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(54) **Composite structure having a non-planar interface and method of making same**

(57) A composite structure includes a first portion comprising a first metallic material, a monolayer of particles extending into and bonded with the first portion, and a second portion comprising a second material, the second portion bonded with the monolayer of particles and extending into interstices between the particles. A

method for fabricating a composite structure includes bonding a monolayer of particles to a first portion comprising a first metallic material, such that the monolayer of particles extends into the first portion and bonding a second portion comprising a second material to the monolayer of particles, such that the second portion extends into interstices between the particles.

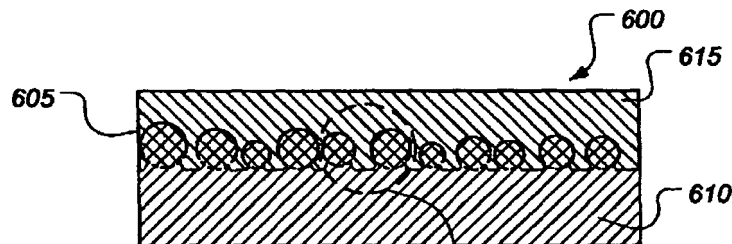


FIG. 6 — **FIGS. 7, 11**

Description

[0001] This invention relates to a composite structure including a non-planar interface and a method of making the composite structure.

[0002] Metallic structures often comprise two or more joined materials that have different properties and characteristics. Often such disparate materials are joined together into one component because portions of the component are subjected to different environments. For example, the body of a drilling bit, such as those used in oilfield operations, is subjected to high torsion loads during drilling, while the cutting surfaces thereof encounter very hard, abrasive materials. Accordingly, rock drilling bit bodies are generally made of steel, while the cutting surfaces often comprise tungsten carbide or polycrystalline diamond composites. Steel provides the material properties required to endure high torsion loads, while tungsten carbide or polycrystalline diamond provides deformation- and wear-resistant material properties. Similar configurations are also found in mining bits and roadbed milling bits used to break apart old roadbeds.

[0003] When such disparate materials are joined together, the mechanical response of the resulting union is affected by the differences in elastic, plastic, and/or thermal expansion properties that cause internal residual stresses to develop within the union, and that cause concentration of applied stress at the interface, enabling premature failure of the union in service. Figure 1 illustrates two disparate material portions 102, 104 joined along an interface 106, which may be planar or non-planar. Such components are often formed using powder metallurgy techniques. For example, the material portion 102 may initially comprise a mixture of steel and tungsten carbide powders and the material portion 104 may comprise a steel powder. The portions 102, 104 may then be cold isostatically pressed to achieve sufficient densification providing handling strength and then either hot forged or hot isostatically pressed to achieve full density. Alternatively, the portion 102 may initially comprise a sintered cemented carbide and the material portion 104 may initially comprise a mixture of diamond and metals powders. The portions 102, 104 may then be hot pressed at very high pressure to achieve full density.

[0004] In both cases, densification involves the heating of the portions 102, 104 in contact with one another under high pressure such that adjacent particles within the portions 102, 104 are plastically deformed and solid state diffusion bonded, or partially melted and resolidified.

[0005] Such structures exhibit a mechanical discontinuity along an interface 106 of the disparate materials. The effects of this discontinuity on mechanical response of the union typically limit the useful strength of these structures. For example, if the portion 102 has a coefficient of thermal expansion (CTE) that is significantly lower than that of the portion 104, merely cooling the joined materials from the final densification temperature may generate sufficient stress at the interface 106 to disbond/

disjoin the portions 102, 104. Even if thermal residual stress in the joined portions 102, 104 were below the failure threshold, the application of external loading on the joined portions 102, 104 would result in a concentration of stress at the interface due to elastic modulus and plastic yielding differences between the portion 102, 104. The superposition of thermal residual stress and concentrated load stress may disbond/disjoin the portions 102, 104.

[0006] Various techniques are known to the art for improving the stress distributions along such disparate material interfaces (e.g., the interface 106) and, thus, improving the useful strength of these structures. For example, one technique is to roughen the interface surface 106 between the disparate materials 102, 104 before joining. Adding topographic complexity in a dimension normal to the interface surface creates a zone of material that behaves as though its properties are intermediate the two joined disparate materials. This configuration is often referred to as a "non-planar interface", whether the interface is broadly planar or curved. In one example, illustrated in Figure 2A, an interface surface 202 of the portion 104 is roughened prior to joining the portion 102 thereto. Alternatively, as shown in Figure 2B, localized areas of an interface surface 204 of the portion 104 are melted, for example, with an electron beam, laser, or other intense, localized heating source prior to joining the portion 102 thereto.

[0007] In either case, when the portion 102 is joined to the portion 104, the material comprising the portion 102 fills the recesses in the roughened surfaces 202, 204 to further retain the portions 102, 104 together. While the techniques described in relation to Figures 2A-2B may be effective in improving the strength of the bond or joint between the portions 102, 104, they each require additional processing to prepare the interface surfaces 202, 204 for joining. The additional processing may, in some instances, also be costly. For example, the electron beam, laser, or other localized, intense heat source equipment used to melt areas of the interface surface 204 may be very expensive to purchase, maintain, and operate.

[0008] Other techniques that have been used to aid in retaining disparate material portions together include machining retention features in one of the portions and urging material of the other portion into the features. Figures 3A-3C illustrates one particular example of such a technique. A plurality of radial grooves 302 (only one labeled for clarity) and a circumferential groove 303 are machined into a face 304 of a cutting blank 306 comprising, for example, steel. A cutting portion 308, comprising a second material, e.g., tungsten carbide, polycrystalline diamond, etc., is formed onto the face 304, such that the cutting portion 308 extends into the grooves 302, 303. The non-planar interface between the cutting blank 306 and the cutting portion 308 aids in retaining the cutting portion 308 on the cutting blank 306, as compared to an interface that omits the grooves 302, 303. Some designs

have further included undercut grooves, such as illustrated in Figure 3C, to further enhance retention of the cutting portion 308 on the cutting blank 306.

