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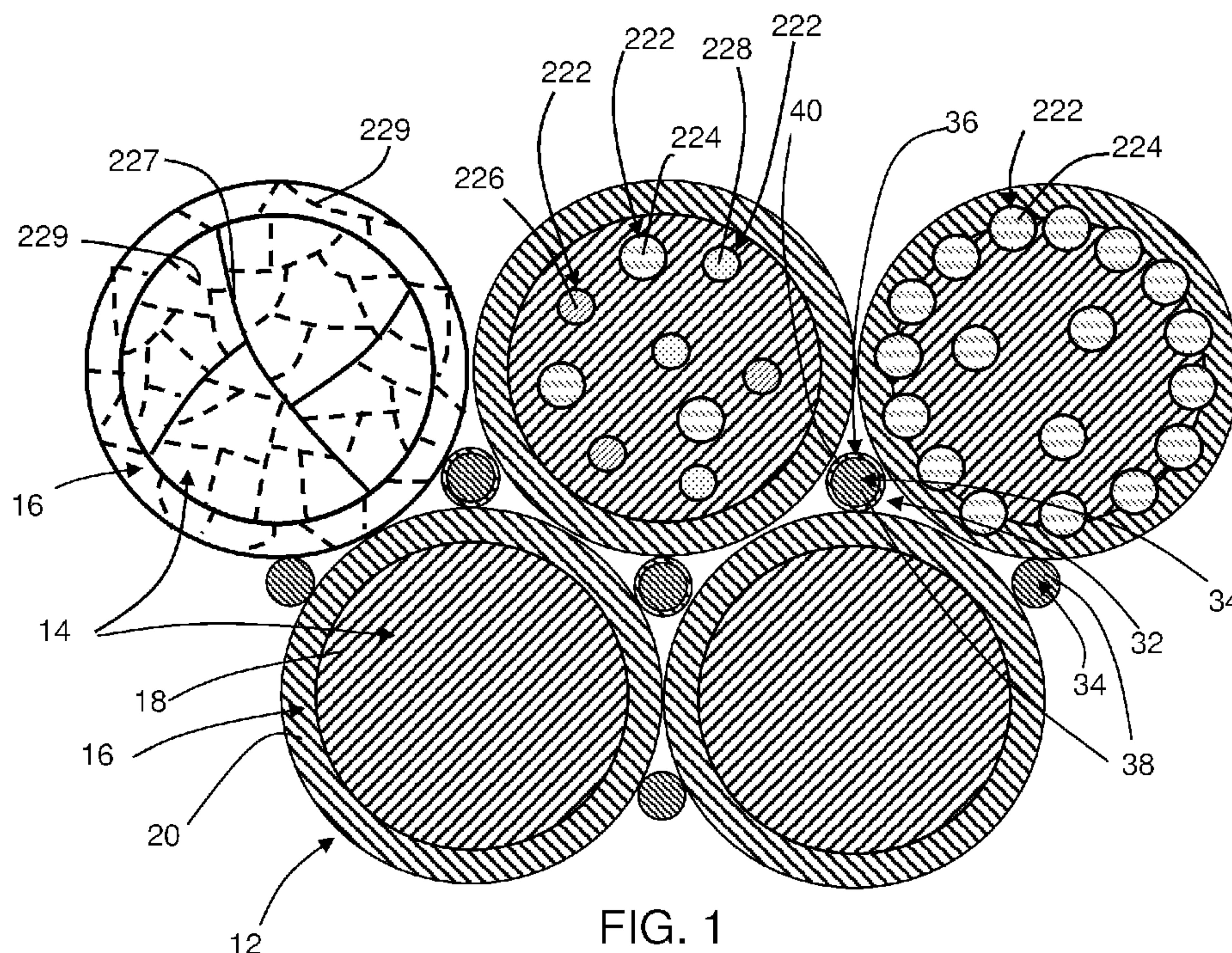


FIG. 1

(57) Abrégé/Abstract:

A powder metal compact is disclosed. The powder metal compact comprises a cellular nanomatrix comprising a metallic nanomatrix material. The powder metal compact also comprises a plurality of dispersed particles comprising a metallic particle core material dispersed in the cellular nanomatrix, the particle core material comprising a nanostructured material.



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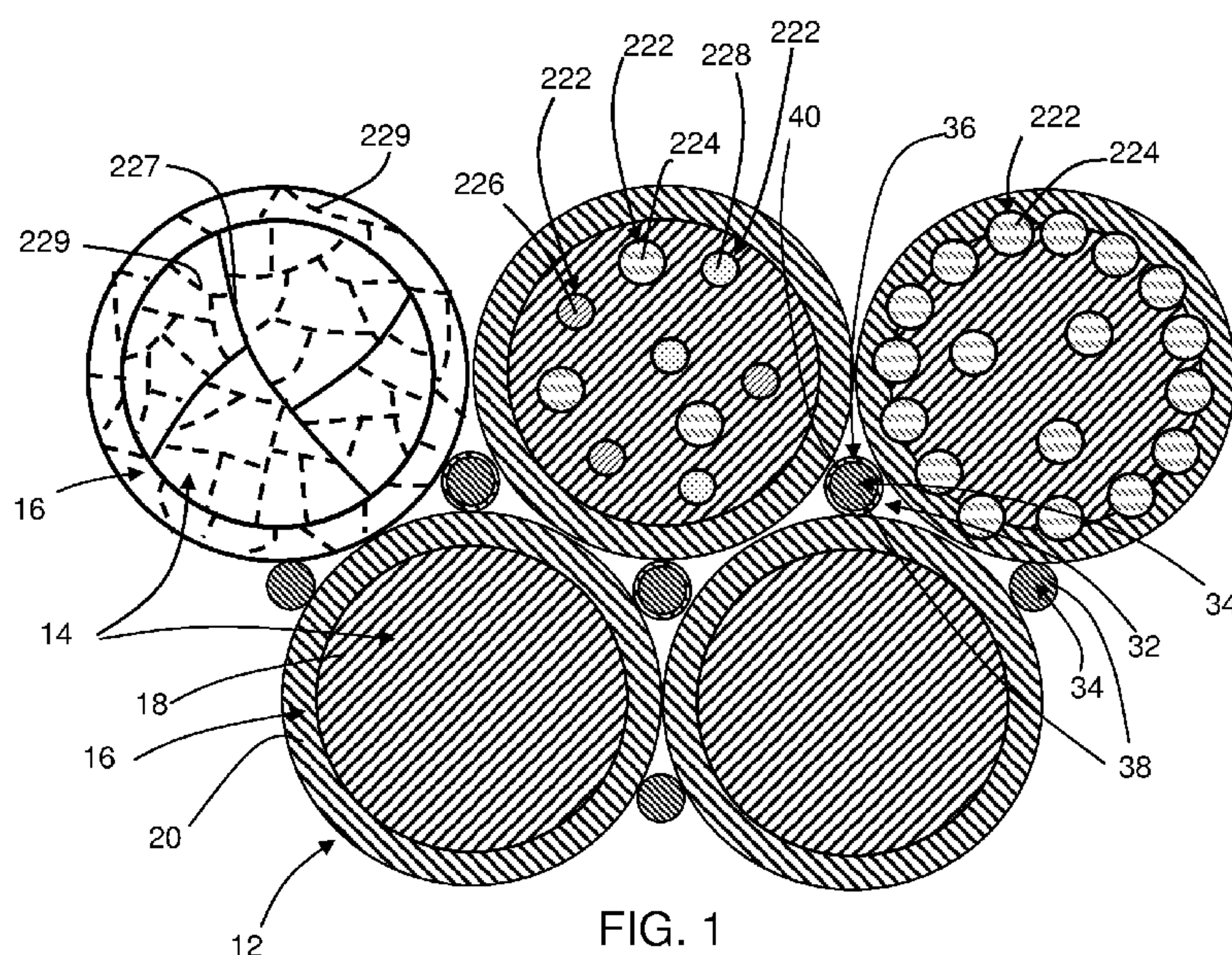
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## Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

