US 20140007517A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2014/0007517 A1

(43) Pub. Date: Jan. 9, 2014

Sarangi et al.

(54) **ABRASIVE ARTICLE FOR LOWER SPEED GRINDING OPERATIONS**

(71) Applicants: **Nilanjan Sarangi**, Shrewsbury, MA (US); **Sandhya Jayaraman Rukmani**, Worcester, MA (US); **Stephen E. Fox**, Worcester, MA (US); **Russell L. Krause**, Shrewsbury, MA (US)

(72) Inventors: **Nilanjan Sarangi**, Shrewsbury, MA (US); **Sandhya Jayaraman Rukmani**, Worcester, MA (US); **Stephen E. Fox**, Worcester, MA (US); **Russell L. Krause**, Shrewsbury, MA (US)

(21) Appl. No.: **13/934,714**

(22) Filed: **Jul. 3, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/668,860, filed on Jul. 6, 2012, provisional application No. 61/677,655, filed on Jul. 31, 2012.

Publication Classification

(51) **Int. Cl.**
B24D 3/06 (2006.01)

(52) **U.S. Cl.**
CPC ***B24D 3/06*** (2013.01)
USPC **51/308**; 51/309

(57) **ABSTRACT**

An abrasive article includes a bonded abrasive body having abrasive particles contained within a bond material. The bonded abrasive body may include an abrasive particle-to-bond material interfacial modulus of elasticity (MOE) of at least about 225 GPa. The bonded abrasive body may be configured to grind a workpiece comprising metal at a speed of less than about 60 m/s.

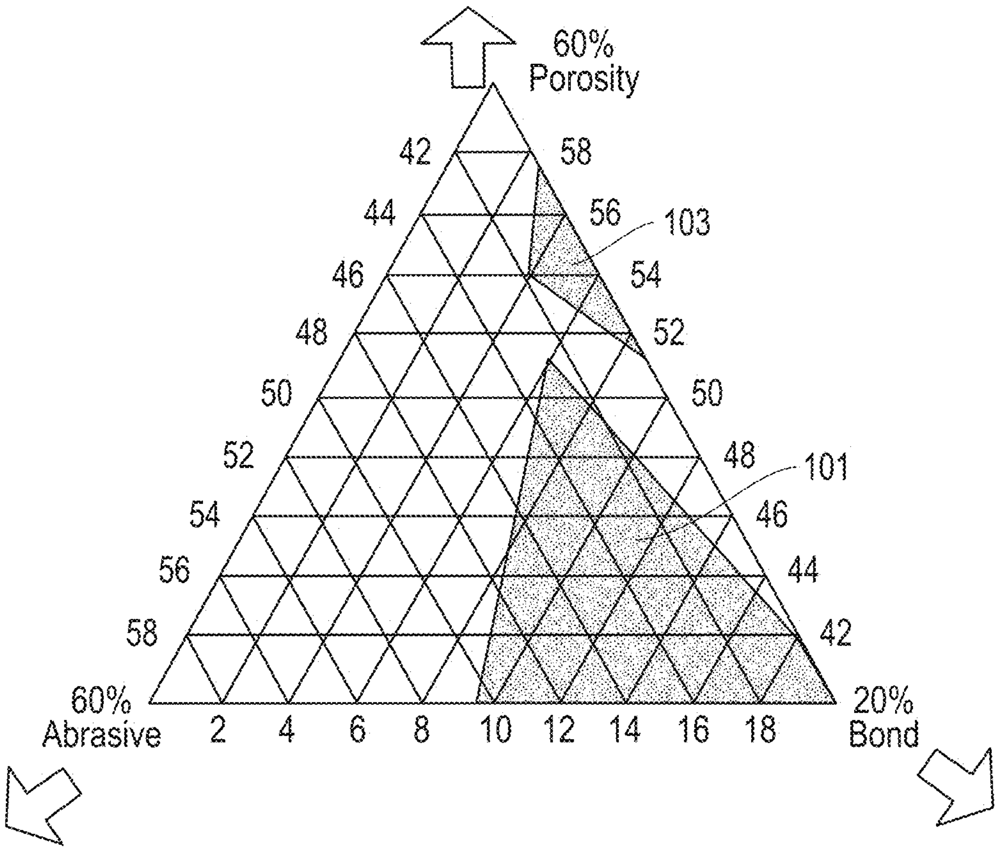
60%
Porosity
42
44
46
48
50
52
54
56
58
58
56
54
52
50
48
46
44
42
103
101
60%
Abrasive
2
4
6
8
10
12
14
16
18
20%
Bond

FIG. 1

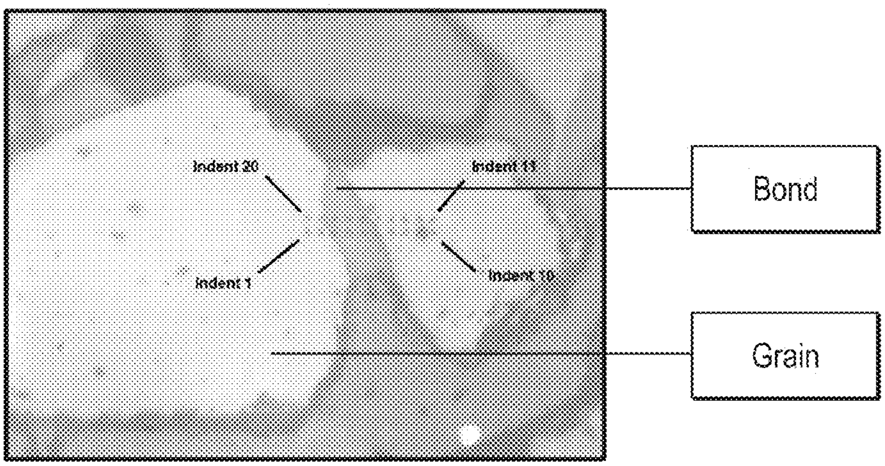

FIG. 2

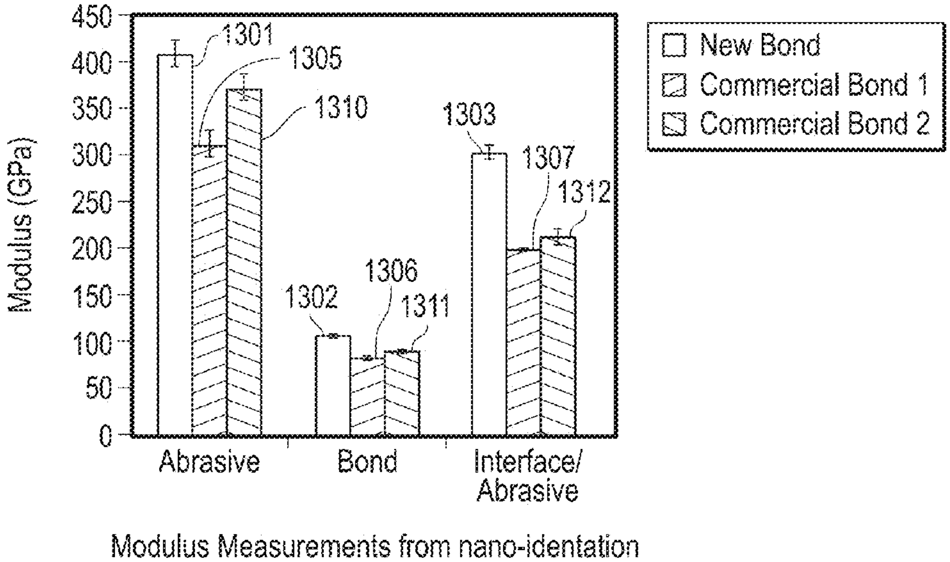
Modulus (GPa)
450
400
350
300
250
200
150
100
50
0
1301
1305
1310
1302
1306
1311
1303
1307
1312
Abrasive
Bond
Interface/
Abrasive
New Bond
Commercial Bond 1
Commercial Bond 2
Modulus Measurements from nano-identation

FIG. 3

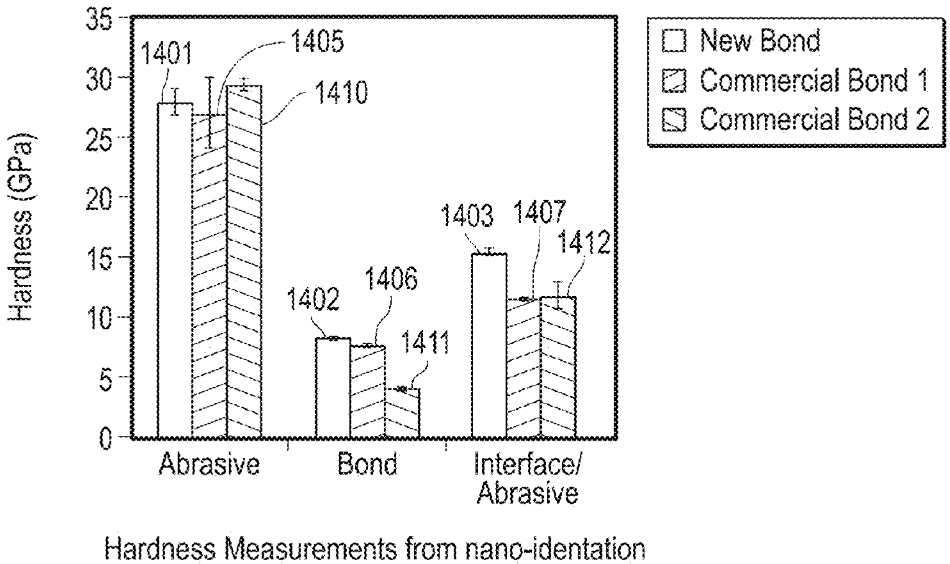
Hardness (GPa)
35
30
25
20
15
10
5
0
1401
1405
1410
1402
1406
1411
1403
1407
1412
Abrasive
Bond
Interface/
Abrasive
New Bond
Commercial Bond 1
Commercial Bond 2
Hardness Measurements from nano-identation