[0009] While such techniques often are successful in retaining disparate materials together, the additional machining steps required to form the grooves 302, 303 may add substantial cost and complexity to the finished product. The preferred die-pressing method for creating irregular or grooved surfaces via powder fabrication is restricted to geometries that provide positive draft to allow die withdrawal. Further, it may be difficult to fully fill the grooves 302, 303, with the second material, especially if they are narrow or undercut (as illustrated in Figure 3C).

[0010] As illustrated in Figure 4, designs have also included protrusions 402 (only one labeled for clarity) extending from a first material portion 404 and into a second material portion 406, forming a non-planar interface 408.

[0011] Yet another technique used to mitigate stress concentrations along such disparate material interfaces is to employ a "functional gradient design," as shown in Figure 5, wherein a third material 502 is disposed in the interface 106 between the two disparate materials 102, 104. The third material 502 has properties that are generally between those of the disparate materials 102 and 104. In other words, the third or gradient material 502 may have, for example, elastic plastic, thermal expansion properties intermediate between those of the first disparate material 102 those of the second disparate material 104. Multiple such intermediate layers or single graduated layer may be employed to further reduce the magnitude(s) of disparities of the included interfaces. While such structures address the property compatibility issues described above, their complexity often adds prohibitive fabrication cost and may be incompatible with preferred fabrication methods.

[0012] The present invention is directed to overcoming, or at least reducing, the effects of one or more of the problems set forth above.

[0013] In one aspect of the present invention, a composite structure is provided. The composite structure includes a first portion comprising a first metallic material, a monolayer of particles extending into and bonded with the first portion, and a second portion comprising a second material, the second portion bonded with the monolayer of particles and extending into interstices between the particles.

[0014] In another aspect of the present invention, an insert for a rock bit is provided. The insert includes a substrate comprising a first metallic material, a plurality of particles bonded with the substrate, and a densified portion comprising a second material, the densified portion bonded with the plurality of particles and extending into interstices between the particles.

[0015] In yet another aspect of the present invention, a composite pick is provided. The pick includes a tip comprising a first metallic material, a plurality of particles bonded with the tip, and a densified portion comprising a second material, the densified portion bonded with the

plurality of particles and extending into interstices between the particles.

[0016] In another aspect of the present invention, a method for fabricating a composite structure is provided.

5 The method includes bonding a monolayer of particles to a first portion comprising a first metallic material, such that the monolayer of particles extends into the first portion and bonding a second portion comprising a second material to the monolayer of particles, such that the second portion extends into interstices between the particles.

10 **[0017]** The invention may be understood by reference to the following description taken in conjunction with the accompanying drawings, in which the leftmost significant digit(s) in the reference numerals denote(s) the first figure in which the respective reference numerals appear.

Figure 1 is a stylized, cross-sectional side view of a first conventional composite structure of the prior art.

20 Figures 2A-2B are stylized, enlarged alternative views of a portion of the composite structure of prior art Figure 1.

25 Figure 3A is a top view of a conventional composite cutter of the prior art.

30 Figure 3B is a cross-sectional view of the conventional composite cutter of the prior art taken along the line 3B-3B in Figure 3A

35 Figure 3C is a cross-sectional view of the conventional composite cutter of the prior art taken along the line 3C-3C in Figure 3A

40 Figure 4 is a stylized, cross-sectional side view of a second conventional composite structure of the prior art.

45 Figure 5 is a stylized, cross-sectional side view of a third conventional composite structure of the prior art.

Figure 6 is a stylized, cross-sectional side view of a first illustrative embodiment of a composite structure having a non-planar interface according to the present invention.

50 Figure 7 is a stylized, cross-sectional, enlarged portion of one illustrative embodiment of the composite structure of Figure 6 illustrating neck bonds.

55 Figure 8 is a stylized, cross-sectional side view of an intermediate stage during fabrication of the composite structure of Figure 6.

Figure 9 is a stylized, cross-sectional side view illustrating filling fine powder around the particles of the

composite structure intermediate stage of Figure 8.

Figure 10 is a stylized, cross-sectional side view illustrating densifying the powder of Figure 9.

Figure 11 is a stylized, cross-sectional side view illustrating infusing molten metal around the particles of the composite structure intermediate stage of Figure 8.

Figure 12 is a stylized, cross-sectional, enlarged portion of one illustrative embodiment of the composite structure of Figure 6.

Figure 13 is a stylized, cross-sectional side view illustrating various particulate shape embodiments according to the present invention.

Figure 14 is a stylized, cross-sectional side view of a second illustrative embodiment of a composite structure according to the present invention.

Figure 15 is a perspective view of an exemplary roller-cone rock bit including inserts or cutters according to the present invention.

Figure 16 is a side view of an exemplary fixed cutter rock bit including inserts or cutters according to the present invention.

Figure 17 is a perspective view of an illustrative embodiment of an intermediate stage of a rock bit insert according to the present invention.

Figure 18 is a top view of a first alternative embodiment of an intermediate stage of a rock bit insert according to the present invention.

Figure 19 is a top view of a second alternative embodiment of an intermediate stage of a rock bit insert according to the present invention.

Figure 20 is a perspective view of an illustrative embodiment of a road or mining pick tip according to the present invention.

Figure 21 is a depiction of the macrostructure of one particular embodiment of a road or mining pick according to the present invention.

Figure 22 is a depiction of a portion of the microstructure of the road or mining pick of Figure 21.

