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(54) Title:

**METHODS OF GRINDING WORKPIECES COMPRISING  
SUPERABRASIVE MATERIALS**

(57) Abstract:

A method of grinding a superabrasive workpiece includes placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the bonded abrasive article comprises a body including abrasive grains contained within a bond material, and the superabrasive workpiece has an average Vickers hardness of at least about 1 GPa, and removing material from the superabrasive workpiece at an average specific grinding energy (SGE) of not greater than about 350 J/mm<sup>3</sup>, at an average material removal (MRR) rate of at least about 8 mm<sup>3</sup>/sec for a centerless grinding operation.



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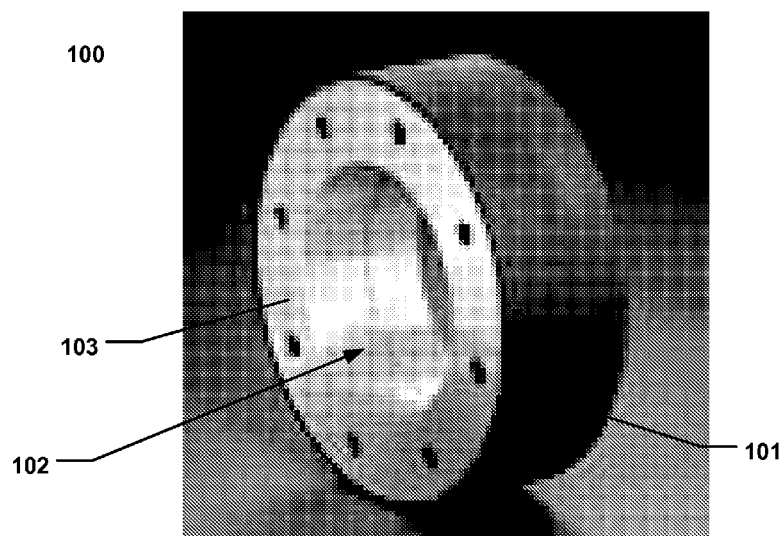
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(54) Title: METHODS OF GRINDING WORKPIECES COMPRISING SUPERABRASIVE MATERIALS



**FIG. 1**

(57) Abstract: A method of grinding a superabrasive workpiece includes placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the bonded abrasive article comprises a body including abrasive grains contained within a bond material, and the superabrasive workpiece has an average Vickers hardness of at least about 1 GPa, and removing material from the superabrasive workpiece at an average specific grinding energy (SGE) of not greater than about 350 J/mm<sup>3</sup>, at an average material removal (MRR) rate of at least about 8 mm<sup>3</sup>/sec for a centerless grinding operation.



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## METHODS OF GRINDING WORKPIECES COMPRISING SUPERABRASIVE MATERIALS

## TECHNICAL FIELD

The following is directed to abrasive articles, and more particularly, methods of using abrasive articles for grinding superabrasive workpieces.

## 5 BACKGROUND ART

Abrasives used in machining applications typically include bonded abrasive articles and coated abrasive articles. Coated abrasive articles generally include a layered article including a backing and an adhesive coat to fix abrasive grains to the backing, the most common example of which is sandpaper. Bonded abrasive tools consist of rigid, and  
10 typically monolithic, three-dimensional, abrasive composites in the form of wheels, discs, segments, mounted points, hones and other tool shapes, which can be mounted onto a machining apparatus, such as a grinding or polishing apparatus.

Bonded abrasive tools usually have three phases including abrasive grains, bond material, and porosity, and can be manufactured in a variety of `grades` and `structures` that have  
15 been defined according to practice in the art by the relative hardness and density of the abrasive composite (grade) and by the volume percentage of abrasive grain, bond, and porosity within the composite (structure).

Some bonded abrasive tools may be particularly useful in grinding and polishing hard materials, such as single crystal materials used in electronics and optics industries as well  
20 as superabrasive materials for use in industrial applications, such as earth boring. For example, polycrystalline diamond compact (PDC) cutting elements are typically affixed to the head of drill bits for earth boring applications in the oil and gas industry. The PDC cutting elements include a layer of superabrasive material (e.g., diamond), which must be ground to particular specifications. One method of shaping the PDC cutting elements is  
25 use of bonded abrasive tools, which typically incorporate abrasive grains contained within an organic bond matrix.

The industry continues to demand improved methods and articles capable of grinding superabrasive workpieces.

#### DISCLOSURE OF INVENTION

According to one aspect, a method of grinding a superabrasive workpiece includes  
5 placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the bonded abrasive article comprises a body including abrasive grains contained within a composite bond material including an organic material and a metal material. The method further includes rotating the bonded abrasive article relative to the superabrasive workpiece to remove material from the superabrasive workpiece, wherein during the step  
10 of removing material, the threshold power is not greater than about 140 W/mm.

In another aspect, a method of grinding a superabrasive workpiece includes placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the bonded abrasive article comprises a body including abrasive grains contained within a composite bond material including an organic material and a metal material, and wherein the  
15 composite bond material comprise a ratio (OM/MM) of organic material (OM) to metal material (MM) of not greater than about 0.25. The method further includes rotating the bonded abrasive article relative to the superabrasive workpiece to remove material from the superabrasive workpiece.

In still another aspect, a method of grinding a superabrasive workpiece includes placing a  
20 bonded abrasive article in contact with a superabrasive workpiece, wherein the bonded abrasive article comprises a body including abrasive grains contained within a bond material, and the superabrasive workpiece has an average Vickers hardness of at least about 5 GPa. The method further includes removing material from the superabrasive workpiece at an average specific grinding energy (SGE) of not greater than about 350  
25 J/mm<sup>3</sup> at an average material removal (MRR) rate of at least about 8 mm<sup>3</sup>/sec for a centerless grinding operation.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure may be better understood, and its numerous features and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

5 FIG. 1 includes an illustration of an abrasive article in accordance with an embodiment.

FIG. 2 includes a diagram of a grinding operation in accordance with an embodiment.