[Continued on next page]

(54) Title: NANOSTRUCTURED POWDER METAL COMPACT



(57) Abstract: A powder metal compact is disclosed. The powder metal compact comprises a cellular nanomatrix comprising a metallic nanomatrix material. The powder metal compact also comprises a plurality of dispersed particles comprising a metallic particle core material dispersed in the cellular nanomatrix, the particle core material comprising a nanostructured material.

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## NANOSTRUCTURED POWDER METAL COMPACT

### CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Application No. 13/220832, filed on August 30, 2011, which is incorporated herein by reference in its entirety.

### BACKGROUND

[0001] Oil and natural gas wells often utilize wellbore components or tools that, due to their function, are only required to have limited service lives that are considerably less than the service life of the well. After a component or tool service function is complete, it must be removed or disposed of in order to recover the original size of the fluid pathway for use, including hydrocarbon production, CO<sub>2</sub> sequestration, etc. Disposal of components or tools has conventionally been done by milling or drilling the component or tool out of the wellbore, which are generally time consuming and expensive operations.

[0002] In order to eliminate the need for milling or drilling operations, the removal of components or tools from the wellbore by dissolution or corrosion using various dissolvable or corrodible materials has been proposed. While these materials are useful, it is also very desirable that these materials be lightweight and have high strength, including a strength comparable to that of conventional engineering materials used to form wellbore components or tools, such as various grades of steel. Thus, the further improvement of dissolvable or corrodible materials to increase their strength, corrodibility and manufacturability is very desirable.

### SUMMARY

[0003] In an exemplary embodiment, a powder metal compact is disclosed. The powder metal compact comprises a cellular nanomatrix comprising a metallic nanomatrix material. The powder metal compact also comprises a plurality of dispersed particles comprising a metallic particle core material dispersed in the cellular nanomatrix, the particle core material comprising a nanostructured material.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Referring now to the drawings wherein like elements are numbered alike in the several Figures:

[0005] FIG. 1 is a schematic illustration of an exemplary embodiment of a powder 10 and powder particles 12;

[0006] FIG. 2 is a schematic of illustration of an exemplary embodiment of the powder compact have an equiaxed configuration of dispersed particles as disclosed herein;

[0007] FIG. 3 is a schematic of illustration of an exemplary embodiment of the powder compact have a substantially elongated configuration of dispersed particles as disclosed herein;

[0008] FIG. 4 is a schematic of illustration of an exemplary embodiment of the powder compact have a substantially elongated configuration of the cellular nanomatrix and dispersed particles, wherein the cellular nanomatrix and dispersed particles are substantially continuous; and

[0009] FIG. 5 is a schematic of illustration of an exemplary embodiment of the powder compact have a substantially elongated configuration of the cellular nanomatrix and dispersed particles, wherein the cellular nanomatrix and dispersed particles are substantially discontinuous.

#### DETAILED DESCRIPTION

[0010] Lightweight, high-strength nanomatrix materials having dispersed particles that include nanostructured particle core material are disclosed. The nanostructured particle core material used to form these nanomatrix materials are high-strength materials. Their strength may also be enhanced through the incorporation of nanostructuring into the nanomatrix materials. The strength of these alloys may also be improved by the incorporation of various strengthening subparticles and second particles. The nanomatrix materials disclosed may also incorporate various microstructural features to control the alloy mechanical properties, such as the incorporation of a substantially elongated particle microstructure to enhance the alloy strength, or a multi-modal particle size in the alloy microstructure to enhance the fracture toughness, or a combination thereof to control both the strength, fracture toughness and other alloy properties.

[0011] The nanomatrix materials disclosed herein may be used in all manner of applications and application environments, including use in various wellbore environments, to make various lightweight, high-strength articles, including downhole articles, particularly tools or other downhole components. In addition to their lightweight, high strength characteristics, these nanomatrix materials may be described as controlled electrolytic materials, which may be selectably and controllably disposable, degradable, dissolvable,

corrodible or otherwise removable from the wellbore. Many other applications for use in both durable and disposable or degradable articles are possible. In one embodiment these lightweight, high-strength and selectably and controllably degradable materials include fully-dense, sintered powder compacts formed from coated powder materials that include various lightweight particle cores and core materials having various single layer and multilayer nanoscale coatings. In another embodiment, these materials include selectably and controllably degradable materials may include powder compacts that are not fully-dense or not sintered, or a combination thereof, formed from these coated powder materials.

[0012] Nanomatrix materials and methods of making these materials are described generally, for example, in US Patent Application 12/633,682 filed on December 8, 2009 and US Patent Application 13/194,361 filed on July 29, 2011, which are hereby incorporated herein by reference in their entirety. These lightweight, high-strength and selectably and controllably degradable materials may range from fully-dense, sintered powder compacts to precursor or green state (less than fully dense) compacts that may be sintered or unsintered. They are formed from coated powder materials that include various lightweight particle cores and core materials having various single layer and multilayer nanoscale coatings. These powder compacts are made from coated metallic powders that include various electrochemically-active (e.g., having relatively higher standard oxidation potentials) lightweight, high-strength particle cores and core materials, such as electrochemically active metals, that are dispersed within a cellular nanomatrix formed from the consolidation of the various nanoscale metallic coating layers of metallic coating materials, and are particularly useful in wellbore applications. The powder compacts may be made by any suitable powder compaction method, including cold isostatic pressing (CIP), hot isostatic pressing (HIP), dynamic forging and extrusion, and combinations thereof. These powder compacts provide a unique and advantageous combination of mechanical strength properties, such as compression and shear strength, low density and selectable and controllable corrosion properties, particularly rapid and controlled dissolution in various wellbore fluids. The fluids may include any number of ionic fluids or highly polar fluids, such as those that contain various chlorides. Examples include fluids comprising potassium chloride (KCl), hydrochloric acid (HCl), calcium chloride ( $\text{CaCl}_2$ ), calcium bromide ( $\text{CaBr}_2$ ) or zinc bromide ( $\text{ZnBr}_2$ ). The disclosure of the '682 and '361 applications regarding the nature of the coated powders and methods of making and compacting the coated powders are generally applicable to provide the lightweight, high-strength nanomatrix materials disclosed herein, and for brevity, are not repeated herein.