[0018] While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of

specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

[0019] Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developer's specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

[0020] The present invention relates to a structure comprising disparate materials joined along a non-planar interface that exhibits, in one illustrative embodiment, an interlocking geometry and a method for fabricating the structure. While it is not so limited, the structure of the present invention is particularly applicable to cemented carbide composites and their incorporation in layered, functionally graded structures with disparate cemented carbides, diamond composites, metals, or metal alloys. The non-planar interface of the present invention allows fabrication of powder preforms incorporating fully dense elements by direct pressing or cold isostatic pressing, and powder forging of such preforms. In particular, the present invention mitigates or avoids the problem of decompression cracking between fully dense and powder regions during the unload portion of an isostatic pressing cycle.

[0021] Figure 6 depicts one illustrative embodiment of a composite structure 600 incorporating a non-planar interface according to the present invention. In this embodiment, the structure 600 comprises a monolayer of particles 605 (only one labeled for clarity) formed integrally with a metallic substrate material 610. The particles 605 define an open framework that is substantially filled with a second material 615. The particles 605 may comprise the same material as the substrate 610, a chemical or metallurgical variant of the substrate 610, a metal or a metal alloy. In one embodiment, shown in Figure 7, the substrate 610 comprises a sintered powder and the particles 605 are co-sintered with the substrate 610. In this embodiment, the particles 605 are attached to the substrate 610 and, in some cases to each other, primarily by metallurgical neck bonds 705 grown during sintering. In some embodiments, the particles 605 extend into the substrate 610. Mechanisms that are operative during neck bond growth include: viscous flow, plastic flow, evaporation-condensation, volume diffusion, grain boundary diffusion, and surface diffusion. The particles 605 may be attached to the substrate 610 by various

processes producing metallurgical bonding, such as liquid phase sintering, solid-state sintering or diffusion bonding, welding, and brazing. Figure 8 illustrates an intermediate configuration, prior to adding the second material 615 to the composite structure 600.

[0022] The second material 615 may be formed by substantially filling the open volume between the particles 605 with a fine metallic powder 905, as shown in Figure 9, then pressure densifying the second material 615 (e.g., the fine powder 905), as shown in Figure 10. Alternatively, the second material 615 may be formed by infiltrating the open volume between the particles 605 with liquid metal and solidifying the metal 1105 as illustrated in Figure 11, to form the second material 615 (of Figure 6). Thus, the second material 615, whether formed using powder or liquid metal techniques, comprises a densified portion. Note, as depicted in Figure 12, that the particles 605 extend from the substrate 610 such that the particles 605 and the substrate 610 define recesses 1205. The recesses 1205 exhibit negative draft angles (e.g., the negative draft angle 1210) or are "undercut." Generally, a draft angle of 90 degrees is neutral. Thus, a draft angle of less than 90 degrees (as illustrated in Figure 12) is a negative draft angle. Draft angles that are greater than 90 degrees are considered positive draft angles. While the present invention is not so limited, in particular embodiments, the draft angle may be within a range of about 3 degrees to about 85 degrees.

[0023] The second material 615 extends into the recesses 1205, which provides mechanical locking of the second material 615 to the particles 605. Moreover, the particles 605 provide a tortuous bonding surface having substantially more bonding area for both the substrate 610 and the second material 615 as compared to a planar interface. These factors contribute to improved mechanical interlocking strength during intermediate processing steps and increased interfacial strength in the finished structure.

[0024] While the particles 605 are illustrated in Figure 6 as being substantially spherical, the present invention is not so limited. Rather, the particles 605 may take on many other shapes, such as oblate spheroids 1305, cylinders 1310, and irregular shapes 1315, as illustrated in Figure 13, including, for example, acicular, fibrous, flaky, granular, dendritic, and blocky shapes. Further, the particles 605 may, in some embodiments, be arranged in a particular pattern or they may be randomly dispersed on the substrate material 610.

[0025] Note that substrate 610 may comprise either the "soft" or "hard" portion of the composite structure 600. For example, wherein the substrate 610 comprises a cemented carbide and the second material 615 comprises a polycrystalline diamond material, the cemented carbide substrate 610 represents the "soft" portion of the composite structure 600. As illustrated in Figure 14, the composite structure 600, for example, may be incorporated into a yet larger composite structure 1400 including a second monolayer of particles 1405 (only one labeled for

clarity) and a third material 1410 that is softer than the substrate 610. In such a configuration, the substrate 610 corresponds to the "hard" portion of the composite couple of the substrate 610 and the third material 1410.

[0026] Particular implementations of the present invention depend on many scale and property aspects of the components and component materials. For example, in the case of polycrystalline diamond composite cutters or insert elements, the desirable thickness of the particle layer (e.g., the layers of particles 605, 1405) depends upon the polycrystalline diamond layer thickness and the shape of the substrate surface. For planar or simply curved surfaces, a particle size corresponding to about 80% of the polycrystalline diamond layer thickness may be used. Dimpled, ribbed, or faceted substrate surfaces may require smaller average particle sizes or a wider size distribution for conformation to the substrate surface. Multiple sizes or shapes of particles may be used to enhance particle coverage and effective non-planar interface zone width.

[0027] The non-planar interface structure of the present invention may be implemented in various products, such as a roller-cone rock bit 1500, shown in Figure 15, or a fixed cutter rock bit 1600, shown in FIG 16. The rock bits 1500, 1600 comprises a plurality of polycrystalline diamond coated inserts 1505, 1605, respectively, (only one labeled in each figure for clarity) that ablate rock formations during oilfield drilling operations. Figure 17 illustrates one particular embodiment of such an insert 1705 at an intermediate stage of fabrication. The insert 1705 comprises a plurality of tungsten carbide/cobalt spherical pellets 1710 sintered onto a cemented carbide substrate 1715 of the same composition. In the illustrated example, the pellets 1710 have sizes corresponding to a 16/20 mesh. In other embodiments, the pellets 1710 have sizes corresponding to 80/200 mesh, 40/60 mesh, and 20/30 mesh but may comprise other sizes depending upon the particular implementation.