FIG. 4

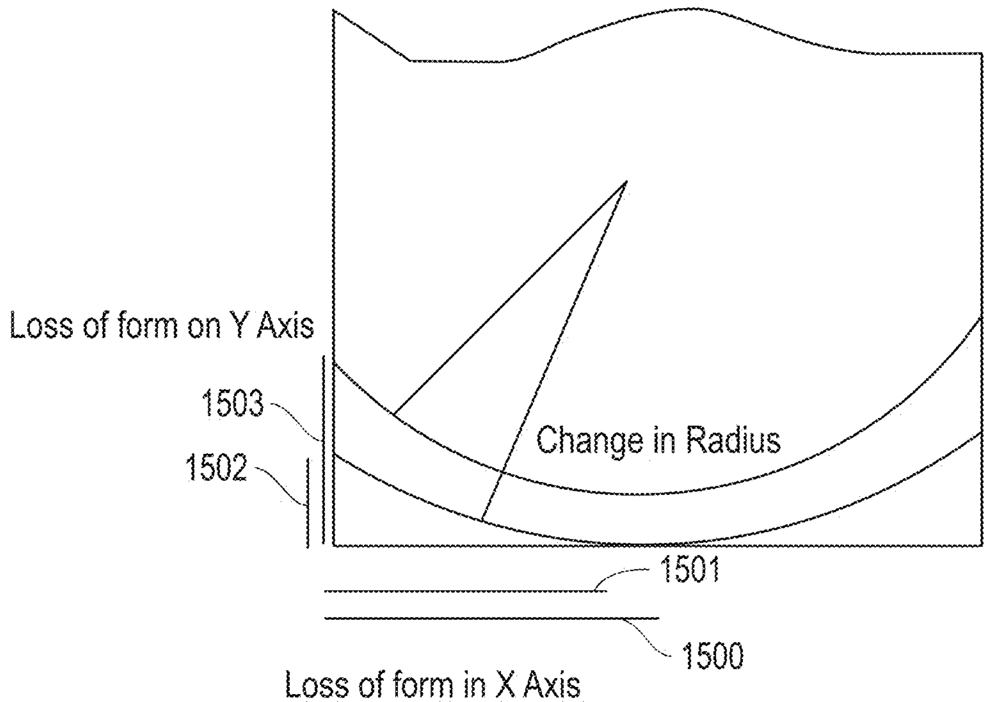
Loss of form on Y Axis
1503
1502
Change in Radius
1501
1500
Loss of form in X Axis

FIG. 5

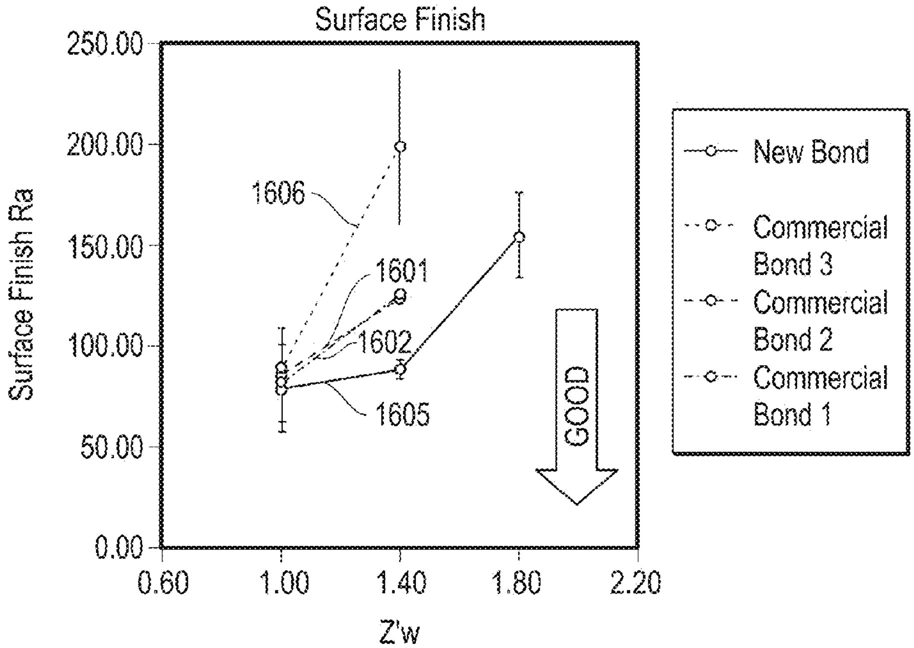
Surface Finish
250.00
200.00
150.00
100.00
50.00
0.00
Surface Finish Ra
0.60
1.00
1.40
1.80
2.20
Z'w
1606
1601
1602
1605
GOOD
New Bond
Commercial Bond 3
Commercial Bond 2
Commercial Bond 1

FIG. 6

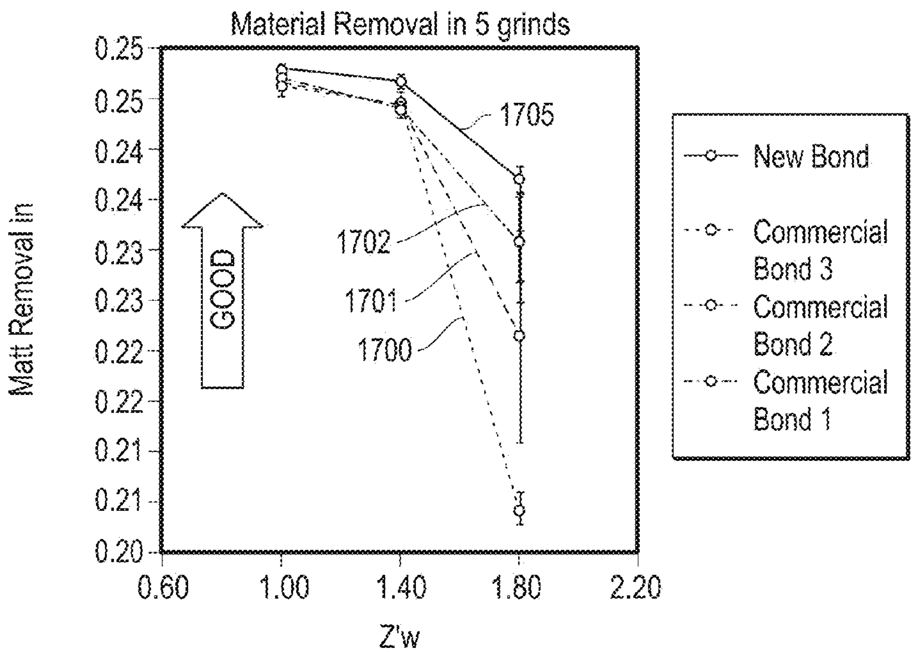
Material Removal in 5 grinds
0.25
0.25
0.24
0.24
0.23
0.23
0.22
0.22
0.21
0.21
0.20
Matt Removal in
0.60
1.00
1.40
1.80
2.20
Z'w
1705
1702
1701
1700
GOOD
New Bond
Commercial Bond 3
Commercial Bond 2
Commercial Bond 1

FIG. 7

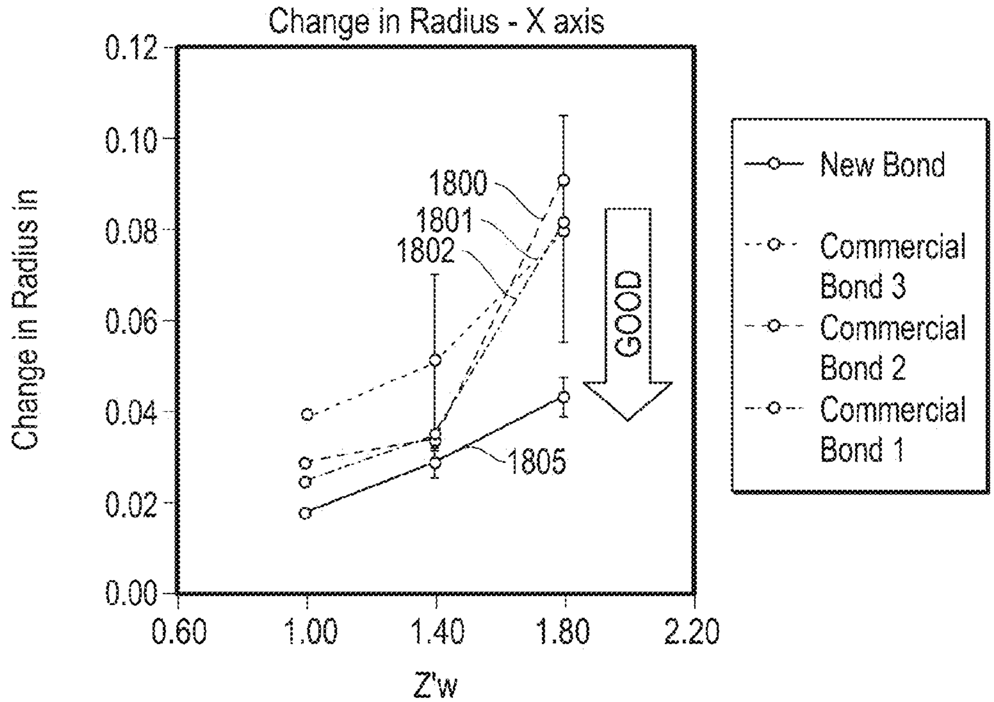
Change in Radius - X axis
Change in Radius in
Z'w
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.60
1.00
1.40
1.80
2.20
1800
1801
1802
1805
GOOD
New Bond
Commercial Bond 3
Commercial Bond 2
Commercial Bond 1

FIG. 8

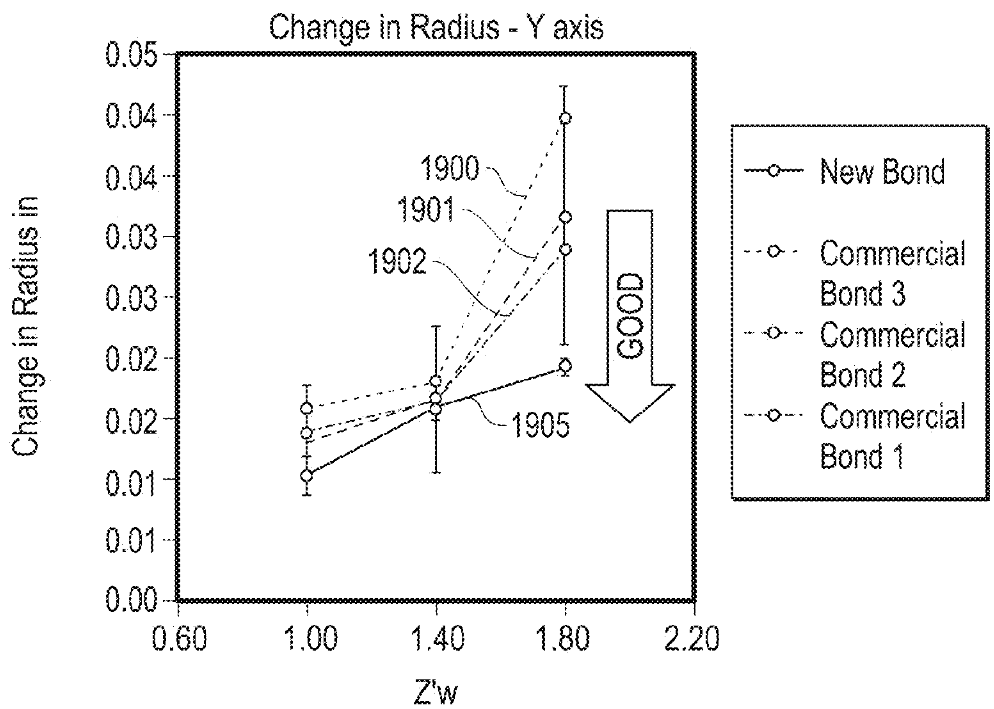
Change in Radius - Y axis
Change in Radius in
Z'w
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
0.60
1.00
1.40
1.80
2.20
1900
1901
1902
1905
GOOD
New Bond
Commercial Bond 3
Commercial Bond 2
Commercial Bond 1