[0013] As illustrated in FIGS. 1 and 2, a powder 10 comprising powder particles 12, including a particle core 14 and core material 18 and metallic coating layer 16 and coating material 20, may be selected that is configured for compaction and sintering to provide a powder metal compact 200 that is lightweight (i.e., having a relatively low density), high-strength and is selectably and controllably removable from a wellbore in response to a change in a wellbore property, including being selectably and controllably dissolvable in an appropriate wellbore fluid, including various wellbore fluids as disclosed herein. The powder metal compact 200 includes a cellular nanomatrix 216 comprising a nanomatrix material 220 and a plurality of dispersed particles 214 comprising a particle core material 218 dispersed in the cellular nanomatrix 216, wherein the particle core material 218 comprises a nanostructured material.

[0014] Dispersed particles 214 may comprise any of the materials described herein for particle cores 14, even though the chemical composition of dispersed particles 214 may be different due to diffusion effects as described herein. The dispersed particles 214 may be formed from any suitable metallic particle core material 220 that includes nanostructure as described herein. In an exemplary embodiment, dispersed particles 214 are formed from particle cores 14 comprising Al, Mg, Zn or Mn, or a combination thereof, as nanostructured particle core material 218. More particularly, in an exemplary embodiment, dispersed particles 214 and particle core material 218 may include various Al or Mg alloys as nanostructured particle core material 218, including various precipitation hardenable alloys Al or Mg alloys. Precipitation hardenable Al or Mg alloys are particularly useful because they afford the opportunity to provide strengthening through both nanostructuring and precipitation hardening through the incorporation of subparticle precipitates as described herein. Dispersed particles 214 and particle core material 218 may also include a rare earth element, or a combination of rare earth elements. As used herein, rare earth elements include Sc, Y, La, Ce, Pr, Nd or Er, or a combination of rare earth elements. Where present, a rare earth element or combination of rare earth elements may be present, by weight, in an amount of about 5 percent or less.

[0015] Dispersed particle 214 and particle core material 218 also comprises a nanostructured material 215. In an exemplary embodiment, a nanostructured material 215 is a material having a grain size, or a subgrain or crystallite size, less than about 200 nm, and more particularly a grain size of about 10 nm to about 200 nm, and even more particularly an average grain size less than about 100 nm. The nanostructure may include high angle boundaries 227, which are usually used to define the grain size, or low angle boundaries 229

that may occur as substructure within a particular grain, which are sometimes used to define a crystallite size, or a combination thereof. The nanostructure may be formed in the particle core 14 used to form dispersed particle 214 by any suitable method, including deformation-induced nanostructure such as may be provided by ball milling a powder to provide particle cores 14, and more particularly by cryomilling (e.g., ball milling in ball milling media at a cryogenic temperature or in a cryogenic fluid, such as liquid nitrogen) a powder to provide the particle cores 14 used to form dispersed particles 214. The particle cores 14 may be formed as a nanostructured material 215 by any suitable method, such as, for example, by milling or cryomilling of prealloyed powder particles of the materials described herein. The particle cores 14 may also be formed by mechanical alloying of pure metal powders of the desired amounts of the various alloy constituents. Mechanical alloying involves ball milling, including cryomilling, of these powder constituents to mechanically enfold and intermix the constituents and form particle cores 14. In addition to the creation of nanostructure as described above, ball milling, including cryomilling, may contribute to solid solution strengthening of the particle core 14 and core material 18, which in turn contribute to solid solution strengthening of dispersed particle 214 and particle core material 218. The solid solution strengthening may result from the ability to mechanically intermix a higher concentration of interstitial or substitutional solute atoms in the solid solution than is possible in accordance with the particular alloy constituent phase equilibria, thereby providing an obstacle to, or serving to restrict, the movement of dislocations within the particle, which in turn provides a strengthening mechanism in particle core 14 and dispersed particle 214. Particle core 14 may also be formed as a nanostructured material 215 by methods including inert gas condensation, chemical vapor condensation, pulse electron deposition, plasma synthesis, crystallization of amorphous solids, electrodeposition and severe plastic deformation, for example. The nanostructure also may include a high dislocation density, such as, for example, a dislocation density between about  $10^{17} \text{ m}^{-2}$  and  $10^{18} \text{ m}^{-2}$ , which may be two to three orders of magnitude higher than similar alloy materials deformed by traditional methods, such as cold rolling.

[0016] Dispersed particle 214 and particle core material 218 may also comprise a subparticle 222, and may preferably comprise a plurality of subparticles. Subparticle 222 provides a dispersion strengthening mechanism within dispersed particle 214 and provides an obstacle to, or serves to restrict, the movement of dislocations within the particle. Subparticle 222 may have any suitable size, and in an exemplary embodiment may have an average particle size of about 10 nm to about 1 micron, and more particularly may have an average

particle size of about 50 nm to about 200 nm. Subparticle 222 may comprise any suitable form of subparticle, including an embedded subparticle 224, a precipitate 226 or a dispersoid 228. Embedded particle 224 may include any suitable embedded subparticle, including various hard subparticles. The embedded subparticle or plurality of embedded subparticles may include various metal, carbon, metal oxide, metal nitride, metal carbide, intermetallic compound or cermet particles, or a combination thereof. In an exemplary embodiment, hard particles may include Ni, Fe, Cu, Co, W, Al, Zn, Mn or Si, or an oxide, nitride, carbide, intermetallic compound or cermet comprising at least one of the foregoing, or a combination thereof. Embedded subparticle 224 may be embedded by any suitable method, including, for example, by ball milling or cryomilling hard particles together with the particle core material 18. A precipitate subparticle 226 may include any subparticle that may be precipitated within the dispersed particle 214, including precipitate subparticles 226 consistent with the phase equilibria of constituents of the materials, particularly metal alloys, of interest and their relative amounts (e.g., a precipitation hardenable alloy), and including those that may be precipitated due to non-equilibrium conditions, such as may occur when an alloy constituent that has been forced into a solid solution of the alloy in an amount above its phase equilibrium limit, as is known to occur during mechanical alloying, is heated sufficiently to activate diffusion mechanisms that enable precipitation. Dispersoid subparticles 228 may include nanoscale particles or clusters of elements resulting from the manufacture of the particle cores 14, such as those associated with ball milling, including constituents of the milling media (e.g., balls) or the milling fluid (e.g., liquid nitrogen) or the surfaces of the particle cores 14 themselves (e.g., metallic oxides or nitrides). Dispersoid subparticles 228 may include, for example, Fe, Ni, Cr, Mn, N, O, C and H. The subparticles 222 may be located anywhere in conjunction with particle cores 14 and dispersed particles 214. In an exemplary embodiment, subparticles 222 may be disposed within or on the surface of dispersed particles 214, or a combination thereof, as illustrated in FIG. 1. In another exemplary embodiment, a plurality of subparticles 222 are disposed on the surface of the particle core 14 and dispersed particles 214 and may also comprise the nanomatrix material 216, as illustrated in FIG. 1.