[0028] As noted above, the particles or pellets may take on various shapes. For example, Figures 18-19 illustrate an exemplary insert comprising rod-shaped or cylindrical tungsten carbide/cobalt particles 1805 sintered onto a substrate 1810 of the same material. In Figure 18, the particles 1805 are arranged in a spiral fashion, while they are arranged randomly in Figure 19. Irrespective of the particle shape and arrangement, the interstices between the particles or pellets 1710, 1805 are filled with diamond-containing particle mixes, held in place by a formed can that defines the final external shape. The assembly is subsequently densified at high temperature and pressure, achieving full density of the composite structure.

[0029] Another exemplary implementation of the non-planar interface structure of the present invention is that of a composite road pick used for milling roadbeds prior to resurfacing. Such picks are also used in earth-boring equipment for mining applications. Figure 20 depicts a sintered, cemented carbide tip 2005 with an integral par-

ticulate non-planar interface layer 2010 disposed on an undulant surface 2015. In this example, fine nickel particles are coated on the particulate layer 2010, followed by injection co-molding with a fugitive-bound mixed cemented carbide and steel powder composite perform. The assembly is placed in an elastomer mold with steel powders and a carbide particulate surface layer as described in U.S. Patent No. 5,967,248 (which is hereby incorporated by reference for all purposes) and densified by cold isostatic pressing to produce a final composite powder preform. The final preform is then preheated to forging temperature and densified by forging, e.g., in a hot powder bed. The resulting fully dense functionally-graded composite tool is then finish machined and heat treated.

[0030] Figure 21 illustrates the macrostructure of such a composite road or mining pick 2100, including the cemented carbide tip 2005, the particulate layer 2010, the undulant surface 2015, the steel shank 2105 formed during cold isostatic pressing, and the densified cemented carbide and steel powder 2110. Figure 20 depicts the microstructure of the non-planar interface, including the cemented carbide tip 2005, nickel layer 2005, and the densified cemented carbide and steel powder 2110.

[0031] In one particular embodiment of the present invention, a composite structure is provided. The composite structure includes a first portion comprising a first metallic material, a monolayer of particles extending into and bonded with the first portion, and a second portion comprising a second material, the second portion bonded with the monolayer of particles and extending into interstices between the particles.

[0032] In another particular embodiment of the present invention, an insert for a rock bit is provided. The insert includes a substrate comprising a first metallic material, a plurality of particles bonded with the substrate, and a densified portion comprising a second material, the densified portion bonded with the plurality of particles and extending into interstices between the particles.

[0033] In yet another particular embodiment of the present invention, a composite road pick is provided. The road pick includes a tip comprising a first metallic material, a plurality of particles bonded with the tip, and a densified portion comprising a second material, the densified portion bonded with the plurality of particles and extending into interstices between the particles.

[0034] In another particular embodiment of the present invention, a method for fabricating a composite structure is provided. The method includes bonding a monolayer of particles to a first portion comprising a first metallic material, such that the monolayer of particles extends into the first portion and bonding a second portion comprising a second material to the monolayer of particles, such that the second portion extends into interstices between the particles.

[0035] This concludes the detailed description. The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in

different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the invention. Accordingly, the protection sought herein is as set forth in the claims below.

Claims

1. A composite structure, comprising:
 - a first portion comprising a first metallic material; a monolayer of particles extending into and bonded with the first portion; and
 - a second portion comprising a second material, the second portion bonded with the monolayer of particles and extending into interstices between the particles.
2. A composite structure, according to claim 1, wherein at least some of the particles and the first portion define recesses exhibiting negative draft angles into which the second portion extends.
3. A composite structure, according to claim 1, wherein the monolayer of particles is co-sintered with the first portion.
4. A composite structure, according to claim 1, wherein the monolayer of particles is bonded to the first portion by metallurgical neck bonds.
5. A composite structure, according to claim 1, wherein the monolayer of particles comprises one of the first metallic material, a chemical variant of the first metallic material, a metallurgical variant of the first metallic material, a metal, and a metal alloy.
6. A composite structure, according to claim 1, wherein the first metallic material comprises a first cemented carbide and the second material comprises one of a second cemented carbide, a diamond composite material, a metal, and a metal alloy.
7. A composite structure, according to claim 1, wherein the monolayer of particles comprises at least one of spherical particles, oblate spherical particles, cylindrical particles, rod-shaped particles, and irregular shaped particles.
8. A composite structure, according to claim 1, wherein the first portion is harder than the second portion.

