is indicated by 1107. Note that this tensile stress maximum is just above the interfacial boundary layer 1103 at or close to the cylindrical free surface of the PCD material volume. This tensile stress maximum thus forms an extended circumferential position. In Figures 11a and 11b, the positions of the combined radial and hoop dominated principal tensile residual stress maximum in the cemented hard metal substrate is indicated by 1108. Note that this tensile stress maximum is positioned just below the interfacial barrier layer 1103 and this general
high tensile stress extends along the interface 1103, such that it diminishes in the direction of the intersection of the interface 1103 and the axes of the bodies.

As described above, during the reduction of pressure and temperature at the end of the high pressure high temperature manufacturing process both the PCD material volume and the cemented hard metal substrate shrink. The shrinkage of typical PCD material volumes is always less than that of the cemented carbide material volume. This is because the linear coefficient of thermal expansion of typical PCD materials is always less than that of cemented hard metal materials. The arrows 1109 and 1110 in Figures 11a and 11b represent the radial shrinkage of the PCD material volume and the cemented hard metal substrate, respectively, on either side of the interfacial barrier layer 1103 in an example PCD material. Note that the arrow 1109 is shorter than the arrow 1110, the difference in arrow length indicating the differential shrinkage. The net result of this differential shrinkage are bending effects which give rise to the residual stress distributions in both the PCD material volume and the cemented hard metal substrate. The axial direction dominated residual stress maximum in the PCD material volume, 1107, and the radial and hoop direction dominated residual stress maximum in the cemented hard metal substrate, 1108, therefore result from the difference in shrinkage. If the material of the PCD material volume is altered as a function of position such that the linear coefficient of thermal expansion increases in the general direction away from 1104 in Figure 11a and 1106 in Figure 11b in the general direction of the interfacial barrier 1103, the differential shrinkage and bending effects may be reduced, resulting in the magnitude of 1107 and 1108 stress maxima being reduced. This general direction is represented by the arrows 1111 which extend from the points of first contact with the rock during rock drilling applications, 1104 and 1106, towards the interfacial barrier layer 1103.

Examples where the linear coefficient of thermal expansion of the PCD material increases in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate may be advantageous due to the reduction of the residual stress maxima. The value of the linear coefficient of thermal expansion of the PCD material at any given position in the PCD material volume is determined by the elemental composition and quantity of the metal component of the PCD material at and close to that given position. Where the metal type or alloy is invariant across the dimension of the PCD material volume, the linear coefficient of thermal expansion is varied by the metal content alone. The higher metal contents correspond to PCD materials of the highest coefficient of thermal expansion. The converse is also true.

Examples where the metal of the PCD material is invariant as regards the metal type or alloy across the dimensions of the PCD material volume and where the metallic content of the PCD material increases in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate may be advantageous due to the reduction of the magnitude of the residual stress maxima. A convenient way of generally increasing the linear
coefficient of thermal expansion across a macroscopic dimension in a particular direction may be to employ discrete adjacent volumes of PCD materials differing in linear coefficient of thermal expansion and metal content. The differential shrinkage of the appropriately differing PCD material adjacent volumes may thus provide for a reduction in the overall shrinkage of the overall PCD material volume. Thus, one or more examples may comprise a PCD material volume comprising two or more layers of differing PCD material, the first layer of lowest linear coefficient of thermal expansion and metal content extends from the free surface and encompasses the functional working volume, with the second or subsequent layers of higher linear coefficient of thermal expansion and metal content separating the first layer from the interfacial barrier which separates the PCD material volume and the cemented hard metal substrate. Such examples using simple layers of differing PCD material may be very conveniently made and may significantly reduce the magnitude of critical residual stress tensile maxima. An example which demonstrates this is shown in Figure 12.

Figure 12 is a half cross-section of an example intended for drag drill bit applications, which is a rock removal body of overall right cylindrical shape, is 16mm in diameter, 16mm in overall length, with a PCD material volume of 6mm thickness and cemented hard metal substrate of close to 10mm long. This overall shape, and the dimensions and thickness of PCD material volume correspond to the example presented in Figure 7b.

Figure 12 shows the form of the residual stress distribution in the example as derived from Finite Element Analysis (FEA). In Figure 12, the PCD material volume, 1201, comprises a first layer of PCD material, 1202, of 3.5mm thickness, with linear coefficient of thermal expansion less than a second layer of PCD material, 1203, of thickness 2.5mm which separates the first PCD material layer from the interfacial barrier layer represented by the line 1204. The catalyst/solvent metal forming the metallic network in the PCD material volume 1201 was cobalt. The first layer of PCD material, 1202, had a cobalt content of 6.7 volume per cent and the second layer of PCD material had a cobalt content of 11.5 volume per cent. The cemented hard metal substrate 1205 was chosen to comprise a tungsten carbide cobalt cemented hard metal with a cobalt content of 13 weight per cent and a linear coefficient of thermal expansion of 5.6 ppm·°K⁻¹. The principal residual stress distribution is presented in Figure 12 by a series of grey shaded volumes which are delineated and separated by contour lines of equal stress. The zero stress contour lines, separating regions of tensile and compressive residual stress are indicated by dotted lines with the volumes under residual compression being cross-hatched. Note that the principal residual stress in the functional working volume is low.