[0017] Powder compact 200 includes a cellular nanomatrix 216 of a nanomatrix material 220 having a plurality of dispersed particles 214 dispersed throughout the cellular nanomatrix 216. The dispersed particles 214 may be equiaxed in a substantially continuous cellular nanomatrix 216, or may be substantially elongated as described herein and illustrated in FIG. 3. In the case where the dispersed particles 214 are substantially elongated, the

dispersed particles 214 and the cellular nanomatrix 216 may be continuous or discontinuous, as illustrated in FIGS. 4 and 5, respectively. The substantially-continuous cellular nanomatrix 216 and nanomatrix material 220 formed of sintered metallic coating layers 16 is formed by the compaction and sintering of the plurality of metallic coating layers 16 of the plurality of powder particles 12, such as by CIP, HIP or dynamic forging. The chemical composition of nanomatrix material 220 may be different than that of coating material 20 due to diffusion effects associated with the sintering. Powder metal compact 200 also includes a plurality of dispersed particles 214 that comprise particle core material 218. Dispersed particle cores 214 and core material 218 correspond to and are formed from the plurality of particle cores 14 and core material 18 of the plurality of powder particles 12 as the metallic coating layers 16 are sintered together to form nanomatrix 216. The chemical composition of core material 218 may also be different than that of core material 18 due to diffusion effects associated with sintering.

[0018] As used herein, the use of the term cellular nanomatrix 216 does not connote the major constituent of the powder compact, but rather refers to the minority constituent or constituents, whether by weight or by volume. This is distinguished from most matrix composite materials where the matrix comprises the majority constituent by weight or volume. The use of the term substantially-continuous, cellular nanomatrix is intended to describe the extensive, regular, continuous and interconnected nature of the distribution of nanomatrix material 220 within powder compact 200. As used herein, "substantially-continuous" describes the extension of the nanomatrix material throughout powder compact 200 such that it extends between and envelopes substantially all of the dispersed particles 214. Substantially-continuous is used to indicate that complete continuity and regular order of the nanomatrix around each dispersed particle 214 is not required. For example, defects in the coating layer 16 over particle core 14 on some powder particles 12 may cause bridging of the particle cores 14 during sintering of the powder compact 200, thereby causing localized discontinuities to result within the cellular nanomatrix 216, even though in the other portions of the powder compact the nanomatrix is substantially continuous and exhibits the structure described herein. In contrast, in the case of substantially elongated dispersed particles 214, such as those formed by extrusion, "substantially discontinuous" is used to indicate that incomplete continuity and disruption (e.g., cracking or separation) of the nanomatrix around each dispersed particle 214, such as may occur in a predetermined extrusion direction 622, or a direction transverse to this direction. As used herein, "cellular" is used to indicate that the nanomatrix defines a network of generally repeating, interconnected, compartments or cells

of nanomatrix material 220 that encompass and also interconnect the dispersed particles 214. As used herein, "nanomatrix" is used to describe the size or scale of the matrix, particularly the thickness of the matrix between adjacent dispersed particles 214. The metallic coating layers that are sintered together to form the nanomatrix are themselves nanoscale thickness coating layers. Since the nanomatrix at most locations, other than the intersection of more than two dispersed particles 214, generally comprises the interdiffusion and bonding of two coating layers 16 from adjacent powder particles 12 having nanoscale thicknesses, the matrix formed also has a nanoscale thickness (e.g., approximately two times the coating layer thickness as described herein) and is thus described as a nanomatrix. Further, the use of the term dispersed particles 214 does not connote the minor constituent of powder compact 200, but rather refers to the majority constituent or constituents, whether by weight or by volume. The use of the term dispersed particle is intended to convey the discontinuous and discrete distribution of particle core material 218 within powder compact 200.

[0019] Powder compact 200 may have any desired shape or size, including that of a cylindrical billet, bar, sheet or other form that may be machined, formed or otherwise used to form useful articles of manufacture, including various wellbore tools and components. The pressing used to form precursor powder compact 100 and sintering and pressing processes used to form powder compact 200 and deform the powder particles 12, including particle cores 14 and coating layers 16, to provide the full density and desired macroscopic shape and size of powder compact 200 as well as its microstructure. The morphology (e.g. equiaxed or substantially elongated) of the dispersed particles 214 and cellular network 216 of particle layers results from sintering and deformation of the powder particles 12 as they are compacted and interdiffuse and deform to fill the interparticle spaces 15 (FIG. 1). The sintering temperatures and pressures may be selected to ensure that the density of powder compact 200 achieves substantially full theoretical density.

[0020] In an exemplary embodiment, dispersed particles 214 are formed from particle cores 14 dispersed in the cellular nanomatrix 216 of sintered metallic coating layers 16, and the nanomatrix 216 includes a solid-state metallurgical bond or bond layer, extending between the dispersed particles 214 throughout the cellular nanomatrix 216 that is formed at a sintering temperature ( $T_s$ ), where  $T_s$  is less than the melting temperature of the coating ( $T_c$ ) and the melting temperature of the particle ( $T_p$ ). As indicated, solid-state metallurgical bond is formed in the solid state by solid-state interdiffusion between the coating layers 16 of adjacent powder particles 12 that are compressed into touching contact during the compaction and sintering processes used to form powder compact 200, as described herein. As such,

sintered coating layers 16 of cellular nanomatrix 216 include a solid-state bond layer that has a thickness defined by the extent of the interdiffusion of the coating materials 20 of the coating layers 16, which will in turn be defined by the nature of the coating layers 16, including whether they are single or multilayer coating layers, whether they have been selected to promote or limit such interdiffusion, and other factors, as described herein, as well as the sintering and compaction conditions, including the sintering time, temperature and pressure used to form powder compact 200.

[0021] As nanomatrix 216 is formed, including the metallurgical bond and bond layer, the chemical composition or phase distribution, or both, of metallic coating layers 16 may change. Nanomatrix 216 also has a melting temperature ( $T_M$ ). As used herein,  $T_M$  includes the lowest temperature at which incipient melting or liquation or other forms of partial melting will occur within nanomatrix 216, regardless of whether nanomatrix material 220 comprises a pure metal, an alloy with multiple phases each having different melting temperatures or a composite, including a composite comprising a plurality of layers of various coating materials having different melting temperatures, or a combination thereof, or otherwise. As dispersed particles 214 and particle core materials 218 are formed in conjunction with nanomatrix 216, diffusion of constituents of metallic coating layers 16 into the particle cores 14 is also possible, which may result in changes in the chemical composition or phase distribution, or both, of particle cores 14. As a result, dispersed particles 214 and particle core materials 218 may have a melting temperature ( $T_{DP}$ ) that is different than  $T_P$ . As used herein,  $T_{DP}$  includes the lowest temperature at which incipient melting or liquation or other forms of partial melting will occur within dispersed particles 214, regardless of whether particle core material 218 comprise a pure metal, an alloy with multiple phases each having different melting temperatures or a composite, or otherwise. In one embodiment, powder compact 200 is formed at a sintering temperature ( $T_S$ ), where  $T_S$  is less than  $T_C$ ,  $T_P$ ,  $T_M$  and  $T_{DP}$ , and the sintering is performed entirely in the solid-state resulting in a solid-state bond layer. In another exemplary embodiment, powder compact 200 is formed at a sintering temperature ( $T_S$ ), where  $T_S$  is greater than or equal to one or more of  $T_C$ ,  $T_P$ ,  $T_M$  or  $T_{DP}$  and the sintering includes limited or partial melting within the powder compact 200 as described herein, and further may include liquid-state or liquid-phase sintering resulting in a bond layer that is at least partially melted and resolidified. In this embodiment, the combination of a predetermined  $T_S$  and a predetermined sintering time ( $t_s$ ) will be selected to preserve the desired microstructure that includes the cellular nanomatrix 216 and dispersed particles 214. For example, localized liquation or melting may be