9. A composite structure, according to claim 1, wherein the first portion is softer than the second portion.
10. A composite structure, according to claim 1, further comprising a second monolayer of particles extending into and bonded with the first portion and a third portion comprising a third material, the third portion bonded with the second monolayer of particles and extending into interstices between the particles of the second monolayer of particles.
11. A composite structure, according to claim 1, wherein the second portion comprises a densified powder.
12. A composite structure, according to claim 1, wherein the second portion comprises a solidified metal or metal alloy.
13. An insert for a rock bit, comprising:
- a substrate comprising a first metallic material; a plurality of particles bonded with the substrate; and
 - a densified portion comprising a second material, the densified portion bonded with the plurality of particles and extending into interstices between the particles.
14. An insert, according to claim 13, wherein at least some of the plurality of particles and the substrate define recesses exhibiting negative draft angles into which the densified portion extends.
15. An insert, according to claim 13, wherein the plurality of particles is co-sintered with the substrate.
16. An insert, according to claim 13, wherein the plurality of particles comprises one of the first metallic material, a chemical variant of the first metallic material, a metallurgical variant of the first metallic material, a metal, and a metal alloy.
17. An insert, according to claim 13, wherein the first metallic material comprises a first cemented carbide and the second material comprises one of a second cemented carbide, a diamond composite material, a metal, and a metal alloy.
18. An insert, according to claim 13, wherein the plurality of particles comprises at least one of spherical particles, oblate spherical particles, cylindrical particles, rod-shaped particles, and irregular shaped particles.
19. A composite pick, comprising:
- a tip comprising a first metallic material; a plurality of particles bonded with the tip; and
 - a densified portion comprising a second material, the densified powder bonded with the plurality of particles and extending into interstices between the particles.
20. A composite pick, according to claim 19, wherein the tip defines an undulant surface and the plurality of particles is bonded with the undulant surface.
21. A composite pick, according to claim 19, wherein at least some of the plurality of particles and the tip define recesses exhibiting negative draft angles into which the second portion extends.
22. A composite pick, according to claim 19, wherein the plurality of particles is co-sintered with the substrate.
23. A composite pick, according to claim 19, wherein the plurality of particles comprises one of the first metallic material, a chemical variant of the first metallic material, a metallurgical variant of the first metallic material, a metal, and a metal alloy.
24. A composite pick, according to claim 19, wherein the first metallic material comprises a first cemented carbide and the second material comprises one of a second cemented carbide, a cemented carbide and steel mixture, a metal, and a metal alloy.
25. A composite pick, according to claim 20, wherein the plurality of particles comprises at least one of spherical particles, oblate spherical particles, cylindrical particles, rod-shaped particles, and irregular shaped particles.
26. A method for fabricating a composite structure, comprising:
- bonding a monolayer of particles to a first portion comprising a first metallic material, such that the monolayer of particles extends into the first portion; and
 - bonding a second portion comprising a second material to the monolayer of particles, such that the second portion extends into interstices between the particles.
27. A method, according to claim 26, wherein bonding the monolayer of particles further comprises co-sintering the monolayer of particles with the first portion.
28. A method, according to claim 26, wherein bonding the second portion further comprises:
- filling the interstices with a powder; and
 - pressure densifying the powder.
29. A method, according to claim 26, wherein bonding the second portion further comprises:

infiltrating the interstices with a liquid metal; and allowing the liquid metal to solidify.

30. A method, according to claim 26, further comprising extending the second portion into recesses defined by the particles and the first portion. 5

31. A method, according to claim 30, wherein the recesses exhibit negative draft angles. 10

32. A method, according to claim 26, further comprising:
bonding a second monolayer of particles to a first portion, such that the second monolayer of particles extends into the first portion; and 15
bonding a third portion comprising a third material to the second monolayer of particles, such that the third portion extends into interstices between the particles of the second monolayer of particles. 20

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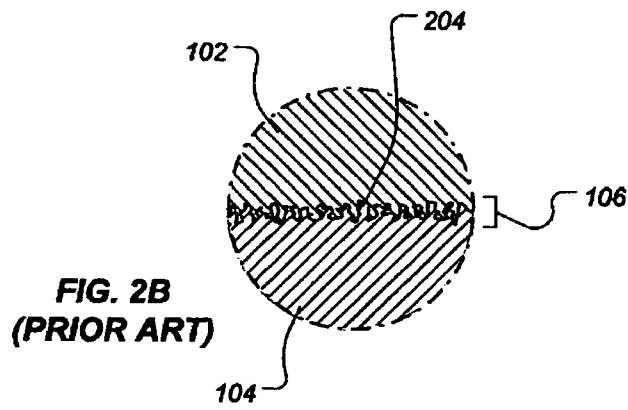
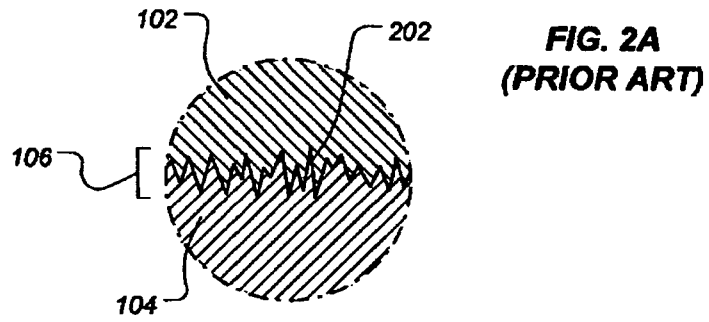
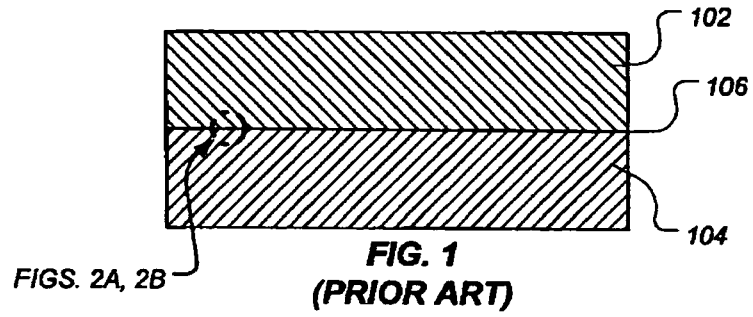
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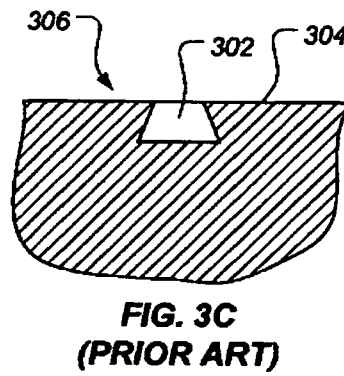
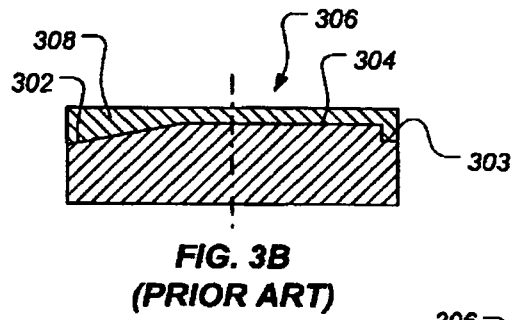
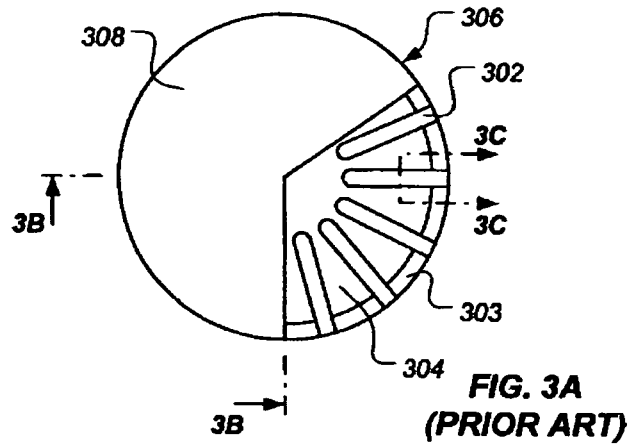
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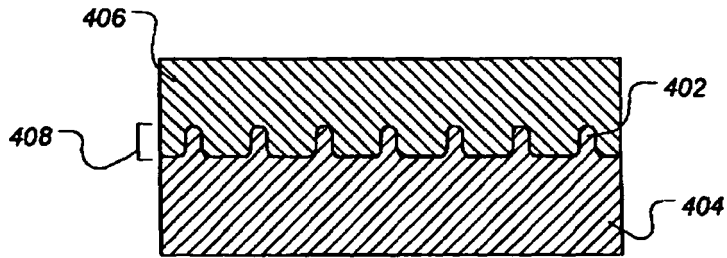