The functional working volume is indicated as the volume of material between the specific point 1206 and the dotted line 1207. 1206 is the specific point on the circumferential edge of the PCD volume which is chosen to initially bear on the rock during the application. The functional working volume extends down the circumferential free surface by a chosen 3mm. The principal tensile residual stress maximum, 1208, is at a position on the circumferential free surface of the PCD material volume immediately above the interfacial barrier layer 1204, forming a ring around the circumference in the second PCD material layer 1203. This residual stress maximum, 1208, is dominated by an axial
tensile stress and corresponds in position to the maximum tensile residual stress indicated in Figure 11a, 1107, and Figure 7b, 709. Note that the principal residual stress in the cemented hard metal substrate at the base and circumferential free surface is low, ostensibly neutral. In the general direction from the base towards the interfacial barrier layer 1204, the tensile residual stress progressively increases in magnitude and reaches a maximum immediately below the interfacial barrier layer 1204. The position of this maximum principal tensile residual stress is indicated by 1209. The maximum residual tensile stress 1209 corresponds to the tensile stress maximum in Figure 11a, 1108, and the indicated maximum in Figure 7b, 707. This tensile residual stress maximum is dominated by radial and hoop tensile stress components at this position in the cemented hard metal substrate.

When the magnitude of the tensile stress maxima in Figure 7b, 709 and 707, are compared with the magnitude of the corresponding tensile stress maxima in Figure 12, 1208 and 1209, using the ABAQUS finite element analysis program well known in the art, it was found that both maxima had been reduced by around 10%. This reduction for the example of Figure 12 may be considered to be significant and favourable. In the example represented by Figure 12, where the PCD material volume comprises two or more layers of differing PCD material, the first layer of lowest linear coefficient of thermal expansion and metal content extends from the free surface and encompasses the functional working volume, with the second or subsequent layers of higher linear coefficient of thermal expansion and metal content separating the first layer from the interfacial barrier which separates the PCD material volume and the cemented hard metal substrate. Such examples may be valuable for some applications as these critical stress maxima may be significantly reduced in magnitude. This reduction may provide for a beneficial reduced tendency for the cemented hard metal substrates of these examples to delaminate and split during rock drilling applications.

As discussed above, graduating the properties of the cemented hard metal substrate may also be employed to reduce the differential shrinkage indicated by the arrows 1109 and 1110 in Figure 11a and 11b. A reduction in the differential shrinkage may give rise to lowering the bending effect which occurs at the end of the high pressure high temperature manufacturing process which may result in a beneficial reduction of the magnitude of the tensile stress maxima already described and indicated by 1107 and 1108. If the composition and resultant properties of the cemented hard material are altered such that the linear coefficient of thermal expansion decreases in the general direction from the central point of the base of the substrate 1112, towards the interfacial barrier layer 1103, indicated by the arrows 1113, such a reduction of the magnitude of the tensile residual stress maxima may occur. Thus, some of the examples may have a linear coefficient of thermal expansion of the cemented hard metal substrate decreasing in the general direction away from the central point of the base of the body towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate. If the cemented hard metal substrate is made of one type of hard metal material such that the cementing metal and the hard compound are invariant as regards metal type and molecular composition, then the amount of cementing metal may decrease in the general direction away from
the central point of the base of the body towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate.

A convenient way of generally decreasing the linear coefficient of thermal expansion of the cemented hard metal substrate across a macroscopic dimension in a chosen general direction may be to employ discrete adjacent volumes of cemented hard metal materials differing in linear coefficient of thermal expansion and cementing metal content. A set of examples in this regard may use parallel layers of differing hard metal material of varying thickness. In some examples, where, for example, the cemented hard metal substrate comprises two or more layers of differing hard metal material, the first layer of highest linear coefficient of thermal expansion and metal content may extend from the basal free surface of the substrate, with the second or subsequent layers of lower linear coefficient of thermal expansion and metal content separating the first layer from the interfacial barrier which separates the PCD material volume and the cemented hard metal substrate.

Figure 13 is an example based upon the shape and dimensions of the example represented by Figure 7b, which illustrates the potential benefits of employing such appropriately arranged discrete layers of differing cemented hard carbide materials. In Figure 13, the PCD material volume 1301 may comprise, for example, a homogeneous PCD material with a linear coefficient of thermal expansion of around 4.0 ppm°K-1 and a cobalt content of around 9 volume per cent (around 20 weight per cent).

The cemented hard metal substrate, 1302, comprises two layers of differing material 1303 and 1304. The boundary between these layers is substantially planar and parallel to the base of the substrate. In some examples, the layer 1303 extending from the base of the substrate may be around 8mm thick and made of a tungsten carbide cobalt hard metal with around 14 weight per cent cobalt (around 22.2 volume per cent) and may have a linear coefficient of thermal expansion of around 6.01 ppm°K-1.

The layer 1304, which separates the layer 1303 from the interfacial barrier layer 1305 may be around 2mm thick and may comprise a tungsten carbide cobalt hard metal with around 6 weight per cent (10.1 volume per cent) cobalt and a linear coefficient of thermal expansion of around 5.09 ppm°K-1.

The principal residual stress distributions in this example are presented as zones of varying shades of grey as before, with the same general qualitative character as exhibited in Figures 7b and 12.

The positions of the axial dominated tensile principal residual stress maximum, 1306, in the PCD material volume, 1301, corresponds to 709 in Figure 7b, 1107 in Figure 11a and 1208 in Figure 12. The position of the radial and hoop component dominated tensile principal stress maximum, 1307, in the hard metal substrate 1302 corresponds to 707 in Figure 7b and 1108 in Figure 11a and 1208 in Figure 12. Finite element analysis carried out on this example demonstrated that the magnitude of both the critical tensile stress maxima, 1306 and 1307, is reduced by around 35 per cent as compared to the corresponding maxima 709 and 707 in Figure 7b. Thus, this example may be considered to show a significant reduction in the magnitude of these critical tensile stress magnitudes. This may be highly beneficial, leading to a significantly reduced risk and probability of delamination and splitting of the cemented hard metal substrate during rock drilling applications.
The examples of Figure 12 and Figure 13 may be combined to form yet another example which is shown in Figure 14. The two layered arrangement of differing PCD materials of Figure 12 are combined with the two layer arrangement of differing tungsten carbide cobalt hard metal of Figure 13. Finite element analysis of this example shows that the magnitude of the tensile principal stress maxima, 1401 and 1402, corresponding to the critical stress maxima, 709 and 707 in Figure 7b, and 1107 and 1108 in Figure 11a, may reduced by around 60 per cent. This may, in some applications, be considered to be a highly desirable and beneficial situation of significantly reduced critical residual stress distributions, leading to an expectation that delamination and splitting of the hard metal substrate during drilling operations may become unlikely. This example illustrates the potential value in combining the grading of the PCD material volume in composition and structure such that the linear coefficient of thermal expansion of the PCD material increases in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate, with the decreasing of the linear coefficient of thermal expansion of the hard metal substrate in the general direction away from the central point of the base of the body towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate.