FIG. 9

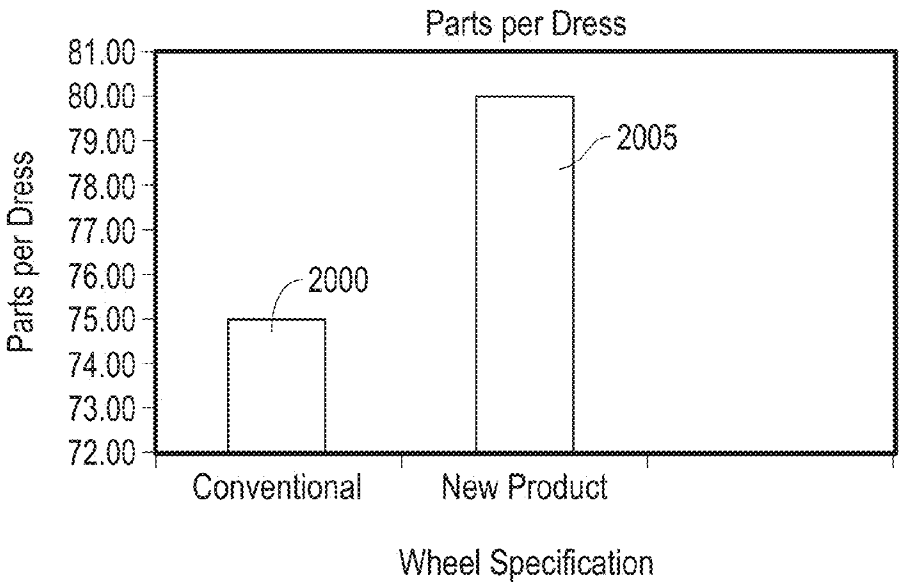
Parts per Dress
81.00
80.00
79.00
78.00
77.00
76.00
75.00
74.00
73.00
72.00
Parts per Dress
2000
2005
Conventional
New Product
Wheel Specification

FIG. 10

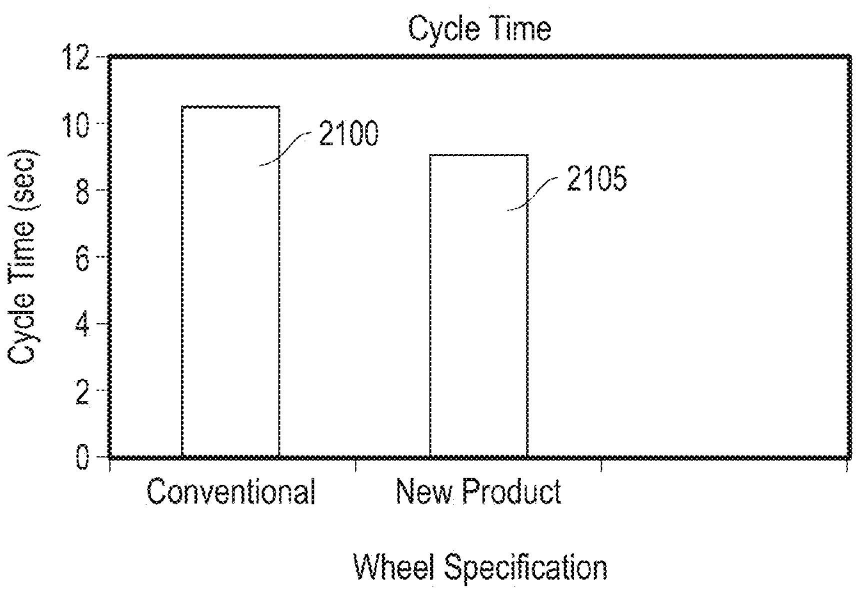
Cycle Time
12
10
8
6
4
2
0
Cycle Time (sec)
2100
2105
Conventional
New Product
Wheel Specification

FIG. 11

ABRASIVE ARTICLE FOR LOWER SPEED GRINDING OPERATIONS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This present application claims priority to and the benefit of U.S. Provisional Patent Application No. 61/668,860 entitled "Abrasive Article For Lower Speed Grinding Operations" by Nilanjan Sarangi, Sandhya Jayaraman Rukmani, Stephen E. Fox, Russell L. Krause, filed Jul. 6, 2012, and U.S. Provisional Patent Application No. 61/677,655 entitled "Abrasive Article For Lower Speed Grinding Operations" by Nilanj an Sarangi, Sandhya Jayaraman Rukmani, Stephen E. Fox, Russell L. Krause, filed Jul. 31, 2012, both of which are incorporated herein by reference in their entirety.

BACKGROUND

[0002] 1. Field of the Disclosure

[0003] The following is directed to abrasive articles, and particularly bonded abrasive articles suitable for conducting lower speed grinding operations.

[0004] 2. Description of the Related Art

[0005] Abrasive tools are generally formed to have abrasive grains contained within a bond material for material removal applications. Superabrasive grains (e.g., diamond or cubic boron nitride (CBN)) or seeded (or even unseeded) sintered sol gel alumina abrasive grain, also referred to as microcrystalline alpha-alumina (MCA) abrasive grain, can be employed in such abrasive tools. The bond material can be organic materials, such as a resin, or an inorganic material, such as a glass or vitrified material. In particular, bonded abrasive tools using a vitrified bond material and containing MCA grains or superabrasive grains are commercially useful for grinding.

[0006] Certain bonded abrasive tools, particularly those utilizing a vitrified bond material, require high temperature forming processes, oftentimes on the order of 1100° C. or greater, which can have deleterious effects on abrasive grains of MCA. In fact, it has been recognized that at such elevated temperatures necessary to form the abrasive tool, the bond material can react with the abrasive grains, particularly MCA grains, and damage the integrity of the abrasives, reducing the grain sharpness and performance properties. As a result, the industry has migrated toward reducing the formation temperatures necessary to form the bond material in order to curb the high temperature degradation of the abrasive grains during the forming process. The industry continues to demand improved performance of such bonded abrasive articles.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] 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.

[0008] FIG. **1** includes a diagram of percent porosity, percent abrasive, and percent bond for prior art bonded abrasive bodies and bonded abrasive bodies according to embodiments herein.

[0009] FIG. **2** includes a photograph illustrating modulus and hardness testing of abrasive grains, bonds and their interfaces.

[0010] FIG. **3** includes a chart of modulus of elasticity (MOE) for the abrasive, bond and abrasive-to-bond interfaces of two conventional bonded abrasive articles compared to a bonded abrasive article according to an embodiment herein.

[0011] FIG. **4** includes a chart of hardness for the abrasive, bond and abrasive-to-bond interfaces of two conventional bonded abrasive articles compared to a bonded abrasive article according to an embodiment herein.

[0012] FIG. **5** includes a schematic diagram of an abrasive article illustrating loss of form along both the x-axis and y-axis.

[0013] FIG. **6** includes a plot of surface finish Ra versus in-feed rate (Z'w) for conventional bonded abrasive articles and a bonded abrasive article according to an embodiment.

[0014] FIG. **7** includes a plot of material removal in 5 grinds versus in-feed rate (Z'w) for conventional bonded abrasive articles and a bonded abrasive article according to an embodiment.

[0015] FIG. **8** includes a plot of change in x-axis radius versus in-feed rate (Z'w) demonstrating a corner holding factor for conventional bonded abrasive articles and a bonded abrasive article according to an embodiment.

[0016] FIG. **9** includes a plot of change in y-axis radius versus in-feed rate (Z'w) demonstrating a corner holding factor for conventional bonded abrasive articles and a bonded abrasive article according to an embodiment.

[0017] FIG. **10** includes a chart of parts per dress for a conventional bonded abrasive article and a bonded abrasive article according to an embodiment.

[0018] FIG. **11** includes a chart of cycle time for a conventional bonded abrasive article and a bonded abrasive article according to an embodiment.

[0019] The use of the same reference symbols in different drawings indicates similar or identical items.

DETAILED DESCRIPTION

[0020] The following is directed to bonded abrasive articles, which may be suitable for grinding and shaping of workpieces. Notably, the bonded abrasive articles of embodiments herein can incorporate abrasive particles within a vitreous bond material. Suitable applications for use of the bonded abrasive articles of the embodiments herein include grinding operations including for example, centerless grinding, cylindrical grinding, crankshaft grinding, various surface grinding operations, bearing and gear grinding operations, creepfeed grinding, and various toolroom applications.

[0021] According to an embodiment, the method of forming a bonded abrasive article of an embodiment can be initiated by forming a mixture of suitable compounds and components to form a bond material. The bond can be formed of compounds of inorganic material, such as oxide compounds. For example, one suitable oxide material can include silicon oxide (SiO_2). In accordance with an embodiment, the bond material can be formed from not greater than about 55 wt % silicon oxide for the total weight of the bond material. In other embodiments, the content of silicon oxide can be less, such as not greater than about 54 wt %, not greater than about 53 wt %, not greater than about 52 wt %, or even not greater than about 51 wt %. Still, in certain embodiments the bond material may be formed from at least about 45 wt %, such as at least about 46 wt %, on the order of at least about 47 wt %, at least about 48 wt %, or even at least about 49 wt % silicon oxide for the total weight of the bond material. It will be appreciated that the amount of silicon oxide can be within a range between any of the minimum and maximum percentages noted above.

[0022] The bond material can also incorporate a certain content of aluminum oxide (Al_2O_3). For example, the bond material can include at least about 12 wt % aluminum oxide for the total weight of the bond material. In other embodiments, the amount of aluminum oxide can be at least about 14 wt %, at least about 15 wt %, or even at least about 16 wt %. In certain instances, the bond material may include an amount of aluminum oxide that is not greater than about 23 wt %, not greater than about 21 wt %, not greater than about 20 wt %, not greater than about 19 wt %, or even not greater than about 18 wt % for the total weight of the bond. It will be appreciated that the amount of aluminum oxide can be within a range between any of the minimum and maximum percentages noted above.

[0023] In certain instances, the bond material can be formed from a particular ratio between the amount of silicon oxide as measured in weight percent versus the amount of aluminum oxide as measured in weight percent. For example, the ratio of silica to alumina can be described by dividing the weight percent of silicon oxide by the weight percent of aluminum oxide within the bond material. In accordance with an embodiment, the ratio of silicon oxide to aluminum oxide can be not greater than about 3.2. In other instances, the ratio of silicon oxide to aluminum oxide within the bond material can be not greater than about 3.1, not greater than about 3.0, or even not greater than about 2.9. Still, the bond material can be formed, in certain instances, such that the ratio of weight percent of silicon oxide to the weight percent of aluminum oxide is at least about 2.2, such as at least about 2.3, such as on the order of at least about 2.4, at least about 2.5, at least about 2.6, or even at least about 2.7. It will be appreciated that the total amount of aluminum oxide and silicon oxide can be within a range between any of the minimum and maximum values noted above.