permitted to occur, for example, within all or a portion of nanomatrix 216 so long as the cellular nanomatrix 216/dispersed particle 214 morphology is preserved, such as by selecting particle cores 14,  $T_s$  and  $t_s$  that do not provide for complete melting of particle cores. Similarly, localized liquation may be permitted to occur, for example, within all or a portion of dispersed particles 214 so long as the cellular nanomatrix 216/dispersed particle 214 morphology is preserved, such as by selecting metallic coating layers 16,  $T_s$  and  $t_s$  that do not provide for complete melting of the coating layer or layers 16. Melting of metallic coating layers 16 may, for example, occur during sintering along the metallic layer 16 /particle core 14 interface, or along the interface between adjacent layers of multi-layer coating layers 16. It will be appreciated that combinations of  $T_s$  and  $t_s$  that exceed the predetermined values may result in other microstructures, such as an equilibrium melt/resolidification microstructure if, for example, both the nanomatrix 216 (i.e., combination of metallic coating layers 16) and dispersed particles 214 (i.e., the particle cores 14) are melted, thereby allowing rapid interdiffusion of these materials.

[0022] Particle cores 14 and dispersed particles 214 of powder compact 200 may have any suitable particle size. In an exemplary embodiment, the particle cores 14 may have a unimodal distribution and an average particle diameter or size of about 5 $\mu$ m to about 300 $\mu$ m, more particularly about 80 $\mu$ m to about 120 $\mu$ m, and even more particularly about 100 $\mu$ m. In another exemplary embodiment, which may include a multi-modal distribution of particle sizes, the particle cores 14 may have average particle diameters or size of about 50nm to about 500 $\mu$ m, more particularly about 500nm to about 300 $\mu$ m, and even more particularly about 5 $\mu$ m to about 300 $\mu$ m. In an exemplary embodiment, the particle cores 14 or the dispersed particles may have an average particle size of about 50 nm to about 500  $\mu$ m.

[0023] Dispersed particles 214 may have any suitable shape depending on the shape selected for particle cores 14 and powder particles 12, as well as the method used to sinter and compact powder 10. In an exemplary embodiment, powder particles 12 may be spheroidal or substantially spheroidal and dispersed particles 214 may include an equiaxed particle configuration as described herein. In another exemplary embodiment, dispersed particles may have a non-spherical shape. In yet another embodiment, the dispersed particles may be substantially elongated in a predetermined extrusion direction 622, such as may occur when using extrusion to form powder compact 200. As illustrated in FIG. 3-5, for example, a substantially elongated cellular nanomatrix 616 comprising a network of interconnected elongated cells of nanomatrix material 620 having a plurality of substantially elongated dispersed particle cores 614 of core material 618 disposed within the cells. Depending on the

amount of deformation imparted to form elongated particles, the elongated coating layers and the nanomatrix 616 may be substantially continuous in the predetermined direction 622 as shown in FIG. 4, or substantially discontinuous as shown in FIG. 5.

[0024] The nature of the dispersion of dispersed particles 214 may be affected by the selection of the powder 10 or powders 10 used to make particle compact 200. In one exemplary embodiment, a powder 10 having a unimodal distribution of powder particle 12 sizes may be selected to form powder compact 200 and will produce a substantially homogeneous unimodal dispersion of particle sizes of dispersed particles 214 within cellular nanomatrix 216. In another exemplary embodiment, a plurality of powders 10 having a plurality of powder particles with particle cores 14 that have the same core materials 18 and different core sizes and the same coating material 20 may be selected and uniformly mixed as described herein to provide a powder 10 having a homogenous, multimodal distribution of powder particle 12 sizes, and may be used to form powder compact 200 having a homogeneous, multimodal dispersion of particle sizes of dispersed particles 214 within cellular nanomatrix 216. Similarly, in yet another exemplary embodiment, a plurality of powders 10 having a plurality of particle cores 14 that may have the same core materials 18 and different core sizes and the same coating material 20 may be selected and distributed in a non-uniform manner to provide a non-homogenous, multimodal distribution of powder particle sizes, and may be used to form powder compact 200 having a non-homogeneous, multimodal dispersion of particle sizes of dispersed particles 214 within cellular nanomatrix 216. The selection of the distribution of particle core size may be used to determine, for example, the particle size and interparticle spacing of the dispersed particles 214 within the cellular nanomatrix 216 of powder compacts 200 made from powder 10.

[0025] As illustrated generally in FIGS. 1 and 2, powder metal compact 200 may also be formed using coated metallic powder 10 and an additional or second powder 30, as described herein. The use of an additional powder 30 provides a powder compact 200 that also includes a plurality of dispersed second particles 234, as described herein, that are dispersed within the nanomatrix 216 and are also dispersed with respect to the dispersed particles 214. Dispersed second particles 234 may be formed from coated or uncoated second powder particles 32, as described herein. In an exemplary embodiment, coated second powder particles 32 may be coated with a coating layer 36 that is the same as coating layer 16 of powder particles 12, such that coating layers 36 also contribute to the nanomatrix 216. In another exemplary embodiment, the second powder particles 232 may be uncoated such that dispersed second particles 234 are embedded within nanomatrix 216. As disclosed

herein, powder 10 and additional powder 30 may be mixed to form a homogeneous dispersion of dispersed particles 214 and dispersed second particles 234 or to form a non-homogeneous dispersion of these particles. The dispersed second particles 234 may be formed from any suitable additional powder 30 that is different from powder 10, either due to a compositional difference in the particle core 34, or coating layer 36, or both of them, and may include any of the materials disclosed herein for use as second powder 30 that are different from the powder 10 that is selected to form powder compact 200. In an exemplary embodiment, dispersed second particles 234 may include Ni, Fe, Cu, Co, W, Al, Zn, Mn or Si, or an oxide, nitride, carbide, intermetallic compound or cermet comprising at least one of the foregoing, or a combination thereof.

[0026] Nanomatrix 216 is a substantially-continuous, cellular network of metallic coating layers 16 that are sintered to one another. The thickness of nanomatrix 216 will depend on the nature of the powder 10 or powders 10 used to form powder compact 200, as well as the incorporation of any second powder 30, particularly the thicknesses of the coating layers associated with these particles. In an exemplary embodiment, the thickness of nanomatrix 216 is substantially uniform throughout the microstructure of powder compact 200 and comprises about two times the thickness of the coating layers 16 of powder particles 12. In another exemplary embodiment, the cellular network 216 has a substantially uniform average thickness between dispersed particles 214 of about 50nm to about 5000nm. Powder compacts 200 formed by extrusion may have much smaller thicknesses, and may become non-uniform and substantially discontinuous, as described herein.