In some examples, the metal network in the PCD material volume is cobalt and the cemented hard metal substrate is tungsten carbide cobalt.

The examples for drag bit applications shown in Figures 12, 13 and 14 may be generally applicable, and include the examples intended for use in roller cone applications whereby the rock removal body comprises a right circular cylinder with one end forming a generally convex curved surface with an apex. The PCD material volumes in such examples may extend from the apices and the curved free surface.

Most of the examples so far described above exhibit a flat planar thin interfacial barrier layer derived from a refractory material which acts as a metal diffusion blocking barrier to the molten bonding material of the hard metal substrate and the molten catalyst solvent sintering aid of the polycrystalline material during the high pressure high temperature manufacturing process. However, the residual stress distribution in the PCD material volume of general composite PCD hard metal substrate bodies may be favourably altered by employing a non-flat, non-planar interface or boundary between the PCD material volume and the hard metal substrate. More explicitly, such non-planar interfaces or boundaries may have improved value in reducing tensile residual stress maxima, for example if they exhibit a general arcuitly convex curvature towards the PCD material volume.

**EXAMPLES**

Some further examples are now described in more detail and are not intended to be limiting.

**Example 1**
Rock removal bodies intended for subterranean rock drilling using drag bit designs and technology were made corresponding to the embodiment illustrated in Figure 14. This example was a combination of the two cylindrical layer PCD material volume of Figure 12 and the two cylindrical layer cemented hard metal substrate of Figure 13.

The bodies each comprised a right circular cylinder of 16 mm diameter and overall length 16 mm with one end forming a cylindrical PCD material volume of thickness 6 mm, with a cemented hard metal substrate disposed at the opposite cylindrical end of the body. The PCD material volume of each body was comprised of a first cylindrical layer, 1202, of 3.5 mm thickness extending from the flat top circular free surface of the body and a second layer, 1203, of 2.5 mm thickness separating the first PCD layer from an extant barrier boundary layer and the cemented hard metal substrate. It is intended that the first layer will completely encompass the functional working volume in use, which extends about 3mm down the barrel free surface of the PCD material volume from a chosen point at a circumferential edge of the body, this point being the point of initial contact with the rock strata.

This first layer was made from a multimodal PCD material with an average grain size of close to 10 micro meters, with the grain size distribution extending from about 1 to 30 micro meters. The term multimodal in this context refers to the starting diamond powder, which was produced by combining five separate powers, differing in average particle size distribution. The first layer was made from five component diamond powders having a single maximum in particle size distribution and hence each component being monomodal. The metal employed as catalyst solvent for partial re-crystallization of the diamond was cobalt, resulting in the interpenetrating network of the resultant PCD material being high carbon containing cobalt. The PCD material had a cobalt content of 6.7 % by volume (15.4% by weight). This composition of PCD material is known to have a linear coefficient of thermal expansion of 3.7ppm°K⁻¹.

This second layer was made from a multimodal PCD material with an average grain size of close to 6 micro meters, with the grain size distribution extending from about 1 to 20 micro meters. This layer was made from three component diamond powders having a single maximum in particle size distribution and hence each component being monomodal. The metal employed as catalyst solvent for partial re-crystallization of the diamond was cobalt, resulting in the interpenetrating metallic network of the resultant PCD material being high carbon containing cobalt. The PCD material had a cobalt content of 11.5 % by volume (24.7% by weight). This composition of PCD material is known to have a linear coefficient of thermal expansion of 4.4ppm°K⁻¹.

The two layer hard metal substrate was made from tungsten carbide cemented with cobalt. The layer at the base of the substrate, 1303 in Figure 14, was 8 mm long with 14 weight % (22.2 volume %) cobalt content. This grade of hard metal had a linear coefficient of thermal expansion of 6.01 ppm°K⁻¹. The layer separating this layer from the thin barrier layer material and the PCD material volume, 1304 in Figure 14, was 2 mm thick, with a 6 weight% (10.1 volume %) cobalt content. This grade of hard metal had a linear coefficient of thermal expansion of 5.09ppm°K⁻¹.
Note that for these bodies the linear coefficient of thermal expansion of the PCD material increased in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate, with the linear coefficient of thermal expansion of the hard metal substrate decreasing in the general direction away from the central point of the base of the body towards the interfacial barrier layer separating the PCD material volume and the cemented hard metal substrate.

Precursor compounds for the metal, in this case cobalt, are precipitated, nucleated and grown on the surface of the diamond particles by using reactions between soluble reactants whilst suspending the diamond powder in water. After removal from suspension, drying and subsequent heat treatment in reducing environments the diamond particle surfaces are decorated in pure metal particles, thus ensuring an extremely high degree of homogeneity of mixing with respect to the diamond and metal components.

The stock mass for the material of the first PCD layer was produced using the following procedural steps.

100g of diamond powder was suspended in 2.5 litres of de-ionised water. The diamond powder comprised 5 separate monomodal diamond fractions each differing in average particle size. The diamond powder was thus considered to be multimodal. The 100g of diamond powder was made up as follows: 5g of average particle size 1.8 micro meters, 16g of average particle size 3.5 micro meters, 7g of average particle size 5 micro meters, 44g of average particle size 10 micro meters and 28g of average particle size 20 micro meters. This multimodal particle size distribution extended from about 1 micro meter to about 30 micro meters.