FIG. 3 includes a plot of average power (kW) versus average material removal rate ( $\text{mm}^3/\text{sec}$ ) for a bonded abrasive body according to an embodiment and a conventional sample.

10 FIG. 4 includes an image of a surface of an abrasive article in accordance with an embodiment after conducting a grinding operation.

FIG. 5 includes an image of a surface of a conventional abrasive article after conducting a grinding operation.

The use of the same reference symbols in different drawings indicates similar or identical  
15 items.

## DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The following is generally directed to abrasive articles and methods of using such abrasive articles for particular grinding operations. In particular reference to the process of forming the bonded abrasive article, initially, abrasive grains can be combined with a  
20 bond material. According to one embodiment, the bond material can be a composite bond material, having components of organic material and metal material mixed together. However, the abrasive grains may first be mixed with one of the components of the bond material. For example, the abrasive grains can be mixed with the organic material.

The abrasive grains can include materials such as oxides, carbides, borides, and nitrides  
25 and a combination thereof. In particular instances, the abrasive grains can include

superabrasive materials such as diamond, cubic boron nitride, and a combination thereof. Certain embodiments may utilize abrasive grains that consist essentially of diamond.

In further reference to the abrasive grains, the abrasive grains can have an average grit size of less than 250 microns. In other instances the abrasive grains can have an average  
5 grit size of less than 200 microns, such as less than 170 microns. Certain abrasive articles may utilize abrasive grains having an average grit size within a range between 1 micron and about 250 microns, such as between 50 microns and about 250 microns, and more particularly between about 100 microns and about 200 microns.

The mixture may utilize more than one type of abrasive grain. Moreover, the mixture  
10 may use abrasive grains having more than one average grit size. That is, for example, a mixture of abrasive grains can be used that includes large and small grit sizes. In one embodiment, a first portion of abrasive grains having, for example, a large average grit size, can be combined with a second portion of abrasive grains having, for example, a smaller average grit size than the large abrasive grains of the first portion. The first and  
15 second portions may be equal parts (e.g., weight percent) within the mixture. In other embodiments, one may utilize a mixture having a greater or lesser percentage of large and small grains as compared to each other.

A bonded abrasive article can be formed that includes a first portion of abrasive grains having an average grit size of less than about 150 microns, in combination abrasive  
20 grains having an average grit size that is greater than 150 microns. In one particular instance the mixture can include a first portion of abrasive grains having an average grit size within a range between 100 microns and 150 microns and a second portion of abrasive grains having an average grit size within a range between 150 microns and 200 microns.

25 The mixture can contain a certain content of abrasive grains such that the finally-formed bonded abrasive body includes at least about 5 vol% abrasive grains for the total volume of the body. It will be appreciated that for other exemplary abrasive articles, the content of abrasive grains within the body can be greater, such as at least about 10 vol%, at least about 20 vol%, at least about 30 vol% or even at least about 40 vol% of the total volume

of the body. In some abrasive articles, the mixture can contain an amount of abrasive grains such that the finally-formed body contains between about 5 vol% and about 60 vol%, and more particularly, between about 5 vol% and 50 vol% abrasive grains for the total volume of the body.

5 In reference to the organic material component of the bond material, some suitable organic materials include thermosets and thermoplastics. In particular, the bond material can include materials such as polyimides, polyamides, resins, aramids, epoxies, polyesters, polyurethanes, and a combination thereof. In accordance with a particular embodiment, the organic material can include a polyarenazole. In a more particular  
10 embodiment, the organic material can include polybenzimidazole (PBI). Additionally, the bond material may include some content of resin material, such as phenolic resin. In such embodiments utilizing a resin, the resin can be present in minor amounts, and may be used in combination with other organic materials.

The mixture can contain a certain content of organic material such that the finally-formed  
15 bonded abrasive body includes not greater than about 20 vol% of organic material for the total volume of the bond material. In other embodiments, the amount of organic material within the bond material may be less, for example, not greater than about 18 vol%, not greater than about 16 vol%, not greater than about 14 vol%, or even not greater than about 10 vol%. In particular instances, the body can be formed such the organic material  
20 is present in an amount within a range between about 1 vol% and about 20 vol%, such as between about 1 vol% and about 19 vol%, and more particularly within a range between about 2 vol% and 12 vol%.

After forming a mixture of organic material and abrasive grains, a metal material may be added to facilitate the formation a composite bond material, wherein the composite bond  
25 material contains the organic material and metal material. In certain instances, the metal material can include metals or metal alloys. The metal material may incorporate one or more transition metal elements. In accordance with one embodiment, the metal material can include copper, tin, and a combination thereof. In fact, embodiments herein may



utilize a metal material that consists essentially of bronze, and contains a ratio of copper:tin ratio of approximately 60:40 by weight.

A certain content of metal material may be added to the mixture, such that the finally-formed bonded abrasive body contains at least about 20 vol% metal material for the total  
5 volume of the bond material. In other instances, the amount of metal material within the composite bond material can be greater, such as on the order of at least about 30 vol%, at least about 40 vol%, at least about 50 vol%, or even at least about 60 vol%. Particular embodiments may utilize an amount of metal material within a range between about 20 vol% and about 99 vol%, such as between about 30 vol% and about 95 vol%, or even  
10 between about 50 vol% and about 95 vol% for the total volume of the composite bond material.

After forming the mixture containing the abrasive grains, organic material, and metal material, the mixture can be agitated or mixed for a sufficient duration to ensure uniform distribution of the components within each other. After ensuring the mixture is suitably  
15 mixed, the process of forming the abrasive article can continue by treating the mixture.

In accordance with one embodiment, treating the mixture can include a pressing process. More particularly, the pressing process can include a hot pressing process, wherein the mixture is heated and pressed simultaneously to give the mixture a suitable shape. The hot pressing operation can utilize a mold, wherein the mixture is placed in the mold, and  
20 during the hot pressing operation, the application of heat and pressure is utilized to form the mixture to the contours of the mold and give the mixture a suitable, finally-formed shape.