[0024] In accordance with an embodiment, the bond material can be formed form a certain content of boron oxide (B_2O_3). For example, the bond material can incorporate not greater than about 20 wt % boron oxide for the total weight of the bond material. In other instances, the amount of boron oxide can be less, such as not greater than about 19 wt %, not greater than about 18 wt %, not greater than about 17 wt %, or even not greater than about 16 wt %. Still, the bond material can be formed from at least about 11 wt %, such as at least about 12 wt %, at least about 13 wt %, or even at least about 14 wt % boron oxide for the total weight of the bond material. It will be appreciated that the amount of boron oxide can be within a range between any of the minimum and maximum percentages noted above.

[0025] In accordance with one embodiment, the bond material can be formed such that the total content (i.e. sum) of the weight percent of boron oxide and weight percent of silicon oxide within the bond material can be not greater than about 70 wt % for the total weight of the bond material. In other instances, the total content of silicon oxide and boron oxide can be not greater than about 69 wt %, such as not greater than about 68 wt %, not greater than about 67 wt %, or even not greater than about 66 wt %. In accordance with one particular embodiment, the total weight percent content of silicon oxide and boron oxide can be at least about 55 wt %, such as at least about 58 wt %, at least about 60 wt %, at least about 62 wt %, at least about 63 wt %, at least about 64 wt %, or even at least about 65 wt % for the total weight of the bond material. It will be appreciated that the total weight percent of silicon oxide and boron oxide within the bond material can be within a range between any of the minimum and maximum percentages noted above.

[0026] Moreover, in particular instances, the amount of silicon oxide can be greater than the amount of boron oxide within the bond material, as measured in weight percent. Notably, the amount of silicon oxide can be at least about 1.5 times greater, at least about 1.7 times greater, at least about 1.8 times greater, at least about 1.9 times greater, at least about 2.0 times greater, or even at least about 2.5 times greater than the amount of boron oxide. Still, in one embodiment, the bond material can include an amount of silicon oxide that is not greater than about 5 times greater, such as not more than about 4 times greater, not more than about 3.8 times greater, or even not more than about 3.5 times greater. It will be appreciated that the difference in the amount of silicon oxide as compared to the amount of boron oxide can be within a range between any of the minimum and maximum values noted above.

[0027] In accordance with an embodiment, the bond material can be formed from at least one alkali oxide compound (R_2O), wherein R represents a metal selected from Group IA elements in the Periodic Table of Elements. For example, the bond material can be formed from an alkaline oxide compound (R_2O) from the group of compounds including lithium oxide (Li_2O), sodium oxide (Na_2O), potassium oxide (K_2O), and cesium oxide (Cs_2O), and a combination thereof.

[0028] In accordance with an embodiment, the bond material can be formed from a total content of alkali oxide compounds of not greater than about 20 wt % for the total weight of the bond material. For other bonded abrasive articles according to embodiments herein, the total content of alkali oxide compounds can be not greater than about 19 wt %, not greater than about 18 wt %, not greater than about 17 wt %, not greater than about 16 wt %, or even not greater than about 15 wt %. Still, in one embodiment, the total content of alkali oxide compounds within the bond material can be at least about 10 wt %, such as at least about 12 wt %, at least about 13 wt %, or even at least about 14 wt %. It will be appreciated that the bond material can include a total content of alkali oxide compounds within a range between any of the minimum and maximum percentages noted above.

[0029] In accordance with one particular embodiment, the bond material can be formed from not greater than about 3 individual alkali oxide compounds (R20) as noted above. In fact, certain bond materials may incorporate not greater than about 2 alkali oxide compounds within the bond material.

[0030] Furthermore, the bond material can be formed such that the individual content of any of the alkali oxide compounds is not greater than one half of the total content (in weight percent) of alkali oxide compounds within the bond material. Furthermore, in accordance with one particular embodiment, the amount of sodium oxide can be greater than the content (weight percent) of lithium oxide or potassium oxide. In more particular instances, the total content of sodium oxide as measured in weight percent can be greater than the sum of the contents of lithium oxide and potassium oxide as measured in weight percent. Furthermore, in one embodiment, the amount of lithium oxide can be greater than the content of potassium oxide.

[0031] In accordance with one embodiment, the total amount of alkali oxide compounds as measured in weight percent forming the bond material can be less than the amount (as measured in weight percent) of boron oxide within the bond material. In fact, in certain instances the total weight percent of alkali oxide compounds as compared to the total weight percent of boron oxide within the bond material can be within a range between about 0.9 to 1.5, such as within a range between about 0.9 and 1.3, or even within a range between about 0.9 and about 1.1.

[0032] The bond material can be formed from a certain amount of alkali earth compounds (RO), wherein R represents an element from Group IIA of the Periodic Table of Elements. For example, the bond material can incorporate alkaline earth oxide compounds such as calcium oxide (CaO), magnesium oxide (MgO), barium oxide (BaO), or even strontium oxide (SrO). In accordance with an embodiment, the bond material can contain not greater than about 3.0 wt % alkaline earth oxide compounds for the total weight of the bond material. In still other instances, the bond material may contain less alkaline earth oxide compounds, such as on the order of not greater than about 2.8 wt %, not greater than about 2.2 wt %, not greater than about 2.0 wt %, or not greater than about 1.8 wt %. Still, according to one embodiment, the bond material may contain a content of one or more alkaline earth oxide compounds of at least about 0.5 wt %, such as at least about 0.8 wt %, at least about 1.0 wt %, or even at least about 1.4 wt % for the total weight of the bond material. It will be appreciated that the amount of alkaline earth oxide compounds within the bond material can be within a range between any of the minimum and maximum percentages noted above.

[0033] In accordance with an embodiment, the bond material can be formed from not greater than about 3 different alkaline earth oxide compounds. In fact, the bond material may contain not greater than 2 different alkaline earth oxide compounds. In one particular instance, the bond material can be formed from 2 alkaline earth oxide compounds consisting of calcium oxide and magnesium oxide.

[0034] In one embodiment, the bond material can include an amount of calcium oxide that is greater than an amount of magnesium oxide. Furthermore, the amount of calcium oxide within the bond material may be greater than the content of any of the other alkaline earth oxide compounds present within the bond material.

[0035] The bond material can be formed from a combination of alkali oxide compounds and alkaline earth oxide compounds such that the total content is not greater than about 20 wt % for the total weight of the bond material. In other embodiments, the total content of alkali oxide compounds and alkaline earth oxide compounds within the bond material can be not greater than about 19 wt %, such as not greater than about 18 wt %, or even not greater than about 17 wt %. However, in certain embodiments, the total content of alkali oxide compounds and alkaline earth compounds present within the bond material can be at least about 12 wt %, such as at least about 13 wt %, such as at least about 14 wt %, at least about 15 wt %, or even at least about 16 wt %. It will be appreciated that the bond material can have a total content of alkali oxide compounds and alkaline earth oxide compounds within a range between any of the minimum and maximum percentages noted above.

[0036] In accordance with an embodiment, the bond material can be formed such that the content of alkali oxide compounds present within the bond material is greater than the total content of alkaline earth oxide compounds. In one particular embodiment, the bond material may be formed such that the ratio of total content (in weight percent) of alkali oxide compounds as compared to the total weight percent of alkaline earth oxide compounds (R_2O:RO) is within a range between about 5:1 and about 15:1. In other embodiments, the ratio of total weight percent of alkali oxide compounds to total weight percent of alkaline earth oxide compounds present within the bond material can be within a range between about 6:1 and about 14:1, such as within a range between about 7:1 and about 12:1, or even with a range between about 8:1 and about 10:1.

[0037] In accordance with an embodiment, the bond material can be formed from not greater than about 3 wt % phosphorous oxide for the total weight of the bond material. In certain other instances, the bond material may contain not greater than about 2.5 wt %, such as not greater than about 2.0 wt %, not greater than about 1.5 wt %, not greater than about 1.0 wt %, not greater than about 0.8 wt %, not greater than about 0.5 wt %, or even not greater than about 0.2 wt % phosphorous oxide for the total weight of the bond material. In fact, in certain instances, the bond material may be essentially free of phosphorous oxide. Suitable contents of phosphorous oxide can facilitate certain characteristics and grinding performance properties as described herein.

[0038] In accordance with one embodiment, the bond material can be formed from not greater than a composition comprising not greater than about 1 wt % of certain oxide compounds, including for example, oxide compounds such as MnO_2, $ZrSiO_2$, $CoAl_2O_4$, and MgO. In fact, in particular embodiments, the bond material can be essentially free of the above identified oxide compounds.

[0039] In addition to the bond materials placed within the mixture, the process of forming the bonded abrasive article can further include the incorporation of a certain type of abrasive particles. In accordance with an embodiment, the abrasive particles can include microcrystalline alumina (MCA). In fact, in certain instances, the abrasive particles can consist essentially of microcrystalline alumina.

[0040] The abrasive particles can have an average particle size that is not greater than about 1050 microns. In other embodiments, the average particle size of the abrasive particles can be less, such as on the order of not greater than 800 microns, not greater than about 600 microns, not greater than about 400 microns, not greater than about 250 microns, not greater than about 225 microns, not greater than about 200 microns, not greater than about 175 microns, not greater than about 150 microns, or even not greater than about 100 microns. Still, the average particle size of the abrasive particles can be at least about 1 micron, such as at least about 5 microns, at least about 10 microns, at least about 20 microns, at least about 30 microns, or even at least about 50 microns, at least about 60 microns, at least about 70 microns, or even at least about 80 microns. It will be appreciated that the average particle size of the abrasive particles can be in a range between any of the minimum and maximum values noted above.

[0041] In further reference to abrasive particles utilizing microcrystalline alumina, it will be appreciated that microcrystalline alumina can be formed of grains having an average grain size that is sub-micron sized. In fact, the average grain size of a microcrystalline alumina can be not greater than about 1 micron, such as not greater than about 0.5 microns, not greater than about 0.2 microns, not greater than about 0.1 microns, not greater than about 0.08 microns, not greater than about 0.05 microns, or even not greater than about 0.02 microns.

[0042] Additionally, formation of the mixture, which includes abrasive particles and bond material can further include the addition of other components, such as fillers, pore formers, and materials suitable for forming the finally-formed bonded abrasive article. Some suitable examples of pore forming materials can include but are not limited to bubble alumina, bubble mullite, hollow spheres including hollow glass spheres, hollow ceramic spheres, or hollow polymer spheres, polymer or plastic materials, organic compounds, fibrous materials including strands and/or fibers of glass, ceramic, or polymers. Other suitable pore forming materials can include naphthalene, PDB, shells, wood, and the like. In still another embodiment, the filler can include one or more inorganic materials, including for example oxides, and particularly may include crystalline or amorphous phases of zirconia, silica, titania, and a combination thereof.

[0043] After the mixture is suitably formed, the mixture can be shaped. Suitable shaping processes can include pressing operations and/or molding operations and a combination thereof. For example, in one embodiment, the mixture can be shaped by cold pressing the mixture within a mold to form a green body.