The diamond powder had been rendered hydrophilic by prior acid cleaning and washing in de-ionised water. To the suspension an aqueous solution of cobalt nitrate and a separate aqueous solution of sodium carbonate were simultaneously slowly added while the suspension was vigorously stirred. The cobalt nitrate solution was made by dissolving 93 g of cobalt nitrate hexahydrate crystals, Co(NO$_3$)$_2$.6H$_2$O, in 200ml of de-ionised water. The sodium carbonate solution is made by dissolving 33.9 g of pure anhydrous sodium carbonate, Na$_2$CO$_3$, in 200ml of de-ionised water. The cobalt nitrate and sodium carbonate reacted in solution precipitating cobalt carbonate CoCO$_3$, as per the following equation,

$$\text{Co(NO}_3\text{)}_2 \text{soln} + \text{Na}_2\text{CO}_3 \text{soln} \xrightarrow{\text{H}_2\text{O diamond suspension}} \text{CoCO}_3 \xrightarrow{+ 2\text{NaNO}_3 \text{soln}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldot
diamond particle surfaces. The sodium nitrate product of reaction was removed by a few cycles of decantation and washing in de-ionised water. The powder was finally washed in pure ethyl alcohol, removed from the alcohol by decantation and dried under vacuum at 60°C.

The dried powder was then placed in an alumina ceramic boat with a loose powder depth of about 5mm and heated in a flowing stream of argon gas containing 5% hydrogen. The top temperature of the furnace was 750°C which was maintained for 2 hours before cooling to room temperature. This furnace treatment dissociated and reduced the cobalt carbonate precursor to form pure cobalt particles, with some carbon in solid solution decorating the surfaces of the diamond particles. In this way it was ensured that the cobalt particles were always smaller than the diamond particles with the cobalt being homogeneously distributed. The conditions of the heat treatment were chosen with reference to the standard cobalt carbon phase diagram of the literature. At 750°C it may be seen that the solid solubility of carbon in cobalt is low. At these conditions the formation of amorphous non-diamond carbon at this temperature is low and traces of non-diamond carbon could be detected in the final diamond-metal particulate mass. The resultant powder mass of multimodal diamond particles with an overall 15.4 weight % of cobalt metal decorating the diamond particle surfaces had a pale light grey appearance. This powder stock mass for the first PCD material layer was stored under dry nitrogen in an air-tight container to prevent oxidation of the fine cobalt decorating the diamond surfaces.

The stock mass for the material of the second PCD layer was produced using the following procedural steps.

100g of diamond powder was suspended in 2.5 litres of de-ionised water. The diamond powder comprised 3 separate monomodal diamond fractions each differing in average particle size. The diamond powder was thus considered to be multimodal. The 100g of diamond powder was made up as follows: 18g of average particle size 4 micro meters, 70g of average particle size 6 micro meters and 12g of average particle size 12 micro meters. This multimodal particle size distribution extended from about 1 micro meter to about 20 micro meters.

The same sequential steps were then carried to precipitate a cobalt carbonate precursor for the cobalt metal onto the surfaces of the diamond particles as that for the stock mass for the first PCD layer material save that the cobalt nitrate solution was made by dissolving 160g of cobalt nitrate hexahydrate crystals, Co(NO$_3$)$_2$·6H$_2$O, in 200ml of de-ionised water. The sodium carbonate solution is made by dissolving 60g of pure anhydrous sodium carbonate, Na$_2$CO$_3$ in 200ml of de-ionised water. The resultant powder mass of multimodal diamond particles with an overall 24.7 weight % of cobalt metal decorating the diamond particle surfaces was stored under dry nitrogen in an air-tight container to prevent oxidation of the fine cobalt decorating the diamond surfaces.

For each rock removal body, so called green body assemblies were constructed using thin walled tantalum canisters. The qualitative and geometric arrangement of the green body assemblies is schematically illustrated in Figure 15, the drawing not being to scale.
2.3g of the stock particulate mass for the first PCD material layer, 1501, was pre-compacted into a tantalum canister, 1503, in a uniaxial hard metal compaction die to form a semi-dense right cylindrical layer at the bottom of the canister. This was followed by pre-compacting 2.8g of the stock particulate mass for the second PCD material layer, 1502, into place into canister 1503.

A 2.0 mm thick tungsten carbide 6 weight % (10.1 volume %) cobalt hard metal disc, 1504, was then inserted into the bottom of a tantalum canister, 1506, followed by 8.5 mm thick tungsten carbide 14 weight % (22.2 volume %) cobalt hard metal disc, 1505. These two hard metal discs together formed the substrate. The tantalum encompassed end of the substrate was then inserted into the open end of the diamond mass containing canister, 1503, such that the end wall of the canister, 1506, separated the diamond mass from the substrate, and further uniaxial compacted to form the assembly. After appropriate trimming of the open end of the canisters, the assembly was inserted into a third canister of slightly larger diameter, 1507, vacuum degassed and sealed under vacuum using procedures known in the art. To consolidate further, to a higher green density and to eliminate or radically reduce spatial density variations, the canister assembly was then subjected to a cold isostatic compaction procedure at a pressure of 200MPa. Several so called green body assemblies were produced in this manner.

Note that the end wall of canister, 1506, separates the diamond particulate masses which will form the PCD material volume and the hard metal substrate. This thin, about 50 micro meters thick, tantalum end wall layer acted as a barrier to both the molten cementing cobalt of the substrate and the molten cobalt of the PCD material layer during sintering of the diamond PCD layer at high pressure and temperature. In this way the metallic component of the PCD material volume and the cementing metal of the hard metal substrate were independent of one another, independently derived and did not interacted during the high pressure high temperature manufacturing process. After the high pressure sintering of the PCD material volume an extant partially carburised tantalum layer separated the PCD material volume from the substrate.