In accordance with one embodiment, the hot pressing operation can be conducted at a pressing temperature of not greater than about 600°C. The pressing temperature is  
25 considered the maximum soaking temperature utilized during hot pressing to facilitate proper formation of the bond material. In accordance with another embodiment, hot pressing process can be conducted at a pressing temperature of not greater than about 550°C, such as not greater than 500°C. In particular instances, hot pressing can be

completed at a pressing temperature with a range between about 400°C and 600°C and more particularly within a range between about 400°C and 490°C.

The pressing process can be conducted at a particular pressure that is a maximum and sustained pressure exerted upon the mixture suitable to form the mixture to the desired shape. For example, the hot pressing process can be conducted at a maximum pressing pressure of not greater than about 10 tons/in<sup>2</sup>. In other embodiments, the maximum pressing pressure may be less, such as not greater than about 8 tons/in<sup>2</sup>, not greater than about 6 tons/in<sup>2</sup>. Still, certain hot pressing processes can utilize a pressing pressure within a range between about 0.5 tons/in<sup>2</sup> and about 10 tons/in<sup>2</sup>, such as within a range between 0.5 tons/in<sup>2</sup> and 6 tons/in<sup>2</sup>.

In accordance with an embodiment, the pressing process can be conducted such that the pressing pressure and pressing temperature are held for a duration of at least about 5 minutes. In other embodiments, the duration may be greater, such as at least about 10 minutes, at least about 20 minutes, or even at least 30 minutes.

Generally, the atmosphere utilized during the treating operation can be an inert atmosphere, comprising an inert species (e.g., noble gas), or a reducing atmosphere having a limited amount of oxygen. In other instances, the pressing operation can be conducted in an ambient atmosphere.

Upon completion of the hot pressing operation, the resulting form can be an abrasive article comprising abrasive grains contained within a composite bond material.

FIG. 1 includes an abrasive article in accordance with an embodiment. As illustrated, the abrasive article 100 can include a bonded abrasive body 101 having a generally annular shape and defining a central opening 102 extending axially through the body 101. The bonded abrasive body 101 can include abrasive grains contained within the composite bond material as described herein. In accordance with an embodiment, the abrasive article 100 can be an abrasive wheel having a central opening 102, which aids coupling of the bonded abrasive body to suitable grinding machinery, which is designed to rotate the abrasive article for material removal operations. Moreover, the insert 103 can be placed

around the body 101 and define the central opening 102 and in particular instances, the insert 103 may be a metal material which can facilitated coupling of the body 101 to machinery.

5 The bonded abrasive body 101 can define an abrasive rim extending circumferentially around an edge of the abrasive article 100. That is, the body 101 can extend along the outer peripheral edge of the insert 103, which is affixed (e.g., using fasteners, adhesives, and a combination thereof) to the body 101.

The body 101 can have particular amounts of abrasive grain, bond material, and porosity. The body 101 can include the same amount (vol%) of abrasive grains as described herein.

10 The body 101 can include at least 10 vol% composite bond material for the total volume of the body. In other instances, the body 101 can include a greater content of composite bond material, such as at least 20 vol%, at least about 30 vol%, at least about 40 vol%, or even at least about 50 vol% for the total volume of the body 101. In other instances, the body 101 can be formed such that the composite bond material comprises between about

15 10 vol% and about 80 vol%, such as between about 10 vol% and 60 vol%, or even between about 20 vol% and about 60 vol% bond material for the total volume of the body 101.

Notably, the body 101 can be formed to have a particular ratio based on the volume percent of the organic materials (OM) to metal materials (MM) contained within the composite bond material. For example, the composite bond material can have a ratio

20 (OM/MM) of organic material by volume (OM) to metal material by volume (MM) having a value of not greater than about 0.25. In accordance with other embodiments, the abrasive article can be formed such that the composite bond material ratio is not great than about 0.23, such as not greater than about 0.20, not greater than about 0.18, not

25 greater than about 0.15, or even not greater than about 0.12. In particular instances, the body can be formed such that the composite bond material has a ratio of organic material to metal material (OM/MM) within a range between about 0.02 and 0.25, such as between about 0.05 and 0.20, between about 0.05 and about 0.18, between about 0.05 and about 0.15, or even between about 0.05 and about 0.12.

The abrasive article may be formed such that the body 101 contains a certain content of porosity. For example, the body 101 can have a porosity of not greater than about 10 vol% for the total volume of the body 101. In other instances, the body 101 can have a porosity of not greater than about 8 vol%, such as not greater than about 5 vol%, or even not greater than about 3 vol%. Still, the body, 101 can be formed such that the porosity is within a range between 0.5 vol% and 10 vol%, such as between 0.5 vol% and about 8 vol%, between about 0.5 vol% and 5 vol%, or even between about 0.5 vol% and 3 vol% of the total volume of the body 101. The majority of the porosity can be closed porosity comprising closed and isolated pores within the bond material. In fact, in certain instances, essentially all of the porosity within the body 101 can be closed porosity.

In addition to the features described herein, the body 101 can be formed such that it has a composite bond material wherein not less than about 82% of the abrasive grains within the body 101 are contained within the metal material of the composite bond material. For example, the body 101 can be formed such that not less than 85%, such as not less than about 87%, not less than about 90%, or even not less than about 92% of the abrasive grains within the body 101 are contained within the metal material of the composite bond material. The body 101 can be formed such that between about 82% to about 97%, and more particularly, between 85% and about 95% of the abrasive grains within the body 101 can be contained within the metal material of the bond material.