[0027] Nanomatrix 216 is formed by sintering metallic coating layers 16 of adjacent particles to one another by interdiffusion and creation of bond layer as described herein. Metallic coating layers 16 may be single layer or multilayer structures, and they may be selected to promote or inhibit diffusion, or both, within the layer or between the layers of metallic coating layer 16, or between the metallic coating layer 16 and particle core 14, or between the metallic coating layer 16 and the metallic coating layer 16 of an adjacent powder particle, the extent of interdiffusion of metallic coating layers 16 during sintering may be limited or extensive depending on the coating thicknesses, coating material or materials selected, the sintering conditions and other factors. Given the potential complexity of the interdiffusion and interaction of the constituents, description of the resulting chemical composition of nanomatrix 216 and nanomatrix material 220 may be simply understood to be a combination of the constituents of coating layers 16 that may also include one or more constituents of dispersed particles 214, depending on the extent of interdiffusion, if any, that

occurs between the dispersed particles 214 and the nanomatrix 216. Similarly, the chemical composition of dispersed particles 214 and particle core material 218 may be simply understood to be a combination of the constituents of particle core 14 that may also include one or more constituents of nanomatrix 216 and nanomatrix material 220, depending on the extent of interdiffusion, if any, that occurs between the dispersed particles 214 and the nanomatrix 216.

[0028] In an exemplary embodiment, the nanomatrix material 220 has a chemical composition and the particle core material 218 has a chemical composition that is different from that of nanomatrix material 220, and the differences in the chemical compositions may be configured to provide a selectable and controllable dissolution rate, including a selectable transition from a very low dissolution rate to a very rapid dissolution rate, in response to a controlled change in a property or condition of the wellbore proximate the compact 200, including a property change in a wellbore fluid that is in contact with the powder compact 200, as described herein. Nanomatrix 216 may be formed from powder particles 12 having single layer and multilayer coating layers 16. This design flexibility provides a large number of material combinations, particularly in the case of multilayer coating layers 16, that can be utilized to tailor the cellular nanomatrix 216 and composition of nanomatrix material 220 by controlling the interaction of the coating layer constituents, both within a given layer, as well as between a coating layer 16 and the particle core 14 with which it is associated or a coating layer 16 of an adjacent powder particle 12.

[0029] In an exemplary embodiment, nanomatrix 216 may comprise a nanomatrix material 220 comprising Ni, Fe, Cu, Co, W, Al, Zn, Mn, Mg or Si, or an alloy thereof, or an oxide, nitride, carbide, intermetallic compound or cermet comprising at least one of the foregoing, or a combination thereof.

[0030] The powder metal compacts 200 disclosed herein may be configured to provide selectively and controllably disposable, degradable, dissolvable, corrodible or otherwise removable from a wellbore using a predetermined wellbore fluid, including those described herein. These materials may be configured to provide Al alloys with a rate of corrosion up to about 400 mg/cm<sup>2</sup>/hr, and more particularly a rate of corrosion of about 0.5 to about 100 mg/cm<sup>2</sup>/hr. The Al alloy powder compacts 200 may also be configured to provide high strength, including an ultimate compressive strength up to about 150 ksi, and more particularly from about 60 ksi to about 150 ksi, and even more particularly about 60 ksi to about 120ksi. These materials may also be configured to provide Mg alloys with a rate of corrosion up to about 500 mg/cm<sup>2</sup>/hr, and more particularly a rate of corrosion of about 0.5 to

about 50 mg/cm<sup>2</sup>/hr. The Mg alloy powder compacts 200 may also be configured to provide high strength, including an ultimate compressive strength up to about 85 ksi, and more particularly from about 40 ksi to about 70 ksi.

[0031] The terms "a" and "an" herein do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced items. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., includes the degree of error associated with measurement of the particular quantity). Furthermore, unless otherwise limited all ranges disclosed herein are inclusive and combinable (e.g., ranges of "up to about 25 weight percent (wt.%), more particularly about 5 wt.% to about 20 wt.% and even more particularly about 10 wt.% to about 15 wt.%" are inclusive of the endpoints and all intermediate values of the ranges, e.g., "about 5 wt.% to about 25 wt.%, about 5 wt.% to about 15 wt.%", etc.). The use of "about" in conjunction with a listing of constituents of an alloy composition is applied to all of the listed constituents, and in conjunction with a range to both endpoints of the range. Finally, unless defined otherwise, technical and scientific terms used herein have the same meaning as is commonly understood by one of skill in the art to which this invention belongs. The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including one or more of that term (e.g., the metal(s) includes one or more metals). Reference throughout the specification to "one embodiment", "another embodiment", "an embodiment", and so forth, means that a particular element (e.g., feature, structure, and/or characteristic) described in connection with the embodiment is included in at least one embodiment described herein, and may or may not be present in other embodiments.

[0032] It is to be understood that the use of "comprising" in conjunction with the alloy compositions described herein specifically discloses and includes the embodiments wherein the alloy compositions "consist essentially of" the named components (i.e., contain the named components and no other components that significantly adversely affect the basic and novel features disclosed), and embodiments wherein the alloy compositions "consist of" the named components (i.e., contain only the named components except for contaminants which are naturally and inevitably present in each of the named components).

[0033] While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation.

## CLAIMS:

1. A powder metal compact, comprising:  
a cellular nanomatrix comprising a metallic nanomatrix material;  
a plurality of dispersed particles comprising a metallic particle core material dispersed in the cellular nanomatrix, the particle core material comprising a nanostructured material.
2. The powder metal compact of claim 1, wherein the particle core material comprises Al, Mg, Zn or Mn, or a combination thereof.
3. The powder metal compact of claim 2, wherein the nanomatrix material comprises that comprises an Al alloy or an Mg alloy.
4. The powder metal compact of claim 1, wherein the nanomatrix material comprises a nanostructured material.
5. The powder metal compact of claim 1, wherein the nanostructured material has a grain size less than about 200 nm.
6. The powder metal compact of claim 5, wherein the nanostructured material has a grain size of about 10nm to about 200 nm.
7. The powder metal compact of claim 1, wherein the nanostructured material has an average grain size less than about 100 nm.
8. The powder metal compact of claim 1, wherein the dispersed particle further comprises a subparticle.
9. The powder metal compact of claim 8, wherein the subparticle has an average particle size of about 10 nm to about 1 micron.
10. The powder metal compact of claim 8, wherein the subparticle comprises a preformed subparticle, a precipitate or a dispersoid.
11. The powder metal compact of claim 8, wherein the subparticle is disposed within or on the surface of the dispersed particle, or a combination thereof.
12. The powder metal compact of claim 11, wherein the subparticle is disposed on the surface of the dispersed particle and also comprises the nanomatrix material.
13. The powder metal compact of claim 1, wherein the dispersed particles have an average particle size of about 50nm to about 500 $\mu$ m.
14. The powder metal compact of claim 1, wherein the dispersion of dispersed particles comprises a multi-modal distribution of particle sizes within the cellular nanomatrix.
15. The powder metal compact of claim 1, wherein the particle core material further comprises a rare earth element.