To sinter the diamond particles of PCD material volume, by partial re-crystallisation of the diamond, each green body assembly was then placed in an assembly of compactable ceramic, salt components suitable for high pressure high temperature treatment as well established in the art. The material immediately surrounding the encapsulated green body was made from very low shear strength material such as sodium chloride. This provides for the green bodies being subjected to pressures which approach a hydrostatic condition. In this way pressure gradient induced distortions of the green body may be mitigated.

The green body canister assemblies were then subjected to a pressure of 6GPa and a temperature of approximately 1560°C for 1 hour using a belt type high pressure apparatus as well established in the art. During the end phase of the high pressure high temperature procedure the temperature was slowly reduced over several minutes to approximately 750°C, maintained at this value and then the pressure was reduced to ambient conditions. The high pressure assembly was then allowed to cool to ambient conditions before extraction from the high pressure apparatus. This procedure during the end
phase of the high pressure high temperature treatment was thought to allow the surrounding salt media to remain in a plastic state during the removal of pressure and so prevent or inhibit shear forces bearing upon the now sintered PCD body.

The fully dense, right cylindrical bodies were then brought to dimensions of 16 mm diameter and 16 mm long, by finishing procedure such as fine diamond grinding and polishing as well established in the art. Several samples of the embodiment represented by Figure 14, with two layers of differing PCD material, and two layers of differing tungsten carbide/cobalt hard metal substrate were in this way prepared, performed well in laboratory rock removal testing and did not display significant chipping and spalling behaviour.

Example 2

Rock removal bodies intended for subterranean rock drilling using roller cone bit designs and technology were made corresponding to the example illustrated in Figure 10d. The bodies each comprised a right circular cylinder with one end forming a generally convex surface, specifically a hemisphere, with a PCD material volume extending from the apex, 1001, of the hemisphere. A hard metal substrate was disposed at the opposite cylindrical end of the body. This substrate was made of a cobalt cemented tungsten carbide hard metal, with 12.75 weight percent of cobalt. The PCD material volume was separated from and bonded to the cemented cylindrical hard metal substrate by a partially carburized tantalum interfacial layer of 50 micro meters thickness, indicated by the line 1003 in figure 10d. This layer acted as a barrier during manufacture and prevented the molten cementing metal of the hard metal substrate and the molten metal of the PCD material volume interacting. The diameter of the cylindrical part of the bodies was finished to be 16 mm. The overall length of each body was 27 mm as measured from the apex, 1001, along the axis of the body to the center of the circular base. The length of the PCD material volume as measured from the apex, 1001, to the intersection of the axial line, 1002, with the interfacial layer, 1003, was 16 mm. The length of the tungsten carbide/cobalt substrate was close to 11 mm.

The PCD material volume was made of a multimodal PCD material with an average grain size of close to 10 micro meters, with the grain size distribution extending from about 1 to 30 micro meters. The term multimodal in this context refers to the starting diamond powder, which was produced by combining five separate powers, differing in average particle size distribution. Each made of five component diamond powders having a single maximum in particle size distribution and hence being monomodal. The metal employed as catalyst solvent for partial re-crystallization of the diamond was cobalt, resulting in the interpenetrating network of the resultant PCD material being high carbon containing cobalt. The PCD material had a cobalt content of 9 % by volume (20% by mass).

Precursor compounds for the metal, in this case cobalt, are precipitated, nucleated and grown on the surface of the diamond particles by using reactions between soluble reactants whilst suspending the diamond powder in water. After removal from suspension, drying and subsequent heat treatment in reducing environments the diamond particle surfaces are decorated in pure metal particles, thus
ensuring an extremely high degree of homogeneity of mixing with respect to the diamond and metal components.

The procedural sequential steps of the method for this example are as follows.

100g of diamond powder was suspended in 2.5 litres of de-ionised water. The diamond powder comprised 5 separate monomodal diamond fractions each differing in average particle size. The diamond powder was thus considered to be multimodal. The 100g of diamond powder was made up as follows: 5g of average particle size 1.8 micro meters, 16g of average particle size 3.5 micro meters, 7g of average particle size 5 micro meters, 44g of average particle size 10 micro meters and 28g of average particle size 20 micro meters. This multimodal particle size distribution extended from about 1 micro meter to about 30 micro meters.

The diamond powder had been rendered hydrophilic by prior acid cleaning and washing in de-ionised water. To the suspension an aqueous solution of cobalt nitrate and a separate aqueous solution of sodium carbonate were simultaneously slowly added while the suspension was vigorously stirred. The cobalt nitrate solution was made by dissolving 125 grams of cobalt nitrate hexahydrate crystals, Co(NO$_3$)$_2$.6H$_2$O, in 200ml of de-ionised water. The sodium carbonate solution is made by dissolving 45.5g of pure anhydrous sodium carbonate, Na$_2$CO$_3$, in 200ml of de-ionised water. The cobalt nitrate and sodium carbonate reacted in solution precipitating cobalt carbonate CoCO$_3$, as per the following equation,

$$\text{Co(NO}_3\text{)}_2\text{soln} + \text{Na}_2\text{CO}_3\text{soln} \xrightarrow{\text{H}_2\text{O diamond suspension}} \text{CoCO}_3 + 2\text{NaNO}_3\text{soln} \quad (1)$$

In the presence of the suspended diamond powder particles, with their hydrophilic surface chemistry, the cobalt carbonate crystals nucleated and grew on the diamond particle surfaces. The cobalt carbonate precursor compound for cobalt, took the form of whisker shaped crystals decorating the diamond particle surfaces. The sodium nitrate product of reaction was removed by a few cycles of decantation and washing in de-ionised water. The powder was finally washed in pure ethyl alcohol, removed from the alcohol by decantation and dried under vacuum at 60°C.