The bonded abrasive article of the embodiments can utilize a composite bond having a fracture toughness of not greater than  $3.0 \text{ MPa m}^{0.5}$ . In fact, certain bonded abrasive articles can have a bond material having a fracture toughness that is not greater than about  $2.5 \text{ MPa m}^{0.5}$ , such as not greater than about  $2.0 \text{ MPa m}^{0.5}$ , or even not greater than about  $1.8 \text{ MPa m}^{0.5}$ . Certain bonded abrasive articles can utilize a composite bond material having a fracture toughness between about  $1.5 \text{ MPa m}^{0.5}$  and about  $3.0 \text{ MPa m}^{0.5}$ , such as within a range between about  $1.5 \text{ MPa m}^{0.5}$  and  $2.5 \text{ MPa m}^{0.5}$  and even within a range between about  $1.5 \text{ MPa m}^{0.5}$  and about  $2.3 \text{ MPa m}^{0.5}$ .

The abrasive articles herein may be particularly suitable for removing material from particular workpieces, such as by a grinding process. In particular embodiments, the

bonded abrasive articles of embodiments herein can be particularly suitable for grinding and finishing of workpieces incorporating super hard materials or superabrasive materials. That is, the workpieces can have an average Vicker's hardness of 5 GPa or greater. In fact, certain workpieces, which may be finished by the bonded abrasive  
5 articles of the embodiments herein, can have an average Vicker's hardness of at least about 10 GPa, such as at least about 15 GPa, or even at least about 25 GPa.

In fact, in certain instances, the bonded abrasive articles herein are particularly suitable for grinding of materials, which are also used in abrasive applications. One particular example of such workpieces includes polycrystalline diamond compact (PDC) cutting  
10 elements, which may be placed on the heads of earthboring drill bits used in the oil and gas industry. Generally, PDC cutting elements can include a composite material having an abrasive layer overlying a substrate. The substrate can be a cermet (ceramic/metallic) material. That is, the substrate can include some content of metal, typically an alloy or superalloy material. For example, the substrate can have a metal material that has a  
15 Mohs hardness of at about 8. The substrate can include a metal element, which can include one or more transition metal elements. In more particular instances, the substrate can include a carbide material, and more particularly tungsten carbide, such that the substrate can consist essentially of tungsten carbide.

The workpieces that may be ground by the bonded abrasive articles herein may include  
20 cutting elements. Furthermore, certain workpieces can be particularly brittle materials, having a fracture toughness of at least about  $4.0 \text{ MPa m}^{0.5}$ . In fact, the workpiece can have a fracture toughness of at least about  $5.0 \text{ MPa m}^{0.5}$ , such as at least about  $6.0 \text{ MPa m}^{0.5}$ , or even at least about  $8.0 \text{ MPa m}^{0.5}$ . Further, in certain instances, the workpiece can have a fracture toughness that is not greater than about  $16.0 \text{ MPa m}^{0.5}$ , such as not greater  
25 than  $15.0 \text{ MPa m}^{0.5}$ ,  $12.0 \text{ MPa m}^{0.5}$ , or  $10.0 \text{ MPa m}^{0.5}$ . Certain workpieces can utilize a material having a fracture toughness within a range including about  $4.0 \text{ MPa m}^{0.5}$  to about  $16.0 \text{ MPa m}^{0.5}$ , such as within a range including about  $4.0 \text{ MPa m}^{0.5}$  to  $12.0 \text{ MPa m}^{0.5}$  and even within a range including about  $4.0 \text{ MPa m}^{0.5}$  to about  $10.0 \text{ MPa m}^{0.5}$ .

The abrasive layer of the workpiece may be bonded directly to the surface of the substrate. The abrasive layer can include hard materials such as carbon, fullerenes, carbides, borides, and a combination thereof. In one particular instance, the abrasive layer can include diamond, and more particularly may be a polycrystalline diamond layer.

5 Some workpieces, and particularly PDC cutting elements, can have an abrasive layer consisting essentially of diamond. In accordance with at least one embodiment, the abrasive layer can be formed of a material having a Mohs hardness of at least about 9. Moreover, the workpiece may have a generally cylindrically shaped body, particularly in reference to PDC cutting elements.

10 It has been found that the bonded abrasive articles of embodiments herein are particularly suitable for grinding and/or finishing of workpieces incorporating super-hard materials (e.g., metal and metal alloys such as nickel-based superalloys and titanium-based super alloys, carbides, nitride, borides, fullerenes, diamond, and a combination thereof). During a material removal (i.e., grinding) operation, the bonded abrasive body can be  
15 rotated relative to the workpiece to facilitate material removal from the workpiece.

One such material removal process is illustrated in FIG. 2. FIG. 2 includes a diagram of a grinding operation in accordance with an embodiment. In particular, FIG. 2 illustrates a centerless grinding operation utilizing the abrasive article 100 in the form of an abrasive wheel incorporating the bonded abrasive body 101. The centerless grinding operation  
20 can further include a regulating wheel 201, which can be rotated at a particular speed to control the grinding process. As further illustrated, for a particular centerless grinding operation, a workpiece 203 can be disposed between the abrasive wheel 100 and the regulating wheel 201. The workpiece 203 can be supported in a particular position between the abrasive wheel 100 and the regulating wheel 201 by a support 205,  
25 configured to maintain the position of the workpiece 203 during grinding.

According to one embodiment, during centerless grinding, the abrasive wheel 100 can be rotated relative to the workpiece 203, wherein the rotation of the abrasive wheel 100 facilitates movement of the bonded abrasive body 101 relative a particular surface (e.g., a circumferential side surface of the cylindrical workpiece) of the workpiece 203, and thus,

grinding of the surface of the workpiece 203. Additionally, the regulating wheel 201 can be rotated at the same time the abrasive wheel 100 is rotated to control the rotation of the workpiece 203 and control certain parameters of the grinding operation. In certain instances, the regulating wheel 201 can be rotated in the same direction as the abrasive wheel 100. In other grinding processes, the regulating wheel 201 and the abrasive wheel 100 can be rotated in opposite directions relative to each other.