16. The powder metal compact of claim 1, wherein the dispersed particles have an equiaxed particle shape and the nanomatrix is substantially continuous.

17. The powder metal compact of claim 1, wherein the nanomatrix and the dispersed particles are substantially elongated in a predetermined direction.

18. The powder metal compact of claim 17, wherein the nanomatrix and the dispersed particles are substantially continuous.

19. The powder metal compact of claim 17, wherein the nanomatrix and the dispersed particles are substantially discontinuous.

20. The powder metal compact of claim 1, further comprising a plurality of dispersed second particles, wherein the dispersed second particles are also dispersed within the cellular nanomatrix and with respect to the dispersed particles.

21. The powder metal compact of claim 1, wherein the dispersed second particles comprise a metal, carbon, metal oxide, metal nitride, metal carbide, intermetallic compound or cermet, or a combination thereof.

22. The powder metal compact of claim 21, wherein the dispersed second particles comprise Ni, Fe, Cu, Co, W, Al, Mg, Zn, Mn or Si, or an oxide, nitride, carbide, intermetallic compound or cermet comprising at least one of the foregoing, or a combination thereof.

23. The powder metal compact of claim 1, wherein the nanomatrix material comprises a metal, carbon, metal oxide, metal nitride, metal carbide, intermetallic compound or cermet, or a combination thereof.

24. The powder metal compact of claim 1, wherein the nanomatrix material comprises a constituent of a milling medium or a milling fluid.

25. The powder metal compact of claim 23, wherein the nanomatrix material comprises Ni, Fe, Cu, Co, W, Al, Zn, Mn, Mg or Si, or an oxide, nitride, carbide, intermetallic compound or cermet comprising at least one of the foregoing, or a combination thereof.

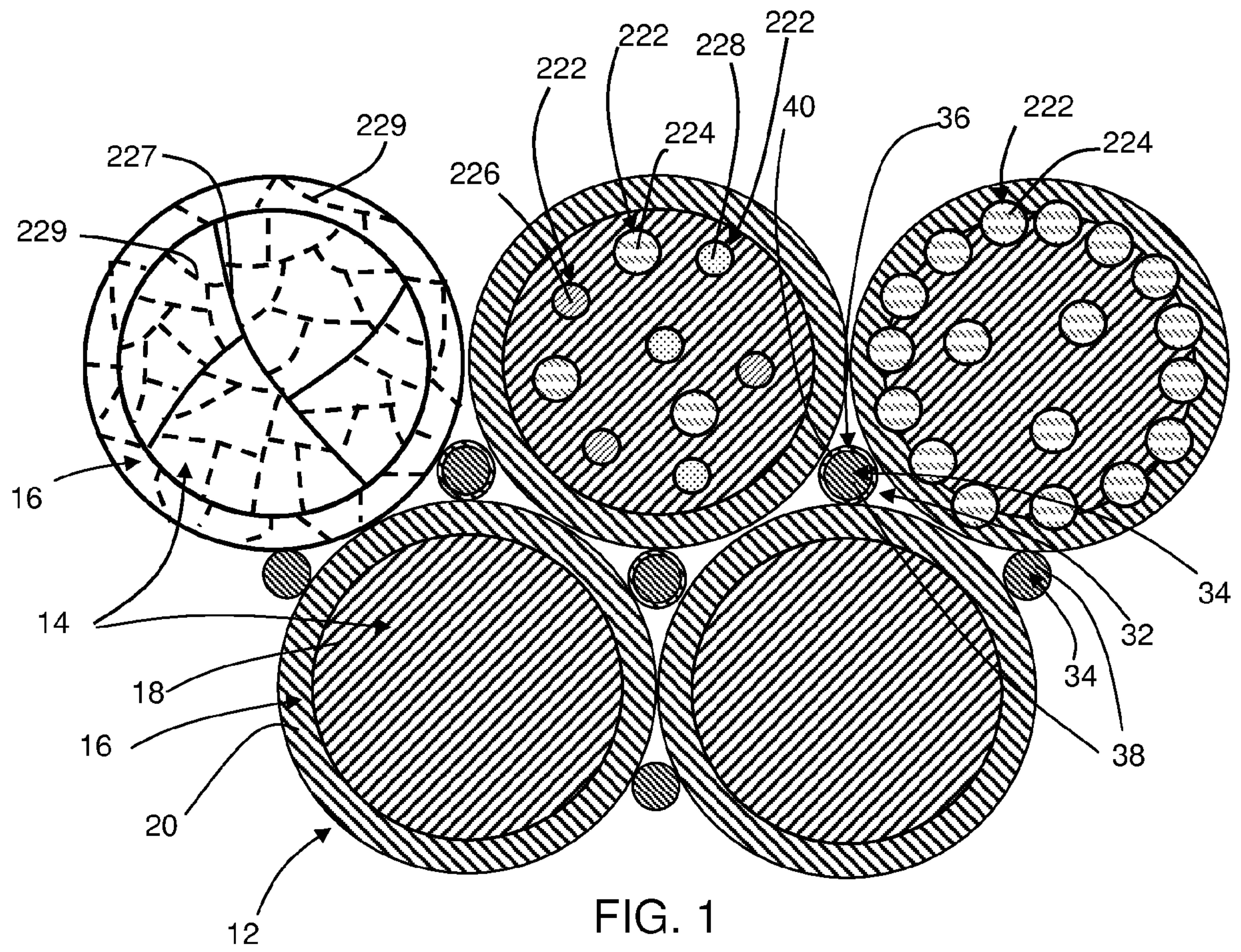
26. The powder metal compact of claim 1, wherein the nanomatrix material comprises a multilayer material.

27. The powder metal compact of claim 1, wherein the nanomatrix material has a chemical composition and the particle core material has a chemical composition that is different than the chemical composition of the nanomatrix material.

28. The powder metal compact of claim 1, wherein the cellular nanomatrix has an average thickness of about 50nm to about 5000nm.

29. The powder metal compact of claim 1, further comprising a bond layer extending throughout the cellular nanomatrix between the dispersed particles.