The dried powder was then placed in an alumina ceramic boat with a loose powder depth of about 5mm and heated in a flowing stream of argon gas containing 5% hydrogen. The top temperature of the furnace was 750°C which was maintained for 2 hours before cooling to room temperature. This furnace treatment dissociated and reduced the cobalt carbonate precursor to form pure cobalt particles, with some carbon in solid solution decorating the surfaces of the diamond particles. In this way it was ensured that the cobalt particles were always smaller than the diamond particles with the cobalt being homogeneously distributed. The conditions of the heat treatment were chosen with reference to the standard cobalt carbon phase diagram of the literature. At 750°C it may be seen that the solid solubility of carbon in cobalt is low. At these conditions the formation of amorphous non-
diamond carbon at this temperature is low and traces of non-diamond carbon could be detected in the final diamond-metal particulate mass. The resultant powder mass of multimodal diamond particles with an overall 20 weight % of cobalt metal decorating the diamond particle surfaces had a pale light grey appearance. The powder mass was stored under dry nitrogen in an air-tight container to prevent oxidation of the fine cobalt decorating the diamond surfaces.

For each rock removal body 11.4g of the stock particulate mass was then pre-compacted into a hemispherical ended tantalum canister in a uniaxial hard metal compaction die to form a semi-dense hemispherical ended right cylindrical body. The 12.75 weight % cobalt, tungsten carbide cylindrical substrate for each body was inserted into a tantalum canister with wall thickness of 50 micro meters. The tantalum encompassed end of the substrate was then inserted into the open end of the diamond mass containing canister such that the end wall of the canister separated the diamond mass from the substrate, and further uniaxial compacted to form an assembly. After appropriate trimming of the open end of the canisters, the assembly was inserted into a third canister of slightly larger diameter, vacuum degassed and sealed under vacuum using procedures known in the art. To consolidate further, to a higher green density and to eliminate or radically reduce spatial density variations, the canister assembly was then subjected to a cold isostatic compaction procedure at a pressure of 200MPa. Several so called green body assemblies were produced in this manner.

Each green body assembly was then placed in an assembly of compactable ceramic, salt components suitable for high pressure high temperature treatment as well established in the art. The material immediately surrounding the encapsulated green body was made from very low shear strength material such as sodium chloride. This provides for the green bodies being subjected to pressures which approach a hydrostatic condition. In this way pressure gradient induced distortions of the green body may be mitigated.

The green body canister assemblies were then subjected to a pressure of 6GPa and a temperature of approximately 1560°C for 1 hour using a belt type high pressure apparatus as well established in the art. During the end phase of the high pressure high temperature procedure the temperature was slowly reduced over several minutes to approximately 750°C, maintained at this value and then the pressure was reduced to ambient conditions. The high pressure assembly was then allowed to cool to ambient conditions before extraction from the high pressure apparatus. This procedure during the end phase of the high pressure high temperature treatment was thought to allow the surrounding salt media to remain in a plastic state during the removal of pressure and so prevent or inhibit shear forces bearing upon the now sintered PCD body.

The fully dense, hemispherical ended right cylindrical bodies were then brought to dimensions of 16mm diameter and 27mm long by finishing procedure such as fine diamond grinding and polishing as well established in the art.

In summary, one or more examples including polycrystalline bodies not deriving their required metal from substrate materials may be formed of PCD bodies of high homogeneity with their greatest dimensions possibly being around 150mm or more, limited only by the design and scale of high
pressure and high temperature apparatus known in the art and currently available. In addition, the PCD materials exploited in such examples may include PCD material compositions not accessible using conventional PCD manufacture, such as fine grained PCD with low metal contents, coarse grain PCD with high metal contents, both outside the band 501 of Figure 5. Also, the range and accuracy of composition of highly specific alloys to aid the diamond particle sintering in the examples may be significantly extended beyond those conventionally accessible, the latter being largely restricted to the cementing metal of sintered hard metal substrates. A potentially beneficial consequence may be that the PCD bodies may be macroscopically residual stress free at a scale greater than ten times the average grain size of the PCD material where the maximum grain size is no more than three times the average grain size. This distinguishes such PCD bodies over conventional prior art PCD bodies made attached to large substrates where, due to differential expansion and contraction on return-to-room conditions during manufacture, large and significant residual stress distributions may arise in both the PCD volume and substrate volume of the overall body. These large residual stress distributions involving both compressive and tensile regions are taught to be the life determining aspects in rock drilling applications. The PCD bodies of the examples therefore may assist in increasing the life of cutters incorporating such PCD bodies in rock drilling applications.

The rock removal bodies of the examples may maintain the conventional overall shape of a simple right cylinder and the well-established custom and practice of brazing these cylinders into the housing bodies of the tools into which they are to be inserted via the cemented hard metal substrate may also be maintained. Thus, some of the examples may provide a means of exploiting the key advantages of free standing PCD bodies but with the inclusion of a substrate attached during the PCD material manufacturing procedure. In this way, the standard extremely well-established designs of drill bits and housing bodies together with the brazing related attachment procedures may be exploited and modifications and re-designs of such aspects may not be required. Thus some examples thus concern the means of making rock removal bodies, of general right cylindrical shape, where the attributes of the procedures of making free standing PCD bodies are made use of but substrates of general hard metal materials are attached in-situ during the manufacturing procedures.

While various embodiments have been described with reference to a number of examples, those skilled in the art will understand that various changes may be made and equivalents may be substituted for elements thereof and that these examples are not intended to limit the particular embodiments disclosed.