[0044] After suitably forming the green body, the green body can be sintered at a particular temperature to facilitate forming an abrasive article having a vitreous phase bond material. Notably, the sintering operation can be conducted at a sintering temperature that is less than about 1000° C. In particular embodiments, the sintering temperature can be less than about 980° C., such as less than about 950° C., and particularly within a range between about 800° C. and 950° C. It will be appreciated that particularly low sintering temperatures may be utilized with the above-noted bond components such that excessively high temperatures are avoided and thus limiting the degradation of the abrasive particles during the forming process.

[0045] According to one particular embodiment, the bonded abrasive body comprises a bond material having a vitreous phase material. In particular instances, the bond material can be a single phase vitreous material.

[0046] The finally-formed bonded abrasive body can have a particular content of bond material, abrasive particles, and porosity. Notably, the body of the bonded abrasive article can have a porosity of at least about 42 vol % for the total volume of the bonded abrasive body. In other embodiments, the amount of porosity can be greater such as at least about 43 vol %, such as at least about 44 vol %, at least about 45 vol %, at least about 46 vol %, at least about 48 vol %, or even at least about 50 vol % for the total volume of the bonded abrasive body. In accordance with an embodiment the bonded abrasive body can have a porosity that is not greater than about 70 vol %, such as not greater than about 65 vol %, not greater than about 62 vol %, not greater than about 60 vol %, not greater than about 56 vol %, not greater than about 52 vol %, or even not greater than about 50 vol %. The bonded abrasive body may include a porosity of about 46% to about 50% of a total volume of the bonded abrasive body, such as a porosity of about 46% to about 48% of a total volume of the bonded abrasive body. It will be appreciated that the bonded abrasive body can have a porosity within a range between any of the minimum and maximum percentages noted above.

[0047] In accordance with an embodiment, the bonded abrasive body can have at least about 35 vol % abrasive particles for the total volume of the bonded abrasive body. In other embodiments, the total content of abrasive particles can be greater, such as at least about 37 vol %, or even at least about 39 vol %. In accordance with one particular embodiment, the bonded abrasive body can be formed such that it has not greater than about 50 vol % abrasive particles, such as not greater than about 48 vol %, or even not greater than about 46 vol % for the total volume of the bonded abrasive body. It will be appreciated that the content of abrasive particles within the bonded abrasive body can be within a range between any of the minimum and maximum percentages noted above.

[0048] In particular instances, the bonded abrasive body is formed such that it contains a minor content (vol %) of bond material as compared to the content of porosity and abrasive particles. For example, the bonded abrasive body can have not greater than about 15 vol % bond material for the total volume of the bonded abrasive body. In other instances, the bonded abrasive body can be formed such that it contains not greater than about 14 vol %, not greater than about 13 vol %, or even not greater than about 12 vol % for the total volume of the bonded abrasive body. In one particular instance, the bonded abrasive body can be formed such that it contains at least about 7 vol %, such as at least about 8 vol %, on the order of at least about 9 vol %, or even at least about 10 vol % bond material for the total volume of the bonded abrasive body.

[0049] FIG. **1** includes a diagram of phases present within a particular bonded abrasive article according to an embodiment. FIG. **1** includes vol % bond, vol % abrasive particles, and vol % porosity. The shaded region 101 represents a conventional bonded abrasive article suitable for grinding applications, while the shaded region 103 represents the phase contents of a bonded abrasive article according to an embodiment herein.

[0050] Notably, the phase content of the conventional bonded abrasive articles (i.e., shaded region 101) is significantly different from the phase content of a bonded abrasive article of an embodiment. Notably, conventional bonded abrasive articles typically have a maximum porosity within a range between approximately 40 vol % and 51 vol %, an abrasive particle content of approximately 42 vol % to 50 vol %, and a bond content of approximately 9 to 20 vol %. Conventional bonded abrasive articles typically have a maximum porosity content of 50 vol % or less because grinding applications require a bonded abrasive body having sufficient strength to deal with the excessive forces encountered during grinding, and highly porous bonded abrasive bodies have not previously been able to withstand said forces.

[0051] According to one embodiment, a bonded abrasive article can have a considerably greater porosity than the conventional bonded abrasive articles. For example, one bonded abrasive article of an embodiment can have a porosity content within a range between about 51 vol % and about 58 vol % for the total volume of the bonded abrasive body. Furthermore, as illustrated in FIG.1, a bonded abrasive article of an embodiment can have an abrasive particle content within a range between about 40 vol % and about 42 vol %, and a particularly low bond content within a range between approximately 2 vol % and about 9 vol % for the total volume of the bonded abrasive article.

[0052] Notably, the bonded abrasive bodies of the embodiments herein can have particular characteristics unlike conventional bonded abrasive bodies. In particular, the bonded abrasive articles herein can have a particular content of porosity, abrasive particles, and bond, while demonstrating particular mechanical characteristics making them suitable for particular applications, such as grinding applications. For example, in one embodiment, the bonded abrasive body can have a particular modulus of rupture (MOR), which can correspond to a particular modulus of elasticity (MOE). For example, the bonded abrasive body can have a MOR of at least 45 MPa for a MOE of at least about 40 GPa. In one embodiment, the MOR can be at least about 46 MPa, such as at least about 47 MPa, at least about 48 MPa, at least about 49 MPa, or even at least about 50 MPa for a MOE of 40 GPa. Still, the bonded abrasive body may have an MOR that is not greater than about 70 MPa, such as not greater than about 65 MPa, or not greater than about 60 MPa for a MOE of 40 GPa. It will be appreciated that the MOR can be within a range between any of minimum and maximum values given above.

[0053] In another embodiment, for certain bonded abrasive bodies having a MOE of 45 GPa, the MOR can be at least about 45 MPa. In fact, for certain bonded abrasive bodies having a MOE of 45 GPa, the MOR can be at least about 46 MPa, such as at least about 47 MPa, at least about 48 MPa, at least about 49 MPa, or even at least about 50 MPa. Still, the MOR may be not greater than about 70 MPa, not greater than about 65 MPa, or not greater than about 60 MPa for a MOE of 45 GPa. It will be appreciated that the MOR can be within a range between any of minimum and maximum values given above.

[0054] MOR can be measured using a standard 3 point bending test on a sample of size 4"×1"×0.5", where the load is applied across the 1"×0.5" plane, generally in accordance with ASTM D790, with the exception of the sample size. The failure load can be recorded and calculated back to MOR using standard equations. MOE can be calculated through measurement of natural frequency of the composites using a GrindoSonic instrument or similar equipment, as per standard practices in the abrasive grinding wheel industry.

[0055] In one embodiment, the bonded abrasive body can have a strength ratio, which is a measure of the MOR divided by the MOE. In particular instances, the strength ratio (MOR/MOE) of a particular bonded abrasive body can be at least about 0.8. In other instances, the strength ratio can be at least about 0.9, such as at least about 1.0, at least about 1.05, at least about 1.10. Still, the strength ratio may be not greater than about 3.00, such as not greater than about 2.50, not greater than about 2.00, not greater than about 1.70, not greater than about 1.50, not greater than about 1.40, or not greater than about 1.30. It will be appreciated that the strength ratio of the bonded abrasive bodies can be within a range between any of the minimum and maximum values noted above.

[0056] In accordance with an embodiment, the bonded abrasive body can be suitable for use in particular grinding operations. For example, it has been discovered that the bonded abrasive bodies of embodiments herein are suitable in grinding operations. In fact, the bonded abrasive bodies can be utilized without damaging the workpiece and providing suitable or improved grinding performance.

[0057] Reference herein to the grinding capabilities of the bonded abrasive body can relate to grinding operations such as centerless grinding, cylindrical grinding, crankshaft grinding, various surface grinding operations, bearing and gear grinding operations, creepfeed grinding, and various toolroom grinding processes. Moreover, suitable workpieces for the grinding operations can include inorganic or organic materials. In particular instances, the workpiece can include a metal, metal alloy, plastic, or natural material. In one embodiment, the workpiece can include a ferrous metal, non-ferrous metal, metal alloy, metal superalloy, and a combination thereof. In another embodiment, the workpiece can include an organic material, including for example, a polymer material. In still other instances, the workpiece may be a natural material, including for example, wood.

[0058] Some versions of the wheel sizes of these abrasive articles may range from greater than about 4.5 inches to about 54 inches in diameter. Typical stock removal amounts may range from about 0.0001 inches to about 0.500 inches, depending on the application.

[0059] In particular instances, it has been noted that the bonded abrasive body is capable of grinding workpieces at particularly high removal rates. For example, in one embodiment, the bonded abrasive body can conduct a grinding operation at a material removal rate of at least about 0.4 in^3/min/in (258 mm^3/min/mm). In other embodiments, the material removal rate can be at least about 0.45 in^3/min/in (290 mm^3/min/mm), such as at least about 0.5 in^3/min/in (322 mm^3/min/mm), at least about 0.55 in^3/min/in (354 mm^3/min/mm), or even at least about 0.6 in^3/min/in (387 mm^3/min/mm). Still, the material removal rate for certain bonded abrasive bodies may be not greater than about 1.5 in^3/min/in (967 mm^3/min/mm), such as not greater than about 1.2 in^3/min/in (774 mm^3/min/mm), not greater than about 1.0 in^3/min/in (645 mm^3/min/mm), or even not greater than about 0.9 in^3/min/in (580 mm^3/min/mm). It will be appreciated that the bonded abrasive bodies of the present application can grind a workpiece at the material removal rates within a range between any of the minimum and maximum values noted above.

[0060] During certain grinding operations, it has been noted that the bonded abrasive bodies of the present application can grind at a particular depth of cut (DOC) or (Zw). For example, the depth of cut achieved by the bonded abrasive body can be at least about 0.003 inches (0.0762 millimeters). In other instances, the bonded abrasive body is capable of achieving a depth of cut during grinding operations of at least about 0.004 inches (0.102 millimeters), such as at least about 0.0045 inches (0.114 millimeters), at least about 0.005 inches (0.127 millimeters), or even at least about 0.006 inches (0.152 millimeters). It will be appreciated that the depth of cut for grinding operations utilizing the bonded abrasive bodies herein may not be greater than about 0.01 inches (0.254 millimeters), or not great than about 0.009 inches (0.229 millimeters). It will be appreciated that the depth of cut can be within a range between any of the minimum and maximum values noted above.

[0061] In other embodiments, it has been noted that the bonded abrasive body can grind a workpiece at a maximum power that does not exceed about 10 Hp (7.5 kW), while the grinding parameters noted above are utilized. In other embodiments, the maximum power during grinding operations may be not greater than about 9 Hp (6.8 kW), such as not greater than about 8 Hp (6.0 kW), or even not greater than about 7.5 Hp (5.6 kW).