It has been noted that by utilizing the bonded abrasive bodies of the embodiments herein, the material removal processes can be conducted in a particularly efficient manner as compared to prior art products and processes. For example, the bonded abrasive body can conduct grinding of a workpiece comprising a superabrasive material at an average specific grinding energy (SGE) of not greater than about  $350 \text{ J/mm}^3$ . In other embodiments, the SGE can be less, such as not greater than about  $325 \text{ J/mm}^3$ , such as greater than about  $310 \text{ J/mm}^3$ , not greater than about  $300 \text{ J/mm}^3$ , or even not greater than  $290 \text{ J/mm}^3$ . Still, for certain grinding operations, the bonded abrasive material can remove material from the workpiece at an average SGE within a range between about  $50 \text{ J/mm}^3$  and about  $350 \text{ J/mm}^3$ , such as between about  $75 \text{ J/mm}^3$  and about  $325 \text{ J/mm}^3$ , or even within a range of between about  $75 \text{ J/mm}^3$  and about  $300 \text{ J/mm}^3$ .

It should be noted that certain grinding parameters (e.g., specific grinding energy) can be achieved in combination with other parameters, including for example, particular material removal rates (MRR). For example, the average material removal rate can be at least about  $8 \text{ mm}^3/\text{sec}$ . In fact, greater material removal rates have been achieved, such as on the order of at least about  $10 \text{ mm}^3/\text{sec}$ , such as at least about  $12 \text{ mm}^3/\text{sec}$ , at least about  $14 \text{ mm}^3/\text{sec}$ , at least about  $16 \text{ mm}^3/\text{sec}$ , or even at least about  $18 \text{ mm}^3/\text{sec}$ . In accordance with particular embodiments, grinding operations utilizing the bonded abrasive bodies herein can achieve average material removal rates within a range between about  $8 \text{ mm}^3/\text{sec}$  and about  $40 \text{ mm}^3/\text{sec}$ , such as between about  $14 \text{ mm}^3/\text{sec}$  and about  $40 \text{ mm}^3/\text{sec}$ , such as between about  $18 \text{ mm}^3/\text{sec}$  and about  $40 \text{ mm}^3/\text{sec}$ , and even between about  $20 \text{ mm}^3/\text{sec}$  and  $40 \text{ mm}^3/\text{sec}$ .

The grinding operation utilizing the bonded abrasive articles of embodiments herein and a workpiece comprising superabrasive material can be conducted at a threshold power that is not greater than about 150 W/mm. Notably, the threshold power is normalized for the contact width of the abrasive article. In other embodiments, the threshold power during the grinding operation can be less, such as not greater than about 140 W/mm, not greater than about 130 W/mm, not greater than about 110 W/mm kW, not greater than about 100 W/mm, not greater than about 90 W/mm, or even not greater than about 75 W/mm. Certain grinding operations can be conducted at a threshold power within a range between about 20 W/mm and about 150 W/mm, such as between about 20 W/mm and about 130 W/mm, such as between about 20 W/mm and 110 W/mm, or even between 20 W/mm and 90 W/mm.

Certain grinding properties (e.g., specific grinding energy, threshold power, material removal rates etc.) can be achieved in combination with particular aspects of the bonded abrasive and grinding process, including for example, particular wheel geometries. For example, the grinding properties herein can be achieved on abrasive articles in the shape of abrasive wheels (see, FIG. 1), wherein the wheels have a diameter of at least about 5 inches, at least about 7 inches, at least about 10 inches, or even at least about 20 inches. In certain instances, the abrasive wheel can have an outer diameter within a range between about 5 inches and about 40 inches, such as between about 7 inches and about 30 inches.

The grinding properties herein can be achieved on abrasive articles in the shape of abrasive wheels (see, FIG. 1), wherein the wheels can have a width, as measured across the width of the abrasive layer defining the rim of the wheel, of at least about 0.5 inches, at least about 1 inch, at least about 1.5 inches, at least about 2 inches, at least about 4 inches, or even at least about 5 inches. Particular embodiments can utilize an abrasive wheel having a width within a range between about 0.5 inches and about 5 inches, such as between about 0.5 inches and about 4 inches, or even between about 1 inch and about 2 inches.



In particular instances, the material removal operations include a centerless grinding operation wherein the speed of the abrasive wheel is at least about 900 m/min, such as on the order of at least about 1000 m/min, at least about 1200 m/min, or even at least about 1500 m/min. Particular processes can utilize a grinding wheel speed within a range  
5 between about 1000 m/min and about 3000 m/min, such as between about 1200 m/min and about 2800 m/min, or even between about 1500 m/min and about 2500m/min.

In particular instances, the material removal operations include a centerless grinding operation wherein the speed of the regulating wheel is at least about 5 m/min, such as on the order of at least about 10 m/min, at least about 12 m/min, or even at least about 20  
10 m/min. Particular processes can utilize a regulating wheel speed within a range between about 5 m/min and about 50 m/min, such as between about 10 m/min and about 40 m/min, or even between about 20 m/min and about 30 m/min.

The grinding process may also utilize a particular through infeed rate per grinding operation, which is a measure of the radial depth of engagement between the abrasive  
15 article and the workpiece. In particular instances, the infeed rate per grind can be at least about 0.01 mm, at least about 0.02 mm, and even at least about 0.03 mm. Still, the grinding operation is typically set up such that the infeed rate per grind is within a range between about 0.01 mm and about 0.5 mm, or even between about 0.02 mm and about 0.2 mm. Additionally, the grinding process can be completed such that the through-feed  
20 rate of the workpieces is between about 20 cm/min and about 150 cm/min, and more particularly between about 50 cm/min and about 130 cm/min.

It will further be appreciated that in certain centerless grinding operations, the regulating wheel can be angled relative to workpiece and the abrasive wheel to facilitate through-feed of the workpieces. In particular instances, the regulating wheel angle is not greater  
25 than about 10 degrees, such as not greater than about 8 degrees, not greater than about 6 degrees, and even not greater than about 4 degrees. For certain centerless grinding operations, the regulating wheel can be angled relative to the workpiece and the abrasive wheel within a range between about 0.2 degrees and about 10 degree, such as between

about 0.5 degrees and about 5 degrees, and more particularly within a range between about 1 degree and about 3 degrees.