30. The powder metal compact of claim 29, wherein the bond layer comprises a substantially solid state bond layer.



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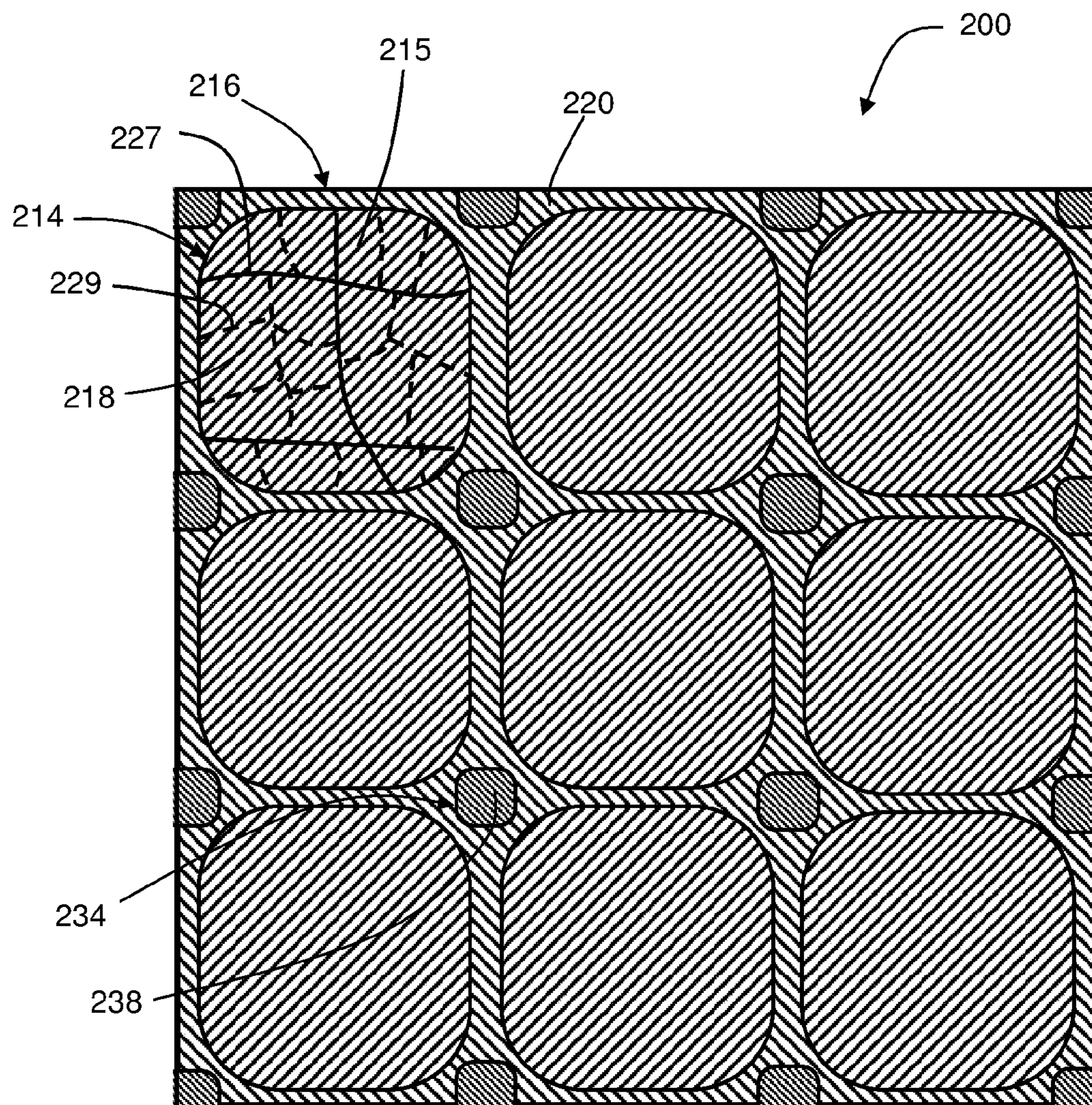


FIG. 2

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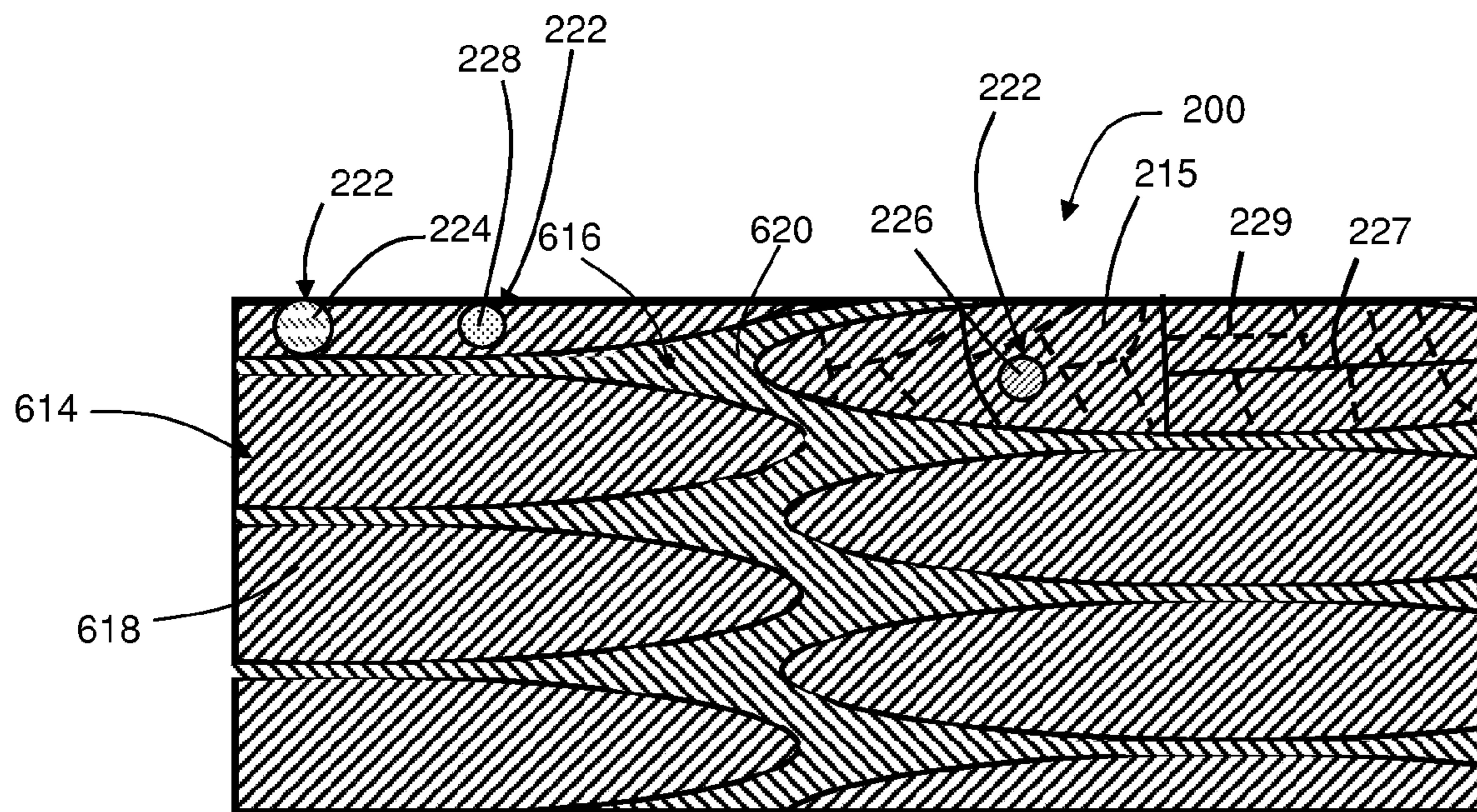


FIG. 3

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