FIG. 4
(PRIOR ART)

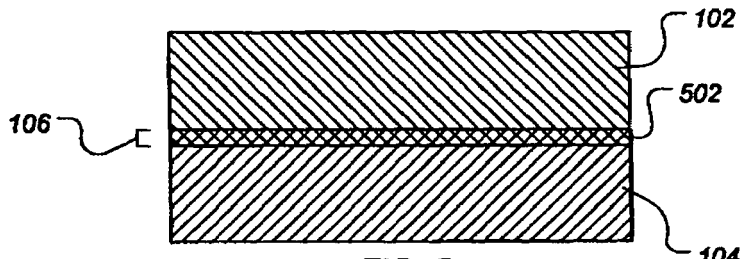


FIG. 5
(PRIOR ART)

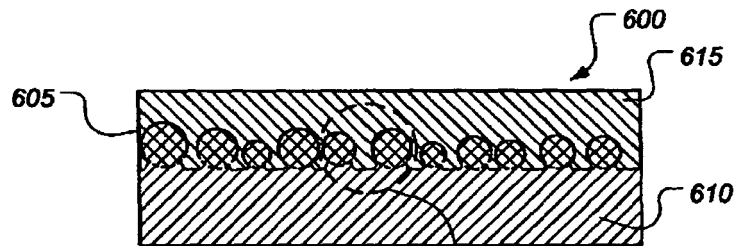


FIG. 6 **FIGS. 7, 11**

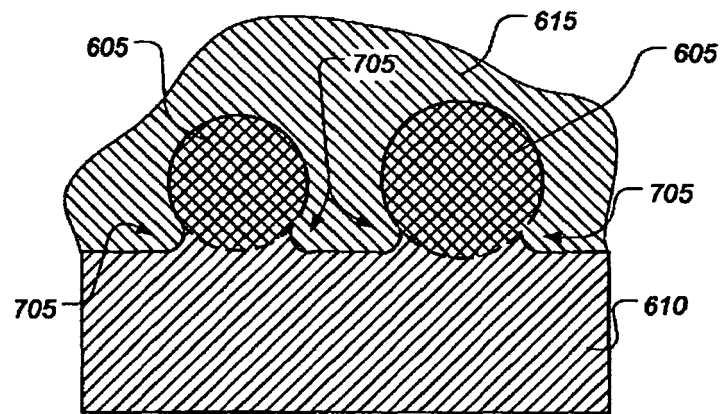


FIG. 7

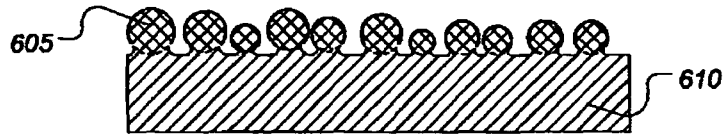


FIG. 8

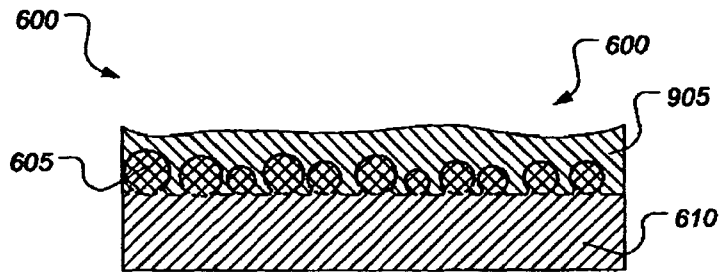


FIG. 9

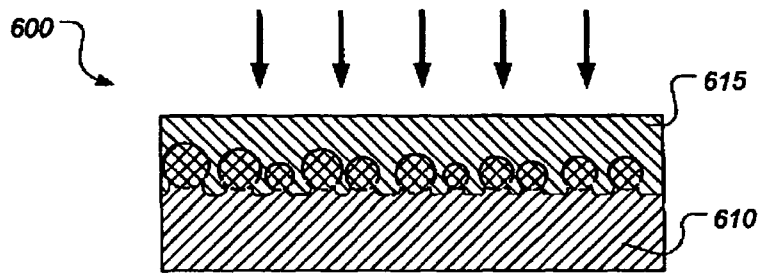