#### EXAMPLE

The following includes a comparative example of a bonded abrasive body (S1) formed  
5 according to an embodiment herein compared to a conventional abrasive material (C1) designed to grind superabrasive materials.

Sample S1 is formed by combining a mixture of large and small diamond grains, wherein the small diamond grains have an average size of U.S. mesh 100/120 (i.e., average grit size of 125-150 microns) and large diamond grains having a U.S. mesh size of 80/100  
10 (i.e., average grit size of 150-175 microns). The large and small mixture of diamond grains are mixed in equal parts.

The mixture of large and small diamonds is mixed with approximately 25 grams of an organic bond material consisting of polybenzimidazole (PBI) commercially available from Boedeker Plastics Inc. Thereafter, approximately 1520 grams of metal bond is  
15 added to the mixture. The metal bond material is a bronze (60/40 of Sn/Cu) composition available as DA410 from Connecticut Engineering Associates Corporation.

The mixture is thoroughly mixed and poured into a mold. The mixture is then hot pressed according to the following procedures. Initially, a line pressure of 60 psi is applied to the mixture. The mixture is then heated to 395°C. A full pressure of 10  
20 tons/in<sup>2</sup> is then applied and the mixture is heated to 450°C for 20 minutes, followed by a cool down.

The finally-formed bonded abrasive article is formed into the shape of an abrasive wheel having an outer diameter of 8 inches and a wheel width of approximately 1 inch. The bonded abrasive article has approximately 62 vol% composite bond material, wherein  
25 90% of the bond material is the metal bond material and 10% of the bond material is the organic material. The bonded abrasive article of sample S1 has approximately 38 vol%

abrasive grains. The bonded abrasive article includes a minor amount of porosity, generally, less than 1 vol%.

The conventional sample (C1) is formed by combining a mixture of large and small diamond grains, wherein the small diamond grains have an average grit of U.S. mesh 140/170 (i.e., 150 microns) and the large diamond grains have an average grit size of U.S. mesh 170/200 (i.e., 181 microns). The large and small mixture of diamond grains are mixed in equal parts.

The mixture of large and small diamonds is mixed with an organic bond material consisting of resin and lime, commonly available as DA69 from Saint-Gobain Abrasives.

An amount of SiC grains are also added to the mixture, wherein the SiC grains have an average grit size of 800 U.S. mesh and are available as DA49 800 Grit from Saint-Gobain Abrasives Corporation. Additionally, a minor amount (i.e., 3-4 vol%) of furfural is added to the mixture as DA148, available from Rogers Corporation, New Jersey, USA.

The mixture is thoroughly mixed and poured into a mold. The mixture is then hot pressed according to the following procedures. Initially, the mixture is placed in the mold and the mixture is heated to 190°C. A full pressure of 3 tons/in<sup>2</sup> is then applied for 15 minutes, followed by a cool down. After hot pressing, the formed abrasive undergoes a post-forming bake at 210°C for 16 hours.

Sample C1 is formed into an abrasive wheel having essentially the same dimensions as the abrasive wheel of Sample S1. Sample C1 has approximately 28 vol% abrasive grains, 42 vol% organic bond material (phenolic resin), approximately 25 vol% of SiC grit (U.S. Mesh 800), and approximately 3-4 vol% furfural. Sample C1 is available from Norton Abrasives as a PCD resinoid grinding wheel. Sample C1 had the same dimensions as the sample S1 wheel.

Samples C1 and S1 are used to grind superabrasive workpieces (i.e., PDC cutting elements having tungsten carbide substrates and polycrystalline diamond abrasive layers) in a centerless grinding operation. The parameters of the centerless grinding operation are as follows: an abrasive wheel speed of 6500ft/min [1981 m/min], a regulating wheel

speed of 94 ft/min [29 m/min], a regulating wheel angle of 2 degrees, a depth of cut approximately 0.001 in radially (0.002 in change in diameter targeted per grind), and a through feed rate with manual assist approximately 40 in/min [101 cm/min].

FIG. 3 includes a plot of average power (kW) versus average material removal rate (mm<sup>3</sup>/sec) for the grinding operation carried out using samples S1 (plot 301) and C1 (plot 302). As clearly illustrated, sample S1 utilizes less power at all measured average material removal rates as compared to the sample C1, thus demonstrating that sample S1 was capable of conducting grinding in a more efficient manner than the sample C1. In fact, even at the highest material removal rate (27 mm<sup>3</sup>/sec [1.2 in<sup>3</sup>/mm]) for sample S1, the average power (approximately 4.5 kW) was about the same or less than the threshold power of sample C1 (approximately 4.8 kW), which is extrapolated based on the plot 302 crossing the y-axis of average power. Note that the threshold power can be normalized to the size of the samples based on the contact width of the wheel, such that the normalized threshold power of 4kW/25.4 mm is equal to 150 W/mm.

Furthermore, upon evaluation of the surfaces of the bonded abrasive samples S1 and C1 after conducting centerless grinding operations on certain workpieces, it was noted that samples C1 and S1 demonstrated significantly different surface morphologies.

FIGs. 4 and 5 include images of the surfaces of the samples S1 and C1 respectively after conducting grinding operations. As illustrated, the surface of sample S1 as provided in FIG. 4, demonstrates regions 401 and 403 along the surface that have maintained significant surface roughness, and therefore provides evidence that the abrasive article is capable of continued abrasive operations. Additionally, the rough regions 401 and 403 demonstrate the bonded abrasive article is capable of performing the abrasive task in an efficient manner and has improved life. By contrast, the surface of the sample C1, as shown in FIG. 5, demonstrates regions 501 of the bond that have smeared and have become smooth. These regions 501 demonstrate a bond that has a high amount of friction with the workpiece, which is evidence of an inefficient grinding operation as compared to the sample S1. In short, sample S1 is capable of achieving greater efficiency during grinding of super-hard workpieces than the conventional sample C1.