References


Claims

1. A rock removal body for a drag bit rock drilling application comprising a polycrystalline diamond (PCD) material volume bonded to a cemented hard metal substrate along an interface; wherein:
   a. the body has an overall body volume, and is of a right circular cylindrical shape having a circumferential edge, and a barrel portion, the PCD material volume being axially asymmetrically disposed at one end of the body;
   b. the PCD material volume has a thickness from the circumferential edge axially along the surface of the barrel portion of around 3mm or greater and a functional working volume, the functional working volume being the volume of PCD material progressively worn away in use during useful life of the rock removal body to a form a final wear surface, the functional working volume having a maximum extent such that the final wear surface does not intersect the interface of the PCD material volume and the substrate;
   c. the interface bonding the polycrystalline diamond material volume to the cemented hard metal substrate comprising a layer of a third material derived from a refractory material, the third material being a metal diffusion blocking barrier material to molten bonding material of the substrate and molten catalyst solvent sintering aid of the PCD material volume during formation of the rock removal body;
   d. the PCD material volume comprising a plurality of inter-bonded diamond grains having an average diamond grain size forming a diamond network and a metallic component forming a metallic network, and the substrate comprising a cementing metal, the metallic component and the cementing metal being independent of one another, independently derived, have not interacted during the high pressure high temperature manufacturing process, are measurably distinguishable and are pre-selected to be different with respect to their alloy composition;
   e. the PCD material at least encompasses the functional working volume and is homogeneous in that the PCD material is spatially constant and invariant with respect to diamond network to metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten times the average diamond grain size, the maximum diamond grain size in the diamond network being less than three times the average diamond grain size.

2. The rock removal body of claim 1, wherein the PCD material volume has a thickness and the substrate has a length along the barrel portion, wherein the ratio of the PCD thickness to the substrate length measured along the barrel portion of the cylinder, is always less than 1.0 and the volume of PCD material in the rock removing body is less than about 50 per cent of the overall body volume.

3. The rock removal body of claim 2, wherein the body has a base formed by a free face of the substrate, and wherein the PCD material volume is a cylindrical layer having a thickness of about 3mm or greater, the thin layer of third material forming the interface between the PCD material volume and the substrate having a thickness, wherein the combined thickness of the thin layer
forming the interface and the length of the substrate is about 8 mm or greater, the thin layer
forming the interface being substantially flat, substantially planar and substantially parallel to the
base of the body.

4. The rock removal body of claim 3, wherein the body has a diameter in the range of about 12mm
to about 20 mm, and the body has an overall length measured along the barrel portion in the
range of about 11mm to about 20mm.

5. The rock removal body of any one of claims 1 to 4, wherein the PCD material which at least
encompasses the functional working volume has an average grain size of less than about 10
microns and a metal content in the range of about 5 to about 9 volume per cent.

6. A rock removal body for a roller cone bit rock drilling application comprising a polycrystalline
diamond (PCD) material volume bonded to a cemented hard metal substrate along an interface;
wherein:

a. the body comprises a right circular cylinder portion having an associated radius, one end of the
cylinder portion forming a generally convex curved surface or surfaces with an apex, or one end
forming a general chisel shape where two or more flat surfaces meet to form an apex, the PCD
material volume being axially asymmetrically disposed extending from and abutting the apex, the
cemented hard metal substrate being disposed at the opposite end of the cylinder;

b. the PCD material volume has a thickness from the apex in the axial direction of the cylinder
portion of the body to the interface with the substrate equal to or greater than the radius of the
cylinder portion of the body, the PCD material volume further comprising a functional working
volume, the functional working volume being the volume of PCD material progressively worn
away in use during useful life of the rock removal body to a form a final wear surface, the
functional working volume having a maximum extent such that the maximum extent of the
functional working volume is less than the thickness of the PCD material volume thickness; the
functional working volume extending from the apex in the axial direction;

c. the interface bonding the PCD material volume to the substrate comprising a thin layer of a third
material derived from a refractory material, the third material being a metal diffusion blocking
barrier material to molten bonding material of the substrate and molten catalyst solvent sintering
aid of the PCD material volume during formation of the rock removal body;

d. the PCD material volume comprising a plurality of inter-bonded diamond grains having an
average diamond grain size forming a diamond network and a metallic component forming a
metallic network, and the substrate comprising a cementing metal, the metallic component and
the cementing metal being independent of one another, independently derived, have not
interacted during the high pressure high temperature manufacturing process, are measurably
distinguishable and are pre-selected to be different with respect to their alloy composition;
e. the PCD material at least encompasses the functional working volume and is homogeneous in
that the PCD material is spatially constant and invariant with respect to diamond network to
metallic network volume ratio, wherein the homogeneity is measured at a scale greater than ten
times the average diamond grain size, the maximum diamond grain size in the diamond network
being less than three times the average diamond grain size.

7. The rock removal body of claim 6, wherein the generally convex curved surface or surfaces
comprising the apex is any one of hemi-spheroidal, prolate hemi-spheroidal, oblate hemi-
spheroidal, or hemispherical; wherein the body comprises a shoulder formed by the line of
departure of the barrel portion extending into the generally convex curved surface; and wherein
the thin layer of the third material forming the interface between the PCD material volume and
the substrate intersects the barrel portion below the shoulder.

8. The rock removal body of claim 7, wherein the generally convex curved surface is hemispherical,
the radius of the cylinder portion of the body being around 8mm.

9. The rock removal body of claim 6, wherein the generally convex curved surface is a cone having
a rounded apex, wherein the rounded apex has an associated radius, the radius of the rounded
apex being between around a quarter to around a half of the radius of the cylinder portion of the
body, wherein the body comprises a shoulder formed by the line of departure of the barrel portion
extending into the generally convex curved surface; and wherein the thin layer of the third
material forming the interface between the PCD material volume and the substrate intersects the
barrel portion below the shoulder.