FIG. 10

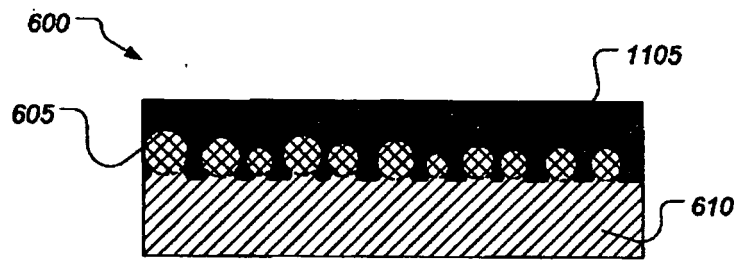


FIG. 11

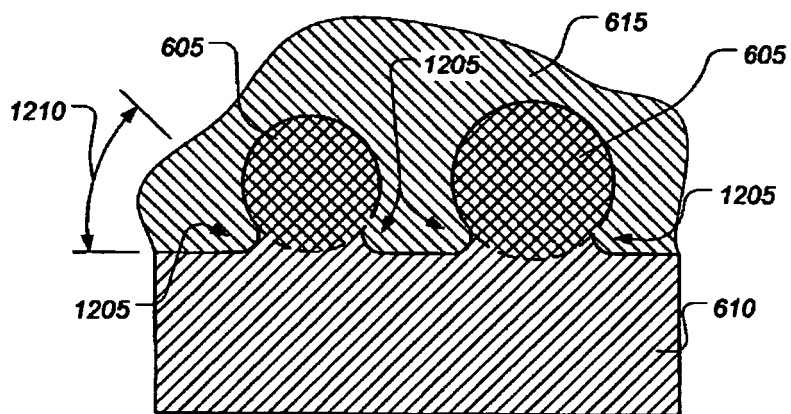


FIG. 12

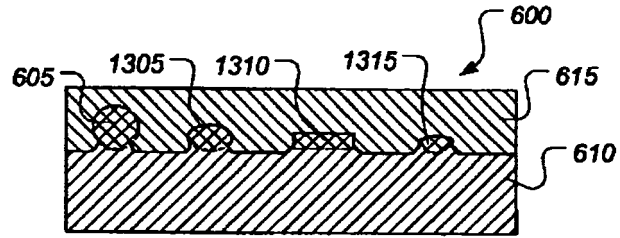


FIG. 13

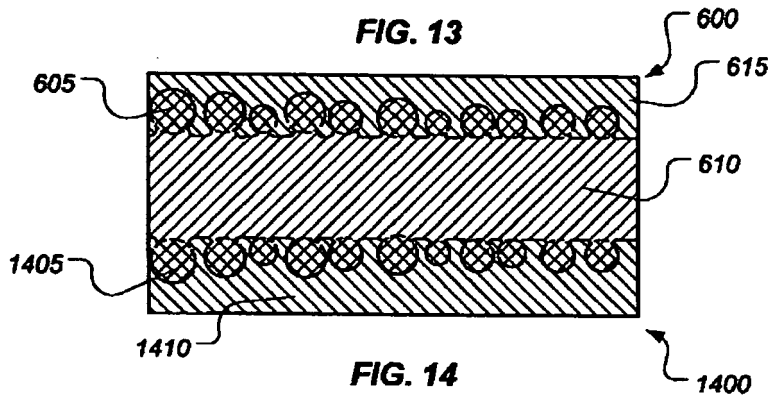


FIG. 14

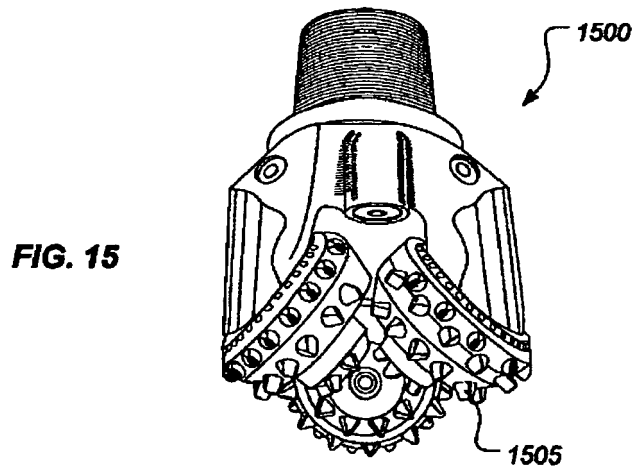


FIG. 15

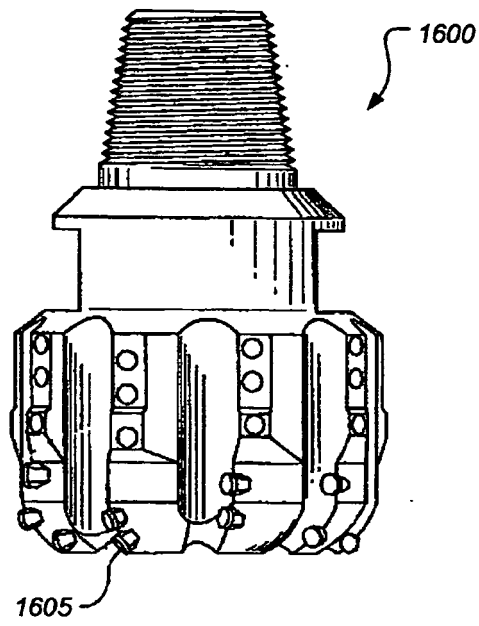


FIG. 16

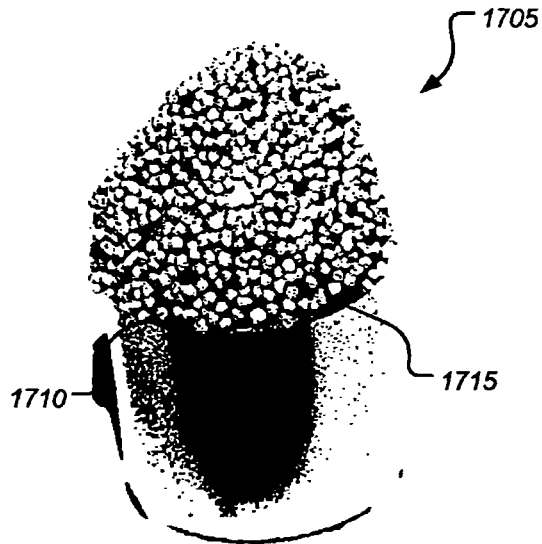