[0062] In accordance with another embodiment, during grinding operations, it has been noted that the bonded abrasive articles of the embodiments herein have superior corner holding ability, particularly as compared to conventional bonded abrasive articles. In fact, the bonded abrasive body can have a corner holding factor of not greater than about 0.07 inches at a depth of cut (Zw) of at least about 1.8, which corresponds to 0.00255 inches/sec,rad. Notably, as used herein, a depth of cut of 1.0 correspond to 0.00142 inches/sec,rad, and a depth of cut (Zw) of 1.4 correspond to 0.00198 inches/sec,rad. It will be appreciated that the corner holding factor is a measure of a change in radius in inches after conducting 5 grinds on a workpiece of 4330V, which is a NiCrMoV hardened and tempered high strength steel alloy.at a particular depth of cut. In certain other embodiments, the bonded abrasive article demonstrates a corner holding factor that is not greater than about 0.06 inches, such as not greater than about 0.05 inches, not greater than about 0.04 inches, for a depth of cut of at least about 1.80.

[0063] In one embodiment, an abrasive article may include a bonded abrasive body having abrasive particles contained within a bond material. The bonded abrasive body may include an abrasive particle-to-bond material interfacial modulus of elasticity (MOE) of at least about 225 GPa. The bonded abrasive body may be configured to grind a workpiece comprising metal at a speed of less than about 60 m/s.

[0064] For example, the abrasive particle-to-bond material interfacial MOE may be at least about 250 GPa, such as at least about 275 GPa, or even at least about 300 GPa. Alternatively, the abrasive particle-to-bond material interfacial MOE may be no greater than about 350 GPa, such as no greater than about 325 GPa, or even no greater than about 320 GPa.

[0065] In another embodiment, an abrasive article may include a bonded abrasive body having abrasive particles contained within a bond material. The bonded abrasive body may include an abrasive particle-to-bond material interfacial hardness of at least about 13 GPa. The bonded abrasive body may be configured to grind a workpiece comprising metal at a speed of less than about 60 m/s. In other examples, the abrasive particle-to-bond material interfacial hardness may be at least about 14 GPa, or even at least about 15 GPa. Alternatively, the abrasive particle-to-bond material interfacial hardness may be no greater than about 20 GPa, such as no greater than about 18 GPa, or even no greater than about 16 GPa.

[0066] In still another example, the bonded abrasive body may include a surface finish of not greater than about 125 micro-inch.

[0067] The bonded abrasive body may perform at an in-feed rate (Z'w) of at least about 1.0 inches/min. For example, Z'w may be not greater than about 1.4 inches/min, such as not greater than about 1.8 inches/min, not greater than about 2.0 inches/min, or even 2.2 inches/min

[0068] In one version, the bonded abrasive body may include a material removal rate of at least about 0.235 in3/min.

[0069] Embodiments of an abrasive article may include a bonded abrasive body having abrasive particles contained within a bond material. The bonded abrasive body may include a grinding factor defined as a change of x-axis radius over a change in in-feed rate. The grinding factor may be not greater than about 0.040. The bonded abrasive body may be configured to grind a workpiece comprising metal at a speed of less than about 60 m/s. The grinding factor may be not greater than about 0.035, such as a grinding factor not greater than about 0.030, or even a grinding factor not greater than about 0.028.

[0070] In a particular embodiment, the bonded abrasive body may include an x-axis corner holding factor of not greater than about 0.080 inches. For example, the x-axis corner holding factor may be not greater than about 0.070 inches, such as not greater than about 0.060 inches, not greater than about 0.050 inches, or even not greater than about 0.042 inches.

[0071] The corner holding factor may be expressed as a percentage change in the radius of a wheel. For example, for a wheel having a 7-inch diameter (i.e., a 3.5-inch radius), an x-axis corner holding factor of 0.080 inches represents a change of: 1-(3.5-0.08)/3.5=2.3% change in the x-axis radius of the wheel. For the x-axis corner holding factors of 0.07, 0.06, 0.05 and 0.042, the change in x-axis radius of the wheel is 2%, 1.7%, 1.4% and 1.2%, respectively. Accordingly, the bonded abrasive body may have a change in x-axis radius of no greater than 3%. For example, the bonded abrasive body may have a change in x-axis radius of no greater than 2.5%, such as no greater than about 2%, no greater than about 1.7%, no greater than about 1.5%, or even no greater than about 1.3%.

[0072] Other embodiments of the bonded abrasive body may include a grinding factor defined as a change of y-axis radius over a change in in-feed rate. The grinding factor may be not greater than about 0.018. Other examples of the grinding factor may be not greater than about 0.016, such as a grinding factor not greater than about 0.014, a grinding factor not greater than about 0.012, or even a grinding factor not greater than about 0.010.

[0073] In a particular embodiment, the bonded abrasive body may include a y-axis corner holding factor of not greater than about 0.033 inches, such as not greater than about 0.030 inches, not greater than about 0.025 inches, or even not greater than about 0.024 inches.

[0074] The corner holding factor may be expressed as a percentage change in the radius of a wheel. For example, for a wheel having a 7-inch diameter (i.e., a 3.5-inch radius), a y-axis corner holding factor of 0.033 inches represents a change of: 1-(3.5-0.033)/3.5=0.94% change in the y-axis radius of the wheel. For the y-axis corner holding factors of 0.03, 0.025 0.024, the change in x-axis radius of the wheel is 0.86%, 0.71% and 0.69%, respectively.

[0075] Accordingly, the bonded abrasive body may have a change in y-axis radius of no greater than about 1%. For example, the bonded abrasive body may have a change in x-axis radius of no greater than about 0.9%, such as no greater than about 0.8%, or even no greater than about 0.7%.

[0076] Other versions of the abrasive article may include the body requiring at least about 3% fewer dressings than a conventional OD abrasive grinding wheel, such as at least about 4% , at least about 5%, or even at least about 6% fewer dressings than a conventional OD abrasive grinding wheel.

[0077] In another example, the body may require at least about 5% less cycle time than a conventional OD abrasive grinding wheel. For example, the body may require at least about 10% less cycle time, such as at least about 15%, or even at least about 18% less cycle time than a conventional OD abrasive grinding wheel.

[0078] Embodiments of the abrasive article may have a bonded abrasive body that can be configured to grind a workpiece comprising metal at a speed of less than about 55 m/s. For example, the speed may be less than about 50 m/s, such as less than about 45 m/s, or even less than about 40 m/s. In still other versions, the speed may be at least about 35 m/s, such as at least about 40 m/s, at least about 45 m/s, or even at least about 50 m/s.

[0079] The abrasive article may have a body including a wheel having an outer diameter in a range of about 24 inches to about 30 inches, such as about 18 inches to about 30 inches, about 10 inches to about 36 inches, or even about 5 inches to about 54 inches.

[0080] Other embodiments of the abrasive article may include a bond material that includes a single phase vitreous material. Some versions of the bonded abrasive body may include a porosity of at least about 42 vol % of the total volume of the bonded abrasive body, such as a porosity of not greater than about 70 vol %.

[0081] The bonded abrasive body may include at least about 35 vol % abrasive particles of the total volume of the bonded abrasive body. In another example, the bonded abrasive body may include not greater than about 15 vol % bond material of the total volume of the bonded abrasive body.

[0082] Examples of the bond material may be formed from not greater than about 20 wt % boron oxide (B_2O_3) for the total weight of the bond material. In another version, the bond material may include a ratio of weight percent silicon oxide (SiO_2) to weight percent aluminum oxide (Al_2O_3) (SiO_2:Al_2O_3) of not greater than about 3.2. The bond material may be formed from not greater than about 3.0 wt % phosphorous oxide (P_2O_5). Alternatively, the bond material may be essentially free of phosphorus oxide (P_2O_5).

[0083] Other embodiments of the bond material may be formed from an alkaline earth oxide compound (RO). For example, a total amount of alkaline earth oxide compound (RO) present in the bond material may be not greater than about 3.0 wt %. The bond material may be formed from not greater than about 3 different alkaline earth oxide compounds (RO) selected from the group of calcium oxide (CaO), magnesium oxide (MgO), barium oxide (BaO), strontium oxide (SrO). The bond material also may include an alkali oxide compound (R_2O) selected from the group of compounds consisting of lithium oxide (Li_2O), sodium oxide (Na_2O), potassium oxide (K_2O), and cesium oxide (Cs_2O) and a combination thereof. The bond material may be formed from a total amount of alkali oxide compound (R_2O) not greater than about 20 wt %. Alternatively, the bond material may include not greater than about 3 alkali oxide compounds (R_2O). In another example, a content (wt %) of any alkali oxide compound present within the bond material may be not greater than half of a total content (wt %) of alkali oxides.

[0084] In still other embodiments, the bond material is formed from not greater than about 55 wt % silicon oxide (SiO_2). The bond material may be formed from at least about 12 wt % aluminum oxide (Al_2O_3). The bond material also may be formed from at least one alkali oxide compound (R_2O) and at least one alkaline earth oxide compound (RO), wherein the total content of the alkali oxide compound and the alkaline earth oxide compound is not greater than about 20 wt %.

[0085] Some examples of the bond may be formed from boron oxide (B_2O_3) and silicon oxide (SiO_2), wherein the total content of boron oxide and silicon oxide may be not greater than about 70 wt %. The content of silicon oxide (SiO_2) may be greater than the content of boron oxide.

[0086] In a particular version, the bond may be formed from a composition comprising not greater than about 1 wt % of oxide compounds selected from the group consisting of MnO_2, $ZrSiO_2$, $CoAl_2O_4$, and MgO. The bond may be formed from a composition essentially free of oxide compounds selected from the group consisting of MnO_2, $ZrSiO_2$, $CoAl_2O_4$, and MgO. In addition, the bonded abrasive body may be sintered at a temperature of not greater than about 1000° C.

[0087] Embodiments of the bond material may include a ratio of weight percent silicon oxide (SiO_2) to weight percent aluminum oxide (Al_2O_3) (SiO_2:Al_2O_3) of about 2.4 to about 3.5. The bond material may include a trace amount (<1%) of each of Fe_2O_3, TiO_2 and Mg, and combinations thereof. The bond material may include a ratio of weight percent silicon oxide (SiO_2) to weight percent CaO (SiO_2:CaO) of about 32 to about 52. The bond material also may include a ratio of weight percent silicon oxide (SiO_2) to weight percent Li_2O (SiO_2: Li_2O) of about 9.6 to about 26. In another example, the bond material may include a ratio of weight percent silicon oxide (SiO_2) to weight percent Na_2O(SiO_2:Na_2O) of about 4.8 to about 10.4. The bond material may include a ratio of weight percent silicon oxide (SiO_2) to weight percent K_2O (SiO_2:K_2O) of about 9.6 to about 26. The bond material also may include a ratio of weight percent silicon oxide (SiO_2) to weight percent B_2O_3 (SiO_2:B_2O_3) of about 2.8 to about 5.2.

[0088] Embodiments of the bond material may include a ratio of weight percent aluminum oxide (Al_2O_3) to weight percent CaO (Al_2O_3:CaO) of about 10 to about 20. The bond material may include a ratio of weight percent aluminum oxide (Al_2O_3) to weight percent Li_2O (Al_2O_3: Li_2O) of about 3 to about 10. The bond material also may include a ratio of weight percent aluminum oxide (Al_2O_3) to weight percent Na_2O (Al_2O_3:Na_2O) of about 1.5 to about 4. An example of the bond material may include a ratio of weight percent aluminum oxide (Al_2O_3) to weight percent K_2O (Al_2O_3:K_2O) of about 3 to about 10. The bond material also may include a ratio of weight percent aluminum oxide (Al_2O_3) to weight percent B_2O_3 (Al_2O_3:B_2O_3) of about 0.9 to about 2.