10. The rock removal body of claim 9, wherein one end of the body forms a chisel shape comprising
a conical surface with a rounded apex modified by two symmetrical inclined flat surfaces which
meet at the rounded apex, wherein the body comprises a shoulder formed by the line of
departure of the barrel portion extending into the generally convex curved surface; and wherein
the thin layer of the third material forming the interface between the PCD material volume and
the substrate intersects the barrel portion below the shoulder.

11. The rock removal body of any one of claims 6 to 10, wherein the volume of the PCD material
volume is greater than the volume of the substrate.

12. The rock removal body of claim 11 wherein the substrate has an associated radius and a
thickness measured as the length of the barrel portion which the substrate forms, the length of
the substrate being greater than the radius of the substrate.
13. The rock removal body of any one of claims 6 to 12, wherein the average diamond grain size of the PCD material volume is in the range of about 1 micron to about 30 microns; and wherein the transverse rupture strength of the PCD material is greater than 1200 MPa as measured using a three point bend test.

14. The rock removal body of claim 13, wherein the average diamond grain size of the PCD material volume is greater than around 10 microns.

15. The rock removal body of any one of claims 1 to 14, wherein the thin layer of the third material forming the interface between the PCD material volume and the substrate comprises a partially carburised refractory metal layer having a thickness of between around 20 microns and around 100 microns, the partially carburised refractory metal layer comprising any one or more of tantalum, vanadium, molybdenum, zirconium, tungsten and alloys thereof.

16. The rock removal body of claim 15, wherein the thin layer of the third material forming the interface between the PCD material volume and the substrate comprises a partially carburised layer of tantalum.

17. The rock removal body of any one of claims 1 to 14, wherein the thin layer of the third material forming the interface between the PCD material volume and the substrate comprises a PVD or a CVD deposited continuous ceramic layer having a thickness of greater than around 3 microns, the thin layer of the third material comprising any one or more of nitrides of the elements of groups IVA, VIA and/or VIa of the periodic table.

18. The rock removal body of claim 17, wherein the thin layer of the third material comprises titanium nitride.

19. The rock removal body of any one of claims 1 to 18, wherein the metallic network of the PCD material comprises a cobalt carbon alloy having an average cobalt content; and wherein the cementing metal of the substrate comprises a cobalt-tungsten-carbon alloy having an associated average cobalt content; the average cobalt content of the PCD material volume being less than around 9 volume per cent (around 20 weight per cent) and the average cobalt content of the substrate being less than around 16.3 volume per cent (around 10 weight per cent).

20. The rock removal body of any one of claims 1 to 19, wherein the PCD material volume has a linear coefficient of thermal expansion that increases in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the thin layer of the third material forming the interface between the PCD material volume and the substrate.
21. The rock removal body of claim 20, wherein the metal forming the metallic network of the PCD material volume is invariant as regards the metal type or alloy across the dimensions of the PCD material volume; and wherein the metallic content of the PCD material increases in the general direction away from a point which is part of the functional working volume which initially bears upon the rock in use, towards the thin layer of the third material forming the interface between the PCD material volume and the substrate.

22. The rock removal body of claim 21, wherein the PCD material volume comprises two or more layers of differing PCD material, the first layer of lowest linear coefficient of thermal expansion and metal content extends from the free surface of the PCD material volume and encompasses the functional working volume, the second or subsequent layers of higher linear coefficient of thermal expansion and metal content separating the first layer from the thin layer forming the interface between the PCD material volume and the substrate.

23. The rock removal body of any one of claims 1 to 22, wherein the body has a base portion formed by the free surface of the substrate; wherein the substrate has an associated linear coefficient of thermal expansion which decreases away from the central point of the base of the body towards the thin layer forming the interface between the PCD material volume and the substrate.

24. The rock removal body of claim 23, wherein the substrate comprises a cementing metal material and a hard compound, the cementing metal material and the hard compound being invariant as regards metal type and molecular composition, the amount of cementing metal decreasing in a direction away from the central point of the base of the body towards the thin layer of the third material forming the interface between the PCD material volume and the substrate.

25. The rock removal body of claim 24, wherein the substrate comprises two or more layers of differing hard metal material, the first layer of highest linear coefficient of thermal expansion and metal content extending from the free surface of the substrate forming the base of the body, the second and/or subsequent layers being of lower linear coefficient of thermal expansion and metal content separating the first layer from the thin layer forming the interface between the PCD material volume and the substrate.

26. The rock removal body of any one of claims 20 to 25, wherein the PCD material volume is graded in composition and structure such that the linear coefficient of thermal expansion of the PCD material increases in a direction away from a point which is part of the functional working volume towards the interface, the linear coefficient of thermal expansion of the substrate decreasing in a direction away from the central point of the base of the body towards the interface.
27. The rock removal body of any one of claims 20 to 26, wherein the metal network in the PCD material volume comprises a cobalt-carbon alloy, and the substrate comprises tungsten carbide cobalt.

28. The rock removal body of any one of claims 1 to 27, wherein the thin layer forming the interface is substantially flat and substantially parallel to the base of the body.

29. The rock removal body of any one of claims 1 to 27, wherein the thin layer forming the interface is substantially non-planar and substantially convex with respect to the PCD material volume.

30. A rock removal body substantially as hereinbefore described with reference to any one embodiment as that embodiment is illustrated in Figures 6 to 15 of the accompanying drawings.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B10/573 B22F7/06 C22C26/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols):
E21B B22F C22C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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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
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“S” document member of the same patent family

Date of the actual completion of the international search
27 January 2015

Date of mailing of the international search report
18/02/2015

Name and mailing address of the ISA/Authorized officer
European Patent Office, P. B. 5818 Patentlaan 2
NL-2280 HV Rijswijk
Tel. (+31-70) 340-2040, Fax. (+31-70) 340-3018
Dekker, Derk

Form PCT/ISA/210 (second sheet) (April 2005)
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