The foregoing bonded abrasive articles of embodiments herein and methods of forming and using such bonded abrasive articles represent a departure from the state-of-the-art. In particular, the bonded abrasive bodies utilize a combination of features including a mixture of abrasive grains, abrasive grain types and sizes, composite bond material  
5 having particular ratios of metal and organic materials, and certain properties that improve the efficiency of grinding operations on super-hard and/or superabrasive workpieces. Moreover, the methods described herein, including the method of making the bonded abrasive and the method of using the bonded abrasive for particular grinding operations represent a departure from the state of the art. It is noted that use of bonded  
10 abrasive articles according to the embodiments herein in certain grinding operations allows for more efficient grinding and extended life of the bonded abrasive article.

In the foregoing, reference to specific embodiments and the connections of certain components is illustrative. It will be appreciated that reference to components as being coupled or connected is intended to disclose either direct connection between said  
15 components or indirect connection through one or more intervening components to carry out the methods as discussed herein. As such, the above-disclosed subject matter is to be considered illustrative, and not restrictive, and the appended claims are intended to cover all such modifications, enhancements, and other embodiments, which fall within the true scope of the present invention. Thus, to the maximum extent allowed by law, the scope  
20 of the present invention is to be determined by the broadest permissible interpretation of the following claims and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

The disclosure will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing description includes various features may be grouped  
25 together or described in a single embodiment for the purpose of streamlining the disclosure. This disclosure is not to be interpreted as reflecting an intention that the claimed embodiments require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive subject matter may be directed to less than all features of any of the disclosed embodiments.

## WHAT IS CLAIMED IS:

1. A method of grinding a superabrasive workpiece comprising:  
placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the  
bonded abrasive article comprises a body including abrasive grains contained  
5 within a bond material, and the superabrasive workpiece has an average Vickers  
hardness of at least about 5 GPa; and  
removing material from the superabrasive workpiece at an average specific grinding  
energy (SGE) of not greater than about  $350 \text{ J/mm}^3$  at an average material removal  
(MRR) rate of at least about  $8 \text{ mm}^3/\text{sec}$  for a centerless grinding operation.

2. A method of grinding a superabrasive workpiece comprising:  
placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the  
bonded abrasive article comprises a body including abrasive grains contained  
within a composite bond material including an organic material and a metal  
15 material, and wherein the composite bond material comprise a ratio (OM/MM) of  
organic material (OM) to metal material (MM) of not greater than about 0.25; and  
rotating the bonded abrasive article relative to the superabrasive workpiece to remove  
material from the superabrasive workpiece.

3. A method of grinding a superabrasive workpiece comprising:  
placing a bonded abrasive article in contact with a superabrasive workpiece, wherein the  
bonded abrasive article comprises a body including abrasive grains contained  
within a composite bond material including an organic material and a metal  
material, and  
25 rotating the bonded abrasive article relative to the superabrasive workpiece to remove  
material from the superabrasive workpiece, wherein during the step of removing  
material, the threshold power is not greater than about  $140 \text{ W/mm}$ .

4. The method of any of claims 1, 2, or 3, wherein the workpiece comprises a superabrasive material selected from the group of materials consisting of diamond, cubic boron nitride, fullerenes, and a combination thereof.

5 5. The method of claim 4, wherein the workpiece comprises a polycrystalline diamond compact (PDC) cutting element.

6. The method of any of claims 1, 2, or 3, wherein the workpiece is a composite material comprising a substrate and an abrasive layer overlying the substrate.

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7. The method of claim 6, wherein the substrate comprises a cermet.

8. The method of claim 6, wherein the substrate comprises a metal.

15 9. The method of claim 7, wherein the substrate comprises a metal having a Mohs hardness of at least about 8.

10. The method of claim 7, wherein the substrate comprises a metal element comprising a transition metal material.

20

11. The method of claim 10, wherein the substrate comprises tungsten carbide.

12. The method of claim 11, wherein the substrate consists essentially of tungsten carbide.

25

13. The method of claim 6, wherein the abrasive layer is bonded directly to the substrate.

14. The method of claim 6, wherein the abrasive layer comprises a material selected  
30 from the group consisting of carbon, fullerenes, carbides, borides, and a combination thereof.

15. The method of claim 14, wherein the abrasive layer comprises diamond.

16. The method of claim 15, wherein the abrasive layer comprises polycrystalline  
5 diamond.

17. The method of claim 15, wherein the abrasive layer consists essentially of  
diamond.

18. The method of claim 6, wherein the abrasive layer has a Mohs hardness of at least  
10 about 9.

19. The method of any of claims 1, 2, or 3, wherein the workpiece is in the shape of  
cylindrical body.

20. The method of any of claims 1, 2, or 3, wherein the process of removing material  
15 is a centerless grinding operation.

21. The method of any of claims 1, 2, or 3, wherein the bonded abrasive article is  
20 rotated relative to the workpiece at a rate of at least about 900 m/min.

22. The method of claim 21, wherein the bonded abrasive article is rotated relative to  
the workpiece at a rate within a range between about 1000 m/min and about 3000 m/min.

23. The method of any of claims 1, 2, or 3, wherein a speed of a regulating wheel is at  
25 least about 5 m/min.

24. The method of claim 23, wherein the speed of the regulating wheel is within a  
range between about 5 m/min and about 50 m/min.



25. The method of any of claims 1, 2, or 3, wherein during the step of removing material, material is removed from the workpiece at an average material removal rate (MRR) of at least about 10 mm<sup>3</sup>/sec, at least about 12 mm<sup>3</sup>/sec, at least about 14 mm<sup>3</sup>/sec, at least about 16 mm<sup>3</sup>/sec, or at least about 18 mm<sup>3</sup>/sec.