[0089] In another example, the bond material may include a ratio of weight percent CaO to weight percent Li_2O (CaO: Li_2O) of about 0.2 to about 0.75. The bond material may include a ratio of weight percent CaO to weight percent Na_2O (CaO:Na_2O) of about 0.1 to about 0.3. The bond material also may include a ratio of weight percent CaO to weight percent K_2O (CaO:K_2O) of about 0.2 to about 0.75. In addition, the bond material may include a ratio of weight percent CaO to weight percent B_2O_3 (CaO:B_2O_3) of about 0.16 to about 0.15.

[0090] Other embodiments of the bond material can include a ratio of weight percent Li_2O to weight percent Na_2O (Li_2O:Na_2O) of about 0.2 to about 1. The bond material can include a ratio of weight percent Li_2O to weight percent K_2O (Li_2O:K_2O) of about 0.4 to about 2.5. The bond material also can include a ratio of weight percent Li_2O to weight percent B_2O_3 (Li_2O:B_2O_3) of about 0.12 to about 0.5.

[0091] A particular embodiment of the bond material may include a ratio of weight percent Na_2O to weight percent K_2O (Na_2O:K_2O) of about 1 to about 5. The bond material also may include a ratio of weight percent Na_2O to weight percent B_2O_3 (Na_2O:B_2O_3) of about 0.3 to about 1. In addition, the bond material can include a ratio of weight percent K_2O to weight percent B_2O_3 (K_2O:B_2O_3) of about 0.12 to about 0.5.

[0092] Other examples of the abrasive article may include a bonded abrasive body having abrasive particles contained within a bond material formed from not greater than about 20 wt % boron oxide (B_2O_3), having a ratio of weight percent silica (SiO_2): weight percent alumina (Al_2O_3) of not greater than about 3.2 (by weight percent) and not greater than about 3.0 wt % phosphorous oxide (P_2O_5), wherein the bonded abrasive body has a porosity of at least about 42 vol % of the total volume of the bonded abrasive body. The bonded abrasive body may be capable of grinding a workpiece comprising metal at a speed of less than about 60 m/s.

[0093] Embodiments of a method of grinding an abrasive article may include forming a bonded abrasive body with abrasive particles contained within a bond material, such that the bonded abrasive body comprises an abrasive particle-to-bond material interfacial modulus of elasticity (MOE) of at least about 225 GPa. The method may include grinding a workpiece comprising metal with the bonded abrasive body at a speed of less than about 60 m/s.

[0094] Another embodiment of a method of grinding an abrasive article may include forming a bonded abrasive body having abrasive particles contained within a bond material, such that the bonded abrasive body comprises an abrasive particle-to-bond material interfacial hardness of at least about 13 GPa. The method may include grinding a workpiece comprising metal with the bonded abrasive body at a speed of less than about 60 m/s.

[0095] Still another embodiment of the method of grinding an abrasive article can include forming a bonded abrasive body having abrasive particles contained within a bond material, such that the bonded abrasive body comprises a grinding factor defined as a change of x-axis radius over a change in in-feed rate, and the grinding factor is not greater than about 0.040 for an in-feed rate (Z'w) of at least about 1.0 inches/min. The method may include grinding a workpiece comprising metal with the bonded abrasive body at a speed of less than about 60 m/s.

[0096] A method of grinding an abrasive article also can include forming a bonded abrasive body having abrasive particles contained within a bond material, such that the bonded abrasive body comprises a grinding factor defined as a change of y-axis radius over a change in in-feed rate, and the grinding factor is not greater than about 0.018 for an in-feed rate (Z' w) of at least about 1.0 inches/min. The method may include grinding a workpiece comprising metal with the bonded abrasive body at a speed of less than about 60 m/s.

[0097] Still another method of grinding an abrasive article can include forming a bonded abrasive body having abrasive particles contained within a bond material formed from not greater than about 20 wt % boron oxide (B_2O_3), having a ratio of weight percent silica (SiO_2): weight percent alumina (Al_2O_3) of not greater than about 3.2 (by weight percent) and not greater than about 3.0 wt % phosphorous oxide (P_2O_5), wherein the bonded abrasive body has a porosity of at least about 42 vol % of the total volume of the bonded abrasive body. The method may include grinding a workpiece comprising metal with the bonded abrasive body at a speed of less than about 60 m/s.

EXAMPLES

Example 1

[0098] The life or performance of a wheel in OD grinding applications may be dependent on the number of grinds it can sustain, or the number of parts that can be ground before the wheel loses its form or corner holding ability, which will also impact the part quality. The life of the wheel also may relate to the dressing frequency needed to generate a fresh surface for the subsequent grinding operation. The form holding or corner holding ability of the wheel also may be related to the ability of the bond to hold the grain and retain its goodness for the efficient grinding operation. In this example, abrasive wheels having 38A fused alumina abrasive particles with different bonds were tested. The test device was an MTS Nanoindenter XP, using a Berkovich-type indenter tip. For each sample, indents were attempted at 20 locations along a double line (see FIG. **2**) extending from an abrasive particle, across the grain boundary to the bond region, and then into the next abrasive particle. Spacing between the indents in the row was 10 microns, and the rows themselves were separated by a distance of 10 microns. Indentation proceeded to a depth of 1 micron.

[0099] FIGS. **3** and **4** depict a comparison of the modulus of elasticity (MOE) and hardness, respectively, for three different bonds. Plots **1301**, **1302**, and **1303** represent the MOE of the abrasive, bond, and abrasive-to-bond interface, respectively, of a sample of the bonded abrasive articles formed according to an embodiment herein. This sample had a range of bond content of approximately 7 vol % to approximately 12 vol % of a total volume of the bonded abrasive body. In addition, this sample had a range of porosity of approximately 46 vol % to approximately 50 vol % of a total volume of the bonded abrasive body.

[0100] In FIG. **3**, a first conventional sample CS**1** produced MOE values **1305**, **1306**, and **1307** for its abrasive, bond, and abrasive-to-bond interface, respectively. Sample CS**1** is a bonded abrasive article commercially available as VS product from Saint Gobain Corporation. A second conventional sample CS**2** is a bonded abrasive article commercially available as VH product from Saint Gobain Corporation. Sample CS**2** produced MOE values **1310**, **1311**, and **1312** for its abrasive, bond, and abrasive-to-bond interface, respectively.

[0101] As shown in FIG. **3**, the interface MOE **1303** of the embodiment significantly outperformed the interface MOEs **1307** and **1312** of conventional samples CS**1** and CS**2**, respectively. Such results show a remarkable improvement in the MOE of the abrasive-to-bond interface of bonded abrasive articles formed according to the embodiments herein over state-of-the-art conventional bonded abrasive articles.

[0102] In FIG. **4**, plots **1401**, **1402**, and **1403** represent the hardness of the abrasive, bond, and abrasive-to-bond interface, respectively, of the sample of the bonded abrasive articles formed according to the embodiment of FIG. **3**. The first conventional sample CS**1** produced hardness values **1405**, **1406**, and **1407** for its abrasive, bond, and abrasive-to-bond interface, respectively. Sample CS**1** is the same as that disclosed above for FIG. **3**. Similarly, the second conventional sample CS**2** produced hardness values **1410**, **1411**, and **1412** for its abrasive, bond, and abrasive-to-bond interface, respectively. Sample CS**2** is the same as that disclosed above for FIG. **3**.

[0103] As shown in FIG. **4**, the interface hardness **1403** of the embodiment significantly outperformed the interface hardnesses **1407** and **1412** of conventional samples CS**1** and CS**2**, respectively. Such results show a remarkable improvement in the hardness of the abrasive-to-bond interface of bonded abrasive articles formed according to the embodiments herein over state-of-the-art conventional bonded abrasive articles.

[0104] Thus, the new bond has higher modulus and hardness. This is particularly significant for the weaker parts in the abrasive wheels (the bond and interface). The improvement in modulus and hardness of interface can help to strengthen the interface and shows that it has better connectivity with the abrasives. These designs are helpful for improving life of abrasive wheels under aggressive grinding conditions.

Example 2

[0105] For this corner holding application and test, four samples of 7-inch wheels were prepared. The four samples included three different conventional bonds and one bond in accordance with an embodiment herein. All four samples included 38A fused alundum grain, and each included a bond content of about 7 vol % to about 12 vol %, as well as a porosity of about 46% to about 50% of a total volume of the bonded abrasive body. The conventional samples used the same VS and VH bonds used in Example 1. Table 1 contains more details regarding the test conditions used in Example 2.

TABLE 1

Material: 4330V
Lot #: 287
Work Speed [rpm]: 232
Sparkout [s]: 0.2

Machine:	Bryant	Hardness:	28-32 RC	Apprx. Whl OD [in]:	7.000
Coolant:	E 812	Part Width [in]:	0.35	Apprx. Wrk OD [in]:	3.745
Wheel Speed [sfpm]:	9915	Grind Width [in]:	0.10	Full Scale [V]:	10.0
Dress Type:	Rotary	Fn (lbs/V):	30.00	Full Scale [V]:	10.0
Dress Comp [in]:	.015" Radius .015" Face	Ft (lbs/V):	30.00	Full Scale [V]:	10.0
Dress Lead [in/sec]:	0.0020	Power [hp/V]:	2.14		
Dresser Speed [rpm]:	3787				

[0106] The four samples were tested on a Bryant grinder in a corner holding configuration. The wheel speed was 50.36 m/s. The test material was 3.745-inch OD 4330V steel (R_c=28-32). The test material speed was 1.15 msec. The grinding mode was external plunge with a 0.100-inch width of grind. Each wheel was dressed with the help of a reverse plated diamond roll. The infeed rates were adjusted to give target material removal rates (Z'W) of 1.0, 1.4 and 1.8 inch^3/min/inch. Five consecutive radial grinds without dressing were performed on each of the test wheels at the target feed rates. Surface finish and waviness were obtained from the work material after the last grind. For the corner radius and radial wear measurements, after each grind, the test wheel was used to grind a Formica blank that records the wheel profile. The measurements were obtained from the blank.

[0107] FIG. **6** includes plots of surface finish Ra versus in-feed rate (Z'w) for the three conventional bonded abrasive articles **1600**, **1601** and **1602** and the embodiment of the bonded abrasive article **1605**. The embodiment of the bonded abrasive body **1605** comprises a surface finish of not greater than about 85 micro-inch at an in-feed rate (Z'w) of 1.4 inches/min. In contrast, the articles **1600**, **1601** and **1602** all exhibited surface finishes of at least about 125 micro-inch at an in-feed rate (Z'w) of 1.4 inches/min.

[0108] FIG. **7** includes plots of material removal in 5 grinds versus in-feed rate (Z'w) for the same three conventional bonded abrasive articles **1700**, **1701** and **1702** and the embodiment of the bonded abrasive article **1705**. The bonded abrasive body **1705** included a material removal rate of at least about 0.241 in^3/min at an in-feed rate (Z'w) of 1.8 inches/min. In contrast, the conventional articles **1700**, **1701** and **1702** all exhibited material removal rates of no greater than about 0.235 in^3/min at an in-feed rate (Z'w) of 1.8 inches/min.

[0109] A schematic diagram of the corner wear or change in radius measurements is shown in FIG. **5**. Dimension **1500** represents the original dimension (i.e., the axial width of 0.875 inches) of a sample along the x-axis, while dimension **1501** represents the post-grinding dimension of the sample along the x-axis. Similarly, dimension **1502** represents the original dimension (i.e., the diameter of 7 inches) of a sample along the y-axis, while dimension **1503** represents the post-grinding dimension of the sample along the y-axis.

[0110] FIG. **8** includes plots of change in x-axis radius versus in-feed rate (Z'w) demonstrating a corner holding factor for the same three conventional bonded abrasive articles **1800**, **1801** and **1802** and the embodiment of the bonded abrasive article **1805**. The embodiment of the bonded abrasive body **1805** included an x-axis corner holding factor of about 0.042 inches at an in-feed rate (Z'w) of 1.8 inches/min. In contrast, the conventional articles **1800**, **1801** and **1802** all exhibited x-axis corner holding factors of at least about 0.080 inches at an in-feed rate (Z'w) of 1.8 inches/min.

[0111] In addition, the bonded abrasive body **1805** included a grinding factor defined as a change of x-axis radius over a change in in-feed rate. The grinding factors are essentially the average slopes of the lines in FIG. **8**. For example, for body **1805**, the grinding factor has a numerator of 0.042-0.019=0.023. The denominator is 1.80-1.00=0.80. 0.023/0.80=grinding factor of about 0.029. In contrast, articles **1800**, **1801** and **1802** had a grinding factor of at least about 0.050.

[0112] Similarly, FIG. **9** includes plots of change in y-axis radius versus in-feed rate (Z'w) demonstrating a corner holding factor for the same three conventional bonded abrasive articles **1900**, **1901** and **1902** and the embodiment of the bonded abrasive article **1905**. The body **1905** exhibited a y-axis corner holding factor of about 0.024 inches at an in-feed rate (Z'w) of 1.8 inches/min. The articles **1900**, **1901** and **1902** had y-axis corner holding factors of at least about 0.033 inches at an in-feed rate (Z'w) of 1.8 inches/min.

[0113] Grinding factors also were calculated based on FIG. **9**. For example, for body **1905**, the grinding factor has a numerator of 0.024-0.016=0.008. The denominator is 1.80-1.00=0.80. 0.008/0.80=grinding factor of about 0.01. In contrast, articles **1900**, **1901** and **1902** had a grinding factor of at least about 0.0188.

[0114] Thus, the change in the corner radius along both the x-axis and the y-axis shows that a product with a bond in accordance with an embodiment herein shows the least amount of corner wear at all material removal rates compared to products made with conventional bond systems.

Example 3

[0115] In this example, and embodiment including a combination of sol-gel and fused alumina abrasive was formed with the bond described above for the previous examples. This sample was tested in a centerless plunge application to finish form against a conventional product having a combination of sol-gel and fused alumina abrasive with the conventional bond VH used previously for the other examples. The grinding wheels had 16-inch diameters and the material ground was mild steel (1014). The objective was to improve productivity by increasing parts per dress. The wheel speed was 57.45 m/sec and part speed was 1.15 m/sec.

[0116] Table 2 contains more details regarding the test conditions used in Example 3.

TABLE 2

Test Conditions		
	Units (if any)	
Machine		Cincinnati Viking Centerless series
Coolant Type		Castrol 9951
Dresser RPM		4200
Radial Depth/Pass	in	0.001
Comps (passes)/Dress		1
Total Dress Depth	in	0.001
Wheel speed	rpm	2700
Infeed Rates (R1)	in/min	1.102
Infeed Rates (R2)	in/min	0.748
Infeed Rates (Finish)	in/min	0.315

[0117] FIG. **10** includes a chart of parts per dress for a conventional bonded abrasive article **2000** and the embodiment of the bonded abrasive article **2005**. Article **2005** showed significant improvement in parts per dress (about 7% improved) with a good surface finish or form, compared to article **2000**.

[0118] Another advantage observed was that the in-feed rates could be significantly increased for the new wheel that helped in reduction of cycle time. Lower cycle times have better efficiency in grinding operations. The same samples described for FIG. **10** were tested for cycle time and the results are displayed in FIG. **11**. FIG. **11** is a chart of cycle time for the conventional bonded abrasive article **2100** and the embodiment of the bonded abrasive article **2105**. Article **2105** showed a significant (approximately 18%) improvement over article **2100**.

[0119] The foregoing embodiments are directed to abrasive products, and particularly bonded abrasive products, which represent a departure from the state-of-the-art. The bonded abrasive products of the embodiments herein utilize a combination of features that facilitate improved grinding performance. As described in the present application, the bonded abrasive bodies of the embodiments herein utilize a particular amount and type of abrasive particles, particular amount and type of bond material, and have a particular amount of porosity. In addition to the discovery that such products could be formed effectively, despite being outside of the known realm of conventional abrasive products in terms of their grade and structure, it was also discovered that such products demonstrated improved grinding performance. Notably, it was discovered that the bonded abrasives of the present embodiments are capable of operating at lower speeds during grinding operations despite having significantly higher porosity than conventional grinding wheels. In fact, quite surprisingly, the bonded abrasive bodies of the embodiments herein demonstrated a capability of operating at wheel speeds of less than about 60 m/s, while also demonstrating improved material removal rates, improved corner holding ability, and suitable surface finish as compared to state-of-the-art grinding wheels.

[0120] 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 components or indirect connection through one or more intervening components as will be appreciated 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 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.

[0121] The Abstract of the Disclosure is provided to comply with Patent Law and is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. In addition, in the foregoing Detailed Description, various features may be grouped 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. Thus, the following claims are incorporated into the Detailed Description, with each claim standing on its own as defining separately claimed subject matter.

1. An abrasive article comprising:

a bonded abrasive body having abrasive particles contained within a bond material, the bonded abrasive body comprises an abrasive particle-to-bond material interfacial modulus of elasticity (MOE) of at least about 225 GPa; and

the bonded abrasive body is configured to grind a workpiece comprising metal at a speed of less than about 60 m/s.

2.-**3**. (canceled)

4. The abrasive article of claim **1**, wherein the bonded abrasive body comprises an abrasive particle-to-bond material interfacial hardness of at least about 13 GPa.

5.-**6**. (canceled)

7. The abrasive article of claim **1**, wherein the bonded abrasive body comprises a surface finish of not greater than about 125 micro-inch at an in-feed rate (Z'w) of not greater than about 1.4 inches/min.

8. The abrasive article of claim **1**, wherein the bonded abrasive body comprises a material removal rate of at least about 0.235 in^3/min at an in-feed rate (Z'w) of not greater than about 1.8 inches/min.

9. The abrasive article of claim **1**, wherein the bonded abrasive body comprises an x-axis corner holding factor of not greater than about 0.080 inches at an in-feed rate (Z'w) of 1.8 inches/min, not greater than about 0.070 inches, not greater than about 0.060 inches, not greater than about 0.050 inches, not greater than about 0.042 inches.

10. The abrasive article of claim **1**, wherein the bonded abrasive body comprises a y-axis corner holding factor of not greater than about 0.033 inches at an in-feed rate (Z'w) of 1.8 inches/min, not greater than about 0.030 inches, not greater than about 0.025 inches, not greater than about 0.024 inches.

11.-**13**. (canceled)

14. The abrasive article of claim **1**, wherein the bonded abrasive body is configured to grind a workpiece comprising metal at a speed of at least about 35 m/s.

15.-**16**. (canceled)

17. The abrasive article of claim **1**, wherein the bonded abrasive body comprises a porosity of at least about 42 vol % to about 70 vol % of a total volume of the bonded abrasive body, and the bonded abrasive body comprises at least about 35 vol % abrasive particles of the total volume of the bonded abrasive body.

18.-**33**. (canceled)

34. The abrasive article of claim **1**, wherein the bond material is formed from at least one alkali oxide compound (R_2O) and at least one alkaline earth oxide compound (RO), wherein a total content of the alkali oxide compound and the alkaline earth oxide compound is not greater than about 20 wt %.

35.-**38**. (canceled)

39. The abrasive article of claim **1**, wherein the bonded abrasive body is sintered at a temperature of not greater than about 1000° C.

40.-**42**. (canceled)

43. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent silicon oxide (SiO_2) to weight percent Li_2O (SiO_2:Li_2O) of about 9.6 to about 26.

44. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent silicon oxide (SiO_2) to weight percent Na_2O(SiO_2:Na_2O) of about 4.8 to about 10.4.

45. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent silicon oxide (SiO_2) to weight percent K_2O(SiO_2:K_2O) of about 9.6 to about 26.

46. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent silicon oxide (SiO_2) to weight percent B_2O_3 (SiO_2:B_2O_3) of about 2.8 to about 5.2.

47.-**55**. (canceled)

56. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent Li_2O to weight percent Na_2O (Li_2O:Na_2O) of about 0.2 to about 1.

57. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent Li_2O to weight percent K_2O (Li_2O:K_2O) of about 0.4 to about 2.5.

58. (canceled)

59. The abrasive article of claim **1**, wherein the bond material comprises a ratio of weight percent Na_2O to weight percent K_2O (Na_2O:K_2O) of about 1 to about 5.

60.-**62**. (canceled)

63. The abrasive article

of claim **1**, wherein the bonded abrasive body comprises a grinding factor defined as a change of x-axis radius over a change in in-feed rate, and the grinding factor is not greater than about 0.040 for an in-feed rate (Z'w) of at least about 1.0 inches/min.

64.-**65**. (canceled)

66. An abrasive article comprising:

a bonded abrasive body having abrasive particles contained within a bond material;

the bonded abrasive body comprises a grinding factor defined as a change of y-axis radius over a change in in-feed rate, and the grinding factor is not greater than about 0.018 for an in-feed rate (Z'w) of at least about 1.0 inches/min; and

the bonded abrasive body is configured to grind a workpiece comprising metal at a speed of less than about 60 m/s.

67.-**68**. (canceled)

69. An abrasive article comprising:

a bonded abrasive body having abrasive particles contained within a bond material formed from not greater than about 20 wt % boron oxide (B_2O_3), having a ratio of weight percent silica (SiO_2): weight percent alumina (Al_2O_3) of not greater than about 3.2 (by weight percent) and not greater than about 3.0 wt % phosphorous oxide (P_2O_5), wherein the bonded abrasive body has a porosity of at least about 42 vol % of the total volume of the bonded abrasive body; and

the bonded abrasive body is capable of grinding a workpiece comprising metal at a speed of less than about 60 m/s.

70.-**76**. (canceled)

* * * * *