FIG. 17

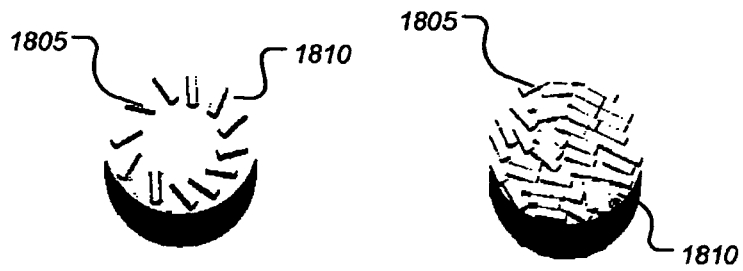


FIG. 18

FIG. 19

FIG. 20

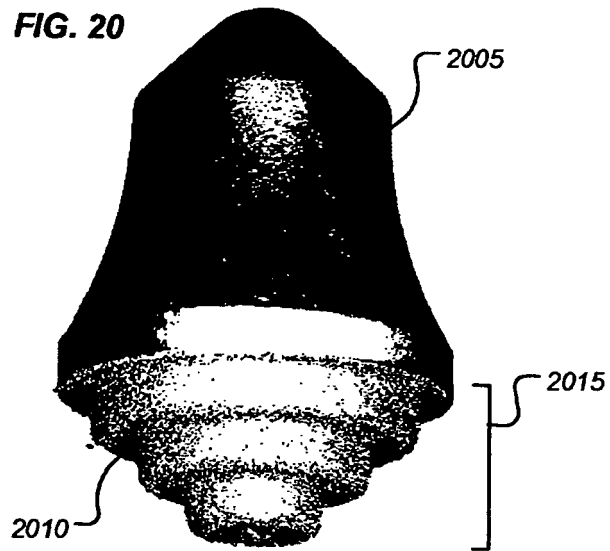
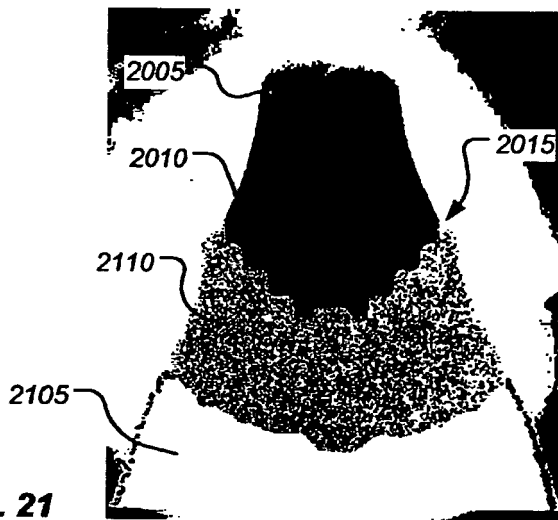


FIG. 21



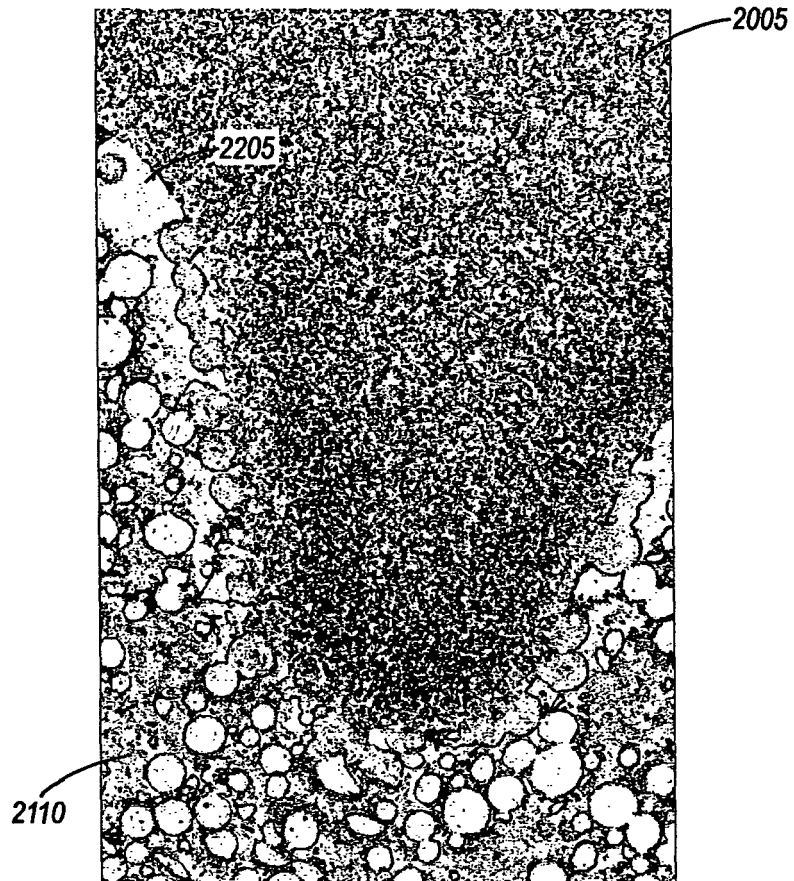


FIG. 22

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

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