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26. The method of claim 25, wherein the average material removal rate (MRR) is within a range between about 8 mm<sup>3</sup>/sec and about 40 mm<sup>3</sup>/sec, between about 14 mm<sup>3</sup>/sec and about 40 mm<sup>3</sup>/sec, between about 18 mm<sup>3</sup>/sec and about 40 mm<sup>3</sup>/sec, or between about 20 mm<sup>3</sup>/sec and about 40 mm<sup>3</sup>/sec.

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27. The method of any of claims 1, 2, or 3, wherein the body comprises a fracture toughness within a range between about 1.5 MPa m<sup>0.5</sup> and about 3.0 MPa m<sup>0.5</sup>.

28. The method of any of claims 1, 2, or 3, wherein the bond material comprise a ratio (OM/MM) of organic material (OM) to metal material (MM) of not greater than about 0.23, not greater than about 0.20, or not greater than about 0.15.

29. The method of any of claims 1, 2, or 3, wherein the body comprises at least about 10 vol% bond material of the total volume of the body.

20

30. The method any of claims 1, 2, or 3, wherein the body comprises at least about 10 vol% abrasive grains of the total volume of the body.

31. The method of any of claims 1, 2, or 3, wherein the body comprises a porosity of not greater than about 10 vol% of the total volume of the body.

25

32. The method of any of claims 1, 2, or 3, wherein the body comprises a porosity within a range between about 0.5 vol% and about 10 vol% of the total volume of the body.

30

33. The method of any of claims 1, 2, or 3, wherein the body comprises an annular shape.

34. The method of any of claims 1, 2, or 3, wherein the body defines an abrasive rim  
5 extending circumferentially around an edge of the abrasive article.

35. The method of any of claims 1, 2, or 3, wherein the workpiece comprises a fracture toughness of at least about  $4.0 \text{ MPa m}^{0.5}$ , at least about  $5.0 \text{ MPa m}^{0.5}$ , at least about  $6.0 \text{ MPa m}^{0.5}$ , or at least about  $8.0 \text{ MPa m}^{0.5}$ .

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36. The method of any of claims 1, 2, or 3, wherein the workpiece comprises a fracture toughness of not greater than about  $16.0 \text{ MPa m}^{0.5}$ , not greater than about  $15.0 \text{ MPa m}^{0.5}$ , not greater than about  $12.0 \text{ MPa m}^{0.5}$ , or not greater than about  $10.0 \text{ MPa m}^{0.5}$ .

15 37. The method of any of claims 1, 2, or 3, wherein the workpiece comprises a fracture toughness within a range including about  $4.0 \text{ MPa m}^{0.5}$  to about  $16.0 \text{ MPa m}^{0.5}$ , about  $4.0 \text{ MPa m}^{0.5}$  to about  $12.0 \text{ MPa m}^{0.5}$ , or about  $4.0 \text{ MPa m}^{0.5}$  to about  $10.0 \text{ MPa m}^{0.5}$ .

20 38. The method of any of claims 1 or 2, wherein during the step of removing material, a threshold power is not greater than about  $150 \text{ W/mm}$ , not greater than about  $140 \text{ W/mm}$ , not greater than about  $130 \text{ W/mm}$ , not greater than about  $120 \text{ W/mm}$ , not greater than about  $110 \text{ W/mm}$ , or not greater than about  $100 \text{ W/mm}$ .

25 39. The method of any of claims 2 or 3, wherein the composite bond material has a fracture toughness of not greater than about  $3.0 \text{ MPa m}^{0.5}$ , not greater than about  $2.5 \text{ MPa m}^{0.5}$ , or not greater than about  $2.0 \text{ MPa m}^{0.5}$ .

30 40. The method of any of claims 2 or 3, wherein the organic material comprises a material selected from the group of materials consisting of polyimides, polyamides, resin, epoxies aramids, polyesters, polyurethanes, and a combination thereof.

41. The method of any of claims 2 or 3, wherein the organic material comprises polybenzimidazole (PBI).

5 42. The method of any of claims 2 or 3, wherein the organic material comprises not greater than about 20 vol% of the total volume of the bond material.

43. The method of any of claims 2 or 3, wherein the organic material comprises between about 1 vol% and about 20 vol% of the total volume of the bond material.

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44. The method of any of claims 2 or 3, wherein the metal material comprises a transition metal element.

45. The method of claim 44, wherein the metal material comprises copper and tin.

15

46. The method of claim 45, wherein the metal material consists essentially of bronze.

47. The method of any of claims 2 or 3, wherein metal material comprises at least about 20 vol% of the total volume of the bond material.

20

48. The method of any of claims 2 or 3, wherein not less than about 82% or not less than 90% of the abrasive grains are contained within the metal material of the composite bond material.

25 49. The method of any of claims 2 or 3, wherein the workpiece comprises an average Vickers hardness of at least about 5 GPa.

50. The method of any of claims 2 or 3, wherein the composite bond material comprises a fracture toughness of not greater than about  $3.0 \text{ MPa m}^{0.5}$ .

30

51. The method of claim 50, wherein the fracture toughness is within a range between about  $1.5 \text{ MPa m}^{0.5}$  and about  $3.0 \text{ MPa m}^{0.5}$ .

52. The method of claim 1, wherein the average Vickers hardness of the workpiece is  
5 at least about 10 GPa, at least about 15 GPa, or at least about 25 GPa.

53. The method of claim 1, wherein the SGE is not greater than about  $325 \text{ J/mm}^3$ , not greater than about  $310 \text{ J/mm}^3$ , not greater than about  $300 \text{ J/mm}^3$ , or not greater than about  $290 \text{ J/mm}^3$ .

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54. The method of claim 1, wherein the SGE is within a range between about  $50 \text{ J/mm}^3$  and about  $350 \text{ J/mm}^3$ , between 11 about  $75 \text{ J/mm}^3$  and about  $325 \text{ J/mm}^3$ , or between about  $75 \text{ J/mm}^3$  and about  $300 \text{ J/mm}^